

893 30 8-2
HR dtd 6/25/79

GEFR-SP 148

DATE June, 1979

CONF-800513--4

TITLE: Inelastic Behavior of a Dissimilar-Metal-Welded Pipe Transition Joint - Comparison of Experimental Measurements and Analytical Prediction

AUTHORS: T. M. Yang & A. W. Dalcher

Prepared for presentation at:

Fourth International Conference on Pressure Vessel Technology
Conference

Held in: London, England
City, State

on: May, 1980
Date

DISCLAIMER
This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof nor any of the employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This paper contains material
resulting from work performed
for: DOE

Under Contract No. AT03-76SF70030 EY-76-C-03-0893, Task 30, Work P...
Under DA _____ task No. SG...

This paper has been authored by a contractor of the U.S. Government under contract No. EY-76-C-03-0893. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.



ADVANCED REACTOR SYSTEMS DEPARTMENT

SUNNYVALE, CALIFORNIA

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

MASTER

MASTER

INELASTIC BEHAVIOR OF A DISSIMILAR METAL WELDED PIPE
TRANSITION JOINT- COMPARISON OF EXPERIMENTAL
MEASUREMENTS AND ANALYTICAL PREDICTION

by

T. M. Yang* and A. W. Dalcher[†]
General Electric Company
Advanced Reactor Systems Department
Sunnyvale, California 94086

Submitted for the Fourth International Conference on Pressure
Vessel Technology, London, 1980

* Senior Engineer, Component Structural Analysis Unit

† Manager, Component Structural Analysis Unit

ABSTRACT

Development of the liquid metal fast breeder reactor (LMFBR) for high temperature operation has made it increasingly important to quantitatively evaluate the mechanical behavior of the welded joints which provide the transition between components made of different materials. Elastic analysis of several types of such joints have generally indicated high stress and prevailing inelastic metal behavior. For this reason, elastic analysis is not sufficient to accurately describe the behavior of these transition joints.

This paper presents the quantitative study of the inelastic (plastic and creep) behavior of a test transition joint. The objectives of the study were: (1) to perform a theoretical analysis of the joint behavior in a realistic manner, (2) to establish the viability of the utilized inelastic analysis procedure, and (3) evaluate the validity of the assumptions and analytical procedure when applied to complex structures such as transition joints. The results of this study will contribute to the procedures for design and application of transition joints and other complex structures requiring inelastic analysis.

The subject study involved the prediction and observed behavior of a dissimilar metal pipe joint made from 2 1/4 Cr-1Mo steel welded to type 316 austenitic stainless steel using a nickel-base filler metal, ERNiCr-3. A two dimensional axi-symmetric finite element model was employed in the analysis, with certain assumptions made relative to the initial stress state of the joint. Internal pressure and thermal loadings which simulated the test conditions experienced by the joint, were used as inputs. Uni-axial stress-strain relationships and creep equations were applied to the multi-axial stress state through the concept of effective stress and equivalent strain.

The analysis indicated that the loading history during the preparatory period (before actual service) has a significant effect on the behavior

of the transition joint in its early service life. The magnitudes of the stresses created at the vicinity of the dissimilar metal interfaces, mainly due to the differences in thermal expansions of the metals, are sufficient to yield the metals, and fast thermal down transients during service will induce more yielding of the metals before shakedown occurs.

Calculated plastic ratchetting and creep responses of the joint metals were compared with strain measurements of the test joint obtained at the Oak Ridge National Laboratory. Very good agreement was shown to exist between the predictions and measurements. This good agreement between predictions and measurements reflects the correctness of the model, the analysis inputs, and the assumptions. A valid inelastic analysis procedure is thus established which may be used for future design analysis.

I. Introduction

Power generating plants usually select different types of steel for the structure of the steam generator and the piping system to suit the particular service environments of the individual components, such as temperature, pressure, coolant chemical contents, and corrosion requirements, etc. This is particularly true for a Liquid Metal Fast Breeder Reactor (LMFBR) in which the heat transporting liquid is normally liquid sodium and high temperature (above 800°F) operation is expected. In the U.S. LMFBR program, 2 1/4 Cr-1 Mo steel is generally selected for the steam generator and Type 316 stainless steel (SS316) for heat transport piping system. When pipes of two different materials are joined and subsequently subjected to pressure and/or thermal loading, local high stresses may be created due to the different physical properties of the materials. The expected high temperature operation has made it increasingly important to quantitatively evaluate the mechanical behavior of these welded joints. The application of transition joints between austenitic and ferritic steels in nuclear power plant piping system demands a high degree of reliability of such joints because of the difficulty in field repair.

Several publications have addressed the problem of transition joints. For example, Carpenter and others^[1]* reported their fatigue test data of transition joints with various weld design. Slaughter and Housley^[2] investigated the behavior of filler metals for joining ferritic steels to austenitic stainless steels and found Inconel 182 to be satisfactory. More recently, Mather^[3] analytically derived the bending stresses at a joint

* Number in brackets refers to References at end of paper.

of a dissimilar metals at elevated temperature and concluded that a conical joint gave lower bending stresses than a long, flat-ended joint. A conference on welding of dissimilar metals was held in England in 1969. However, most presentations were concerned with service experience and metallurgical consideration of dissimilar metal joints. Hardy and others^[4] performed a comprehensive study of bi-metal joints (the filler metal was the same as one of the parent metals) with various weld preparations, subjected to thermal loadings due to the difference in thermal expansions of the parent metals alone. Limited test results were also reported in this paper.

More recently, the authors presented two papers^[5, 6] addressed to this subject. In [5], a parametric study of transition joints was performed to define a design configuration which minimizes the stresses and retain practicality of weldability. However, it was determined with an elastic analysis that even with this configuration, the joint, when applied to a typical LMFBR steam generator sodium inlet, indicates high stress and prevailing inelastic behavior. For this reason, the elastic analysis is not sufficient to accurately describe the behavior of these transient joints. An inelastic method of analysis is expected to be more realistic in predicting the joint behavior. An attempt was made in [6] to study the plastic response of a transition joint.

This paper presents the quantitative study of the inelastic (plastic and creep) behavior of a test transition joint. The objectives of the study are: (1) to perform a theoretical analysis of the joint behavior in a realistic manner, (2) to establish the viability of the utilized inelastic analysis procedure,

and (3) evaluate the validity of the assumptions and analytical procedure when applied to complex structures such as transition joints. The results of this study will contribute to the procedures for design and application of transition joints and other complex structures requiring inelastic analysis.

The manufacturing process of a welded transition joint usually involves heat treatment of the completed piece after welding to relieve any residual stresses in the weld region. After the heat treatment, the joint is cooled down to room temperature for transportation, installation, or other operations. According to [5], the large temperature change from the heat treatment temperature to the room temperature would produce very large stresses in the transition joint due to the differential thermal expansion of the metals. In the case of a bi-metal joint of 2 1/4 Cr-1Mo steel pipe to type 316 stainless steel pipe with ERNiCr-3 as welding material, these thermally induced stresses are sufficient to yield the materials. Plastic strains are expected to occur in the joint region. This phenomenon is quite different from a homogeneous mono-metal pipe joint in which an isothermal temperature change produces no stress.

In [6], the authors presented a plastic analysis of a SS316 to 2 1/4 Cr-1Mo steel joint to simulate the process of joint manufacturing, heat treatment, and cool down to room temperature. The applicability of the simplified Bree diagram to a multi-dimensional stress state was also examined. In the present paper, a more detailed inelastic (plastic and creep) analysis is presented to simulate a pre-test procedure, and the following ratchetting and creep test conducted at the Oak Ridge National Laboratory (ORNL), Oak Ridge,

Tennessee, U.S.A.^[7] The application of this procedure to joint design analysis is discussed.

II. Model and Loadings

The ratchetting and creep test article of a SS316 to 2 1/4 Cr-1Mo steel transition joint conducted at the Oak Ridge National Laboratory (ORNL), Oak Ridge, Tennessee, U.S.A. was selected as the subject of the inelastic analysis. The selection was based on the following considerations:

- (1) The configuration of the test article simulated a typical transition joint configuration from austenitic steel (SS316) pipe to ferritic steel (2 1/4 Cr-1Mo) pipe with conventional weld geometry and ERNiCr-3 welding material.
- (2) Reliable data were expected from this test based on past experience of ratchetting and creep tests with the ORNL test loop and the data acquisition systems.
- (3) Material properties needed for an inelastic analysis were generated from the same heats of materials used in the construction of the test specimen. This would increase the comparability of analytical prediction with the test results and assist in the evaluation of the validity of the analytical procedure.
- (4) The test data would be the earliest available data from an inelastic, multi-metallic welded joint test with full test details available to the authors.

The weld joint of this analysis is a SS316 pipe welded to a 2 1/4 Cr-1 Mo steel pipe with ErNiCr-3 welding metal. The pipe is modelled as axisymmetric structure with outside diameter of 20.3 cm (8 inches) and wall thickness of 0.95 cm (3/8 in.). The analytical model of the pipe wall is depicted in Figure 1. The finished pipe joint has a weld root opening R of approximately 0.25 cm (0.1 in.). The included angle of the weld is 75°. The model assumes straight material interfaces as shown in the figure. Any heat affected or decarburized zones that might exist in the joint structure are not included in the analysis. The model includes a segment of each pipe that is approximately 14 cm (5.5 inches) in length. This length is chosen such that detail stress distribution at the ends will have no effect on the stress distribution at the metal interfaces, where high stresses are expected and which are the most critical areas in design consideration.

The loading history of the test specimen can be divided into two parts: The first part is the pre-test conditions which include the post weld heat treatment, the following isothermal cool down to room temperature for test preparation, and strain gage calibration at high temperatures and various internal pressures. The second part is the ratchetting and creep test loading which includes a thermal downshock followed by a hold period at elevated temperature with internal pressure. Each of these is described in detail in the following.

The pre-test conditions are depicted in Figure 2. Figure 2a shows the temperature history and Figure 2b shows the pressure history. The post-weld

heat treatment was at 732°C (1350°F). At room temperature, the specimen was machined to the final size and strain gages were installed. A series of temperature and pressure changes were then applied to calibrate the strain gages to determine the force exerted from the pipelines on the article, and to obtain apparent strain curves and gage factors of the strain gages at high temperatures. The article was finally maintained at 538°C (1000°F) for the ratchetting and creep test. During this preparation period, the time during which the specimen was at high temperature with high internal pressure was short. Therefore, a plastic analysis simulation was deemed sufficient.

The temperature and pressure history of the ratchetting and creep test are shown in Figure 3. The cycle was initiated by a thermal downshock from 538°C (1000°F) to 371°C (700°F) in 10 seconds followed by a temperature heatup at 28°C (50°F) per hour. This transient was followed by a high temperature hold period of one week. An internal pressure of 3.24MPa (470 psi) was maintained at all times except during a short period when the specimen was at 371°C. This cycle could be repeated. For this analysis, simulation of five test cycles has been performed.

III. Material Properties

The material properties used for this analysis are generally from recognized sources, such as the Nuclear Systems Materials Handbook^[8], whenever possible. For better characterization of the materials, the stress-strain relationships of all three metals were obtained by ORNL from separate cyclic loading tests with a 4% strain range. These tests were performed with material specimens taken from the same heats of material as used in the

construction of the pipe transition joint article. From these tests of stress-strain relationships, the cyclic Young's modulus, plastic modulus and yield stress of the various cycles can be obtained. For an inelastic analysis, Ref. [9] generally recommends that the first cycle and tenth cycle values to be used with some modification for 2 1/4 Cr-1Mo at high temperature. Following this recommendation and with the measured stress-strain relationship, the first and tenth cycle yield stresses were obtained. The stress-strain relationship curves are bi-linearized for this purpose. The procedure of bi-linearization of SS316 and 2 1/4 Cr-1Mo steel follows the recommendations of [9]. For ERNiCr-3, no recommendation has been proposed. However, based on the general shape of the stress-strain curves of this weld metal, it was determined that the bilinearization procedure for 2 1/4 Cr-1Mo steel gives better approximation to the measured stress-strain relationship. The yield stresses so obtained are shown in Figures 4, 5, and 6 for SS316, 2 1/4 Cr-1Mo steel, and ERNiCr-3, respectively.

Note that there is only one value of yield stress for ERNiCr-3 at each temperature for both the first and the tenth cycle. This is due to the fact that the first cycle yield value and the tenth cycle yield value are very close, and the approximation in bi-linearization to obtain these values makes the distinction meaningless. Also note that the two lines denoted as "adjusted" yield stress for SS316. This adjustment is based on the fact that the measured values of first cycle yield are lower than the minimum yield specified in ASME Code [10]. Also, the stress-strain relationship of SS316 was measured with samples from plate material before fabrication into pipe sections. Since SS316 is known to be susceptible to work hardening by

fabrication, it is anticipated that the pipe metal will have higher yield, although the exact values are not known for lack of measurement. The yield stresses of SS316 are, therefore, adjusted upward in a somewhat arbitrary manner. The room temperature yield stress is arbitrarily increased to half way between the measured value and the minimum expected yield value in [10]. It is extended to coincide with the current yield values at 550°F at which the minimum expected yield vs. temperature curve from [10] shows a change of slope. The 10th cycle yield stress values are also adjusted such that at room temperature it assumes the value in [10], 30 ksi. The adjusted curve parallels the 1st cycle curve until it intersects with the current value curve at approximately 630°F. The high temperature yield values use the currently measured results.

ORNL also obtained limited amounts of creep measurements from each material at selected temperatures (1000°F and 1100°F). Based on these measurements, the following creep equations are constructed:

(1) For 2 1/4 Cr-1Mo steel

$$\epsilon_c = \frac{t}{A+Bt} + \dot{\epsilon}_m t$$

where

ϵ_c = creep strain in %

t = time in hours

$$\log_{10} A = 12.26 - 3.348 \times 10^{-6} T^2 + 9.353 \times 10^{-4} \sigma$$

$$\log_{10} B = -52.16 + 8.682 \times 10^{-2} T - 3.368 \times 10^{-5} T^2 - 1.152 (\log_{10} \sigma)^2$$

$$\log_{10} \dot{\epsilon}_m = -29.48 + 1.516 \times 10^{-2} T + 2.001 \times 10^{-3} T (\log_{10} \sigma)$$

σ = stress in ksi

T = temperature in °K

(2) For SS316

$$\epsilon_c = A t_{\sigma}^{m,n} e^{-B/T}$$

where A = 1.912

m = 0.3

n = 4

B = 30850.5

(3) For ERNiCr-3

$$\epsilon_c = A t_{\sigma}^{m,n} e^{-B/T}$$

where

A = 0.00216

m = 0.25

n = 4

B = 9255.2

IV. Structural Response to Pre-test Procedures

The study of structural response in this period was limited to a plastic analysis. Several assumptions were made to simplify the analysis.

These were:

(1) The joint is stress-free after the post weld heat treatment at 732°C.

This is believed realistic due to the high stress relaxation rate of

2 1/4 Cr-1Mo at this temperature.

- (2) Temperature changes are isothermal throughout the structure. This is valid due to the slow rate of temperature changes during the pre-test calibration period; and
- (3) No external mechanical loads act on the specimen except the applied internal pressure. The test loop is carefully adjusted to eliminate loads imposed on the test article from the piping system.

The methodology of plastic analysis is based on the recommended procedures in RDT Standard F9-5T^[9]. The same procedures were used in the analysis reported in [6], and the general features of plastic response are also similar to those reported in [6]. However, because of the difference in material properties and the pre-test procedures between the current analysis and Ref. [6], a new analysis is warranted but only results of significance will be discussed here.

At temperature above 593°C (1100°F) the joint remained elastic. In agreement with the results of [5], the maximum stress was in SS316 near its interface with ERNiCr-3. At 593°C, yielding initiated in SS316. As the temperature continued to decrease, the yield zone gradually expanded. Both the yield stress of the material and the thermally induced stress increased with decreasing temperature. The fact that the yield zone expanded indicated that the thermal stress increased faster than the increase in the yield stress. At 488°C (910°F), the 2 1/4 Cr-1Mo steel yielded. The ERNiCr-3 near the interface with SS316 yielded at 54°C (130°F). All these yield

zones continued to expand as the temperature decreased. Note that SS316 and 2 1/4 Cr-1Mo steel yielded at higher temperatures than those reported in [6] due to their lower yield stresses and ERNiCr-3 yielded at a much lower temperature due to its much higher yield stress than that used in [6]. The weld material at the 2 1/4 Cr-1Mo steel interface did not yield at all during the cooldown cycle, which is again due to the high yield stress of ERNiCr-3. This result is also different from that reported in [6]. Figure 7 shows the extent of the yield zones and the contours of the plastic strains at room temperature. As expected, the plastic zones were around the material interfaces. Because of the high yield stress of ERNiCr-3 and the large stress gradient between the metal interfaces across the weld metal, the yield zone in Inconel 82 is very narrow. The effective stress intensity at this time is shown in Figure 8.

A qualitative discussion of the stress-strain history during the pre-test procedures was given in [6] and is briefly repeated here with the aid of Figure 9. This figure shows the stress-strain history of 2 1/4 Cr-1Mo steel near the weld interface only. Other metals will exhibit similar characteristics and Reference [6] provides a detailed discussion.

This curve shows a stress free state at 732°C (1350°F), the post weld heat treatment temperature. As the structure temperature decreased, the 2 1/4 Cr-1Mo steel near the interface was subjected to a compressive stress because of its smaller coefficient of thermal expansion. The loading continued up to room temperature during the first temperature decrease. Yielding occurred at 488°C (910°F) as indicated by point A. Application of internal pressure

or increase of temperature constituted an unloading (i.e., it causes a reduction in the absolute value of the stress), which is characterized by an elastic stress-strain relationship. Up to 593°C (1100°F) and 4.8 MPa (700 psi), no reversed plasticity occurred and the elastic stress-strain relationship remained valid. The pre-test procedure ended at a specimen temperature of 538°C (1000°F) and no internal pressure (point C). At this time, the article was ready for thermal transient and creep tests. It should be pointed out that the point C of the outer surface and the corresponding point of the inner surface did fall at different locations in the stress-strain plane. That is, the outer surface and the inner surface have different residual stresses. This is reflected in the figures when the ensuing structural responses to thermal transient is discussed.

IV. Structural Response to Thermal Transients and Creep

The analytical evaluation consists of five cycles of the thermal transient with hold time. The structure is maintained at constant 538°C and 3.24 MPa (470 psi) before it is subjected to a thermal downshock. The thermal transient goes from 538°C to 371°C in 10 seconds by carefully running temperature controlled liquid sodium through the test specimen. After the sodium is returned to the storage tank, the specimen is heated up slowly to 538°C and held for one week at 3.24 MPa.

During the thermal downshock, the maximum across the wall thermal gradient in SS316 was 98°C. The high thermal conductivity of 2 1/4 Cr-1Mo reduced the thermal gradient to 82°C in the 2 1/4 Cr-1Mo. This thermal gradient produced stress time histories that are characterized by a tension at the inner surface, because of its lower temperature than the outer surface, and a compression at the outer surface.

The residual stress just before the thermal transient test (indicated by point C in Fig. 9) when superposed with the above mentioned compressive or tensile stress produced two different stress states. Note that the behavior characteristics of subsequent response depend to a great extent upon the stress state indicated by point C. Therefore the pre-test loading history has a substantial effect on the metal response during test. To understand these different stress states, it is necessary to look at the inner surface and the outer surface of the pipe separately.

The circumferential stress-strain histories of the 2 1/4 Cr-1Mo steel near the weld interface are shown in Figures 10 and 11. Figure 10 is the stress-strain history of the outer surface. Point C is the state just before the transient. At the beginning of the transient, a compressive stress was imposed and the stress-strain state moved toward point D. After the thermal downshock, the pipe wall temperature gradient reduced and the tensile stress partially recovered to point E at 371°C (700°F). From E to F the specimen underwent isothermal temperature increase to 538°C. The stress change during this time period is due to the fact that initial residual stress existed and that the material properties (Young's modulus, etc.) are temperature dependent. The ratchetting strain is the strain difference from C to F. The creep period started at F and ended at G. It can be seen that the stress relaxation was quite fast, due to the presence of the primary creep and the high residual stress. A second cycle of thermal transient produced the stress-strain history that is described by the curve GHIJ. During this transient, the circumferential stress actually became negative for a short duration. The general shape of the stress-strain curve is similar to that of the first cycle, except it showed

smaller ratchetting (from G to J). The creep is also smaller because of (1) smaller stress and (2) the diminished influence of primary creep. Similar discussions apply to the third cycle stress-strain curve KLMNP.

The stress-strain history of the inner surface element is shown in Figure 11. Here, the tension stress at the early part of the transient is obvious (from C to E). After yielding occurred, the reduction of the thermal gradient in the later part of the transient produced a compressive stress (from E to H). With a further reduction in the thermal gradient (eventually reaching the isothermal condition) the residual stress settled at a small positive value after the first transient (point I). Stress relaxed during creep to a small negative value (point J). The phenomenon of stress "relaxation" at zero stress is because creep and stress relaxation elsewhere in the structure causes stress redistribution in the whole structure and produces an apparent stress relaxation effect at the point of zero component stress. The stress-strain history of the second test cycle followed very closely in shape to the first except it was displaced slightly. Again, the second cycle creep analysis showed smaller relaxation with the same reasons as discussed earlier.

V. Comparison with Experimental Measurements

The measurements were taken circumferentially at a distance of 18.4 Cm (7.25") and 17.1 Cm (6.75") from the center of weld at the 2 1/4 Cr-1Mo section and the SS316 section, respectively.^[7] These distances are sufficiently long that the bending effect due to differential thermal expansions of the metals at the interface would be negligible. In other words, these measurements mainly reflect the

loadings of thermal gradient and internal pressure. The measurement points of ERNiCr-3 weld metal are at the weld center. Two diametrically located strain gages were used in each material at the outer surface of the pipe.

At 538°C the strain gage readings were set to zero, represented by the origins in Figures 12 to 14. After the pressure was applied, the strains were recorded as indicated in these figures. During the thermal downshock and the isothermal heat - up, the materials went through a mixture of compression and tension and finally settled down. The difference of strains before and after this thermal loading is the plastic ratchetting strain, again shown in the Figures. During the hold time at 538°C, strains were recorded periodically, representing the creep of the materials. This cycle was repeated five times. It can be seen from these figures that the numerical readings of the two diametrically located strain gages compared poorly but did give data with a similar trend. The analytical predictions of the strain history are also shown in these figures.

In agreement with the strain measurement method, the predicted strains at 538°C without pressure are used as reference and plotted at the origin (zero strain). The strains after pressurization and after the thermal transient are indicated and show the ratchetting strain of the materials. The creep strains, because they are calculated from creep equations, are represented by smooth curves. The following observations are made from the comparison of predicted and measured strains:

- (1) The ratchetting strains are small, and tend to be progressively smaller with each cycle. This indicates the material hardening effect. This

trend is correctly predicted by the analysis.

- (2) The analytical procedure employed a strain hardening rule for the creep calculation. This procedure seems to be confirmed by the measurements, which show good agreement with characters of a strain hardened behavior.
- (3) The analytical prediction of SS316 gives a larger than measured initial strain (after pressurization) and also ratchetting strain (Figure 13). This indicates that the SS316 in the test specimen was harder than the material used in property (stress-strain relationship) generation. This could be the result of the manufacturing process in which a plate is rolled into a pipe. SS316 is known to harden in such a process. However, the lack of creep strain of the SS316 section was correctly predicted.
- (4) The prediction of the strain history at the ERNiCr-3 weld region (Figure 11) is considered satisfactory. Because of the complications of this region (such as the not-well-defined metal interfaces, diffused metal with slightly varying properties, etc.), the two measurements show larger discrepancies than the measurements at the two parent metals. The analytical results agree well with one of the measurements.

VI. Discussion and Conclusions

One of the main purposes of this analysis is to investigate the

applicability of an inelastic analysis procedure in which the multi-axial stress-strain state was reduced to an equivalent one dimensional state to predict the response of a complex structure such as a welded transition joint. This procedure is complicated by: (1) large variations on inelastic material properties; (2) assumptions in inelastic analysis theories extended to multi-dimensional states; (3) inability or the impracticality in the modelling of a complex structure and simplification made for the analysis; and (4) sensitivity of structural response at high temperatures to small variations of loading conditions.

As pointed out previously, the material properties, especially the stress-strain relationships and creep rates, of the heats of materials used in the construction of the test specimen showed some discrepancies from the average properties given in various sources. The use of the measured properties increased the prediction accuracy of the analysis with comparison to the actual measurements. However, in a design analysis, average properties will normally be used before the joint is built. The difference between actual properties and average properties can therefore affect the results and conclusions. On the other hand, it has been demonstrated that simplifying a complicated structural interface into a well defined structural boundary does not materially influence either the ratchetting (plastic) response or the creep, as evidenced by the good agreement between the predicted and measured strain history of ERNiCr-3.

The conventional method of inelastic analysis is to reduce the stress and strain into a one dimensional effective stress and equivalent strain to make

use of the one dimensional stress-strain relationship and creep equation. It is also generally assumed that only the deviatoric stress component contributed to the response. This procedure was followed in this analysis and the results indicated that it is reasonable. Also, a strain hardening law was adopted for the creep analysis. The results also indicated that this is acceptable.

The satisfactory results of this analysis can be attributed to the good data from the experiment, and in the careful and detailed simulation in the analytical procedure. An adequately fine finite element model certainly is necessary. The current model is shown to be satisfactory. The over-prediction of SS316 plastic ratchetting is believed to be a consequence of work hardening of the material. The stress-strain relationship was generated with material from the same heat as used to form the pipe section, but in plate form. Since SS316 is known to harden with forming and machining but is less responsive to heat treatment, it is not surprising that the pipe material is harder than the plate material. A check test of stress-strain relationship of the pipe material is very desirable.

The analysis has demonstrated the adequacy of the application of one-dimensional constitutive equations and creep response equations to a multi-axial problem. A properly constructed finite element model sufficient for accurate results without excessive computing cost was achieved. This model and procedure is applicable to future design analysis effort of similar structures.

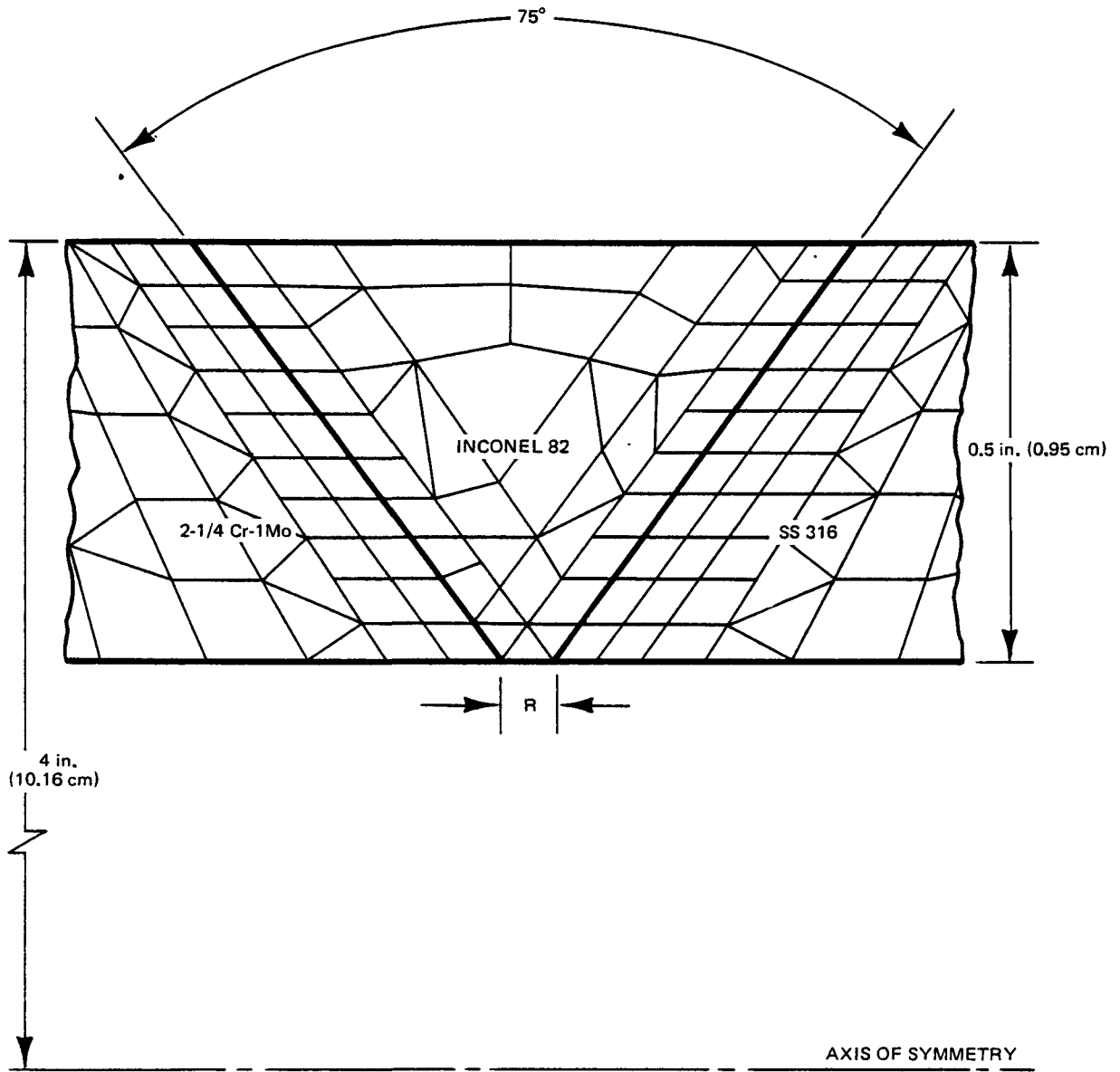
Acknowledgement

This study was performed at the Advanced Reactor Systems Department (formerly,

the Fast Breeder Reactor Department) General Electric Company at Sunnyvale, California, U.S.A., under DOE (formerly, USERDA) contract number AT(04-3)-893-10 during fiscal year 1976. The test data was by courtesy of Dr. J. Corum of the Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A.

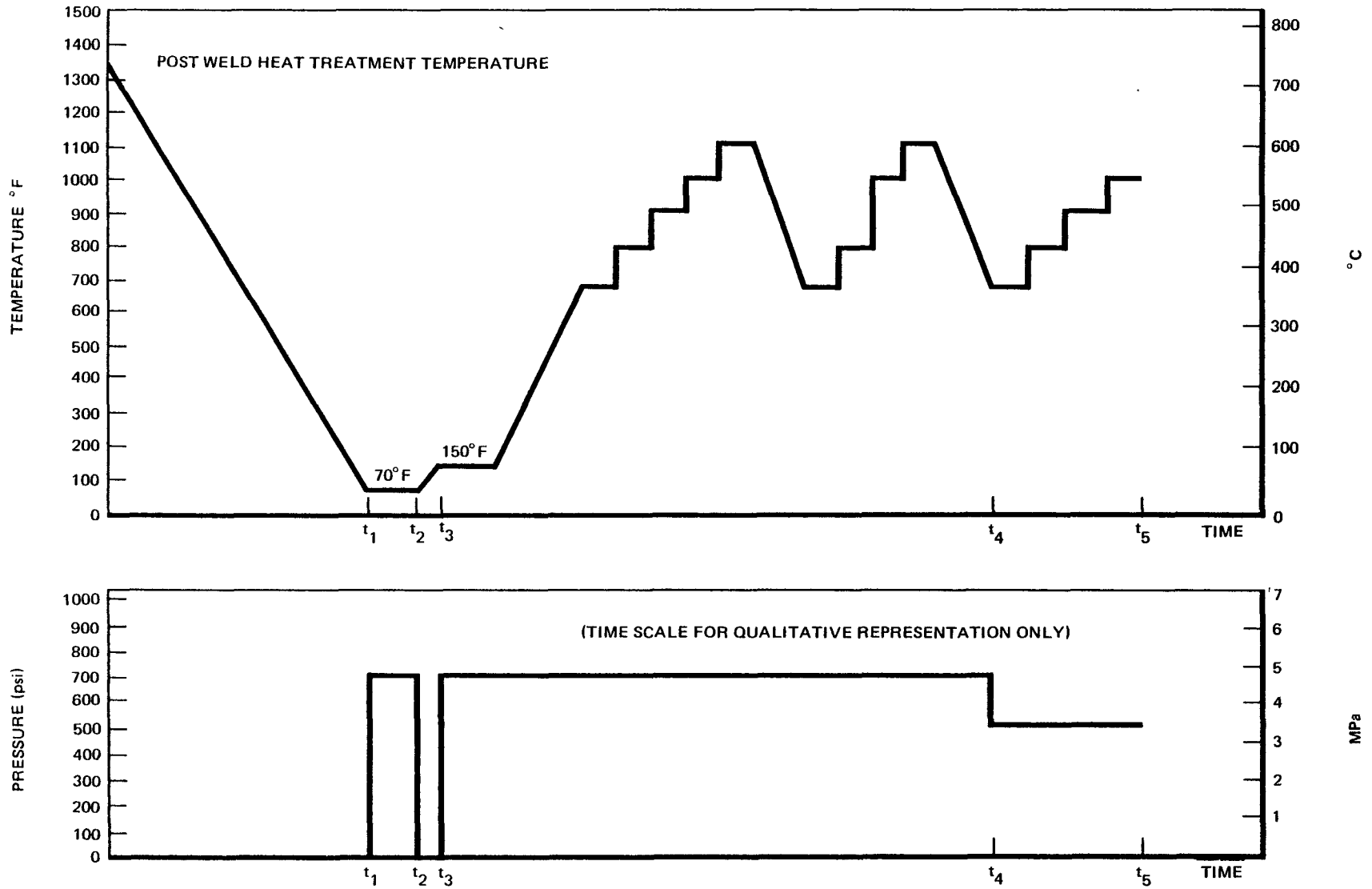
References

1. Carpenter, O.R., Jessen, N.C., Oberg J.L., and Wylie, R.D., "Some Considerations in the Joining of Dissimilar Metals for High Temperature, High Pressure Services," Proceedings ASTM, Volume 50, 1950.
2. Slaughter, G.M. and Housley, T.R., "The Welding of Ferritic Steels to Austenitic Stainless Steels," Welding Journal Research Supplement, October, 1964.
3. Mather, J., "Local Bending Stresses in Joint Pipes of Dissimilar Materials," Metal Construction and British Welding Journal, Volume 1, No. 1, January, 1969.
4. Hardy, A.K., Goodall, I.W., and Rowley, T., "Design and Operational Aspects of Steam Pipe Transition Joints", presented at the International Conference on Welding Research Related to Power Plant, September, 1972.
5. Dalcher, A.W., Yang, T.M., and Chu, C.L., "High Temperature Thermal-Elastic Analysis of Dissimilar Metal Transition Joints", Journal of Engineering Materials and Technology, Vol. 99, No. 1, January, 1977.
6. Dalcher, A.W., and Yang T.M., "Elastic-Plastic Analysis of Dissimilar Metal Welded Pipe Joint", presented at the Joint Petroleum Mechanical Engineering and Pressure Vessel and Piping Conference, Mexico City, Mexico, September, 1976.
7. Satory, W.K., et al, "Thermal Ratchetting Test of 2 1/4 Cr-1Mo Steel to type 316 Stainless Steel Pipe: Test TTT-3", ORNL-5330, October, 1977.
8. "Nuclear Systems Materials Handbook," TID 26666, Hanford Engineering Development Laboratory, Richland, Washington.
9. RDT F9-5T, "Guidelines and Procedures for Design of Nuclear System Components at Elevated Temperature," Westinghouse Electric Corporation, September, 1974. Supplemented by "Constitutive Equation Recommendations for 2 1/4 Cr-1Mo Steel," Oak Ridge National Laboratory, January 15, 1975.
10. ASME Boiler and Pressure Vessel Code Case 1592-4.



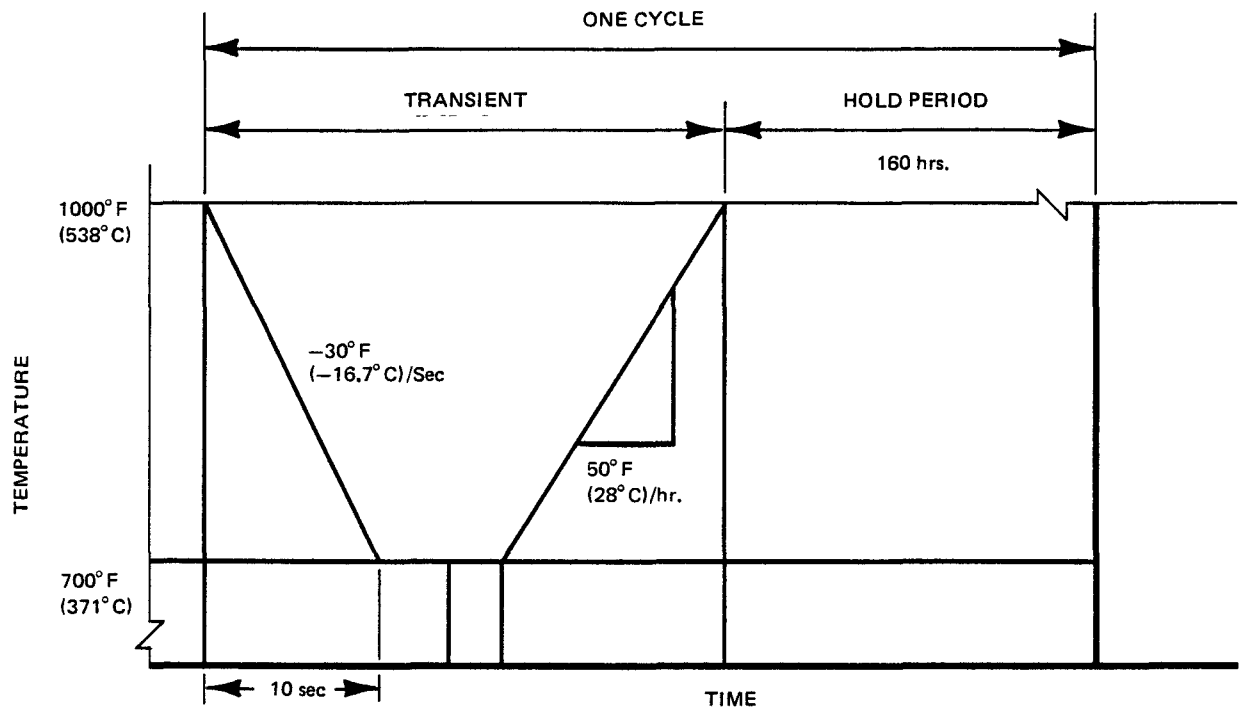
79-290-1

Figure 1. Model of Dissimilar Metal Transition Joint

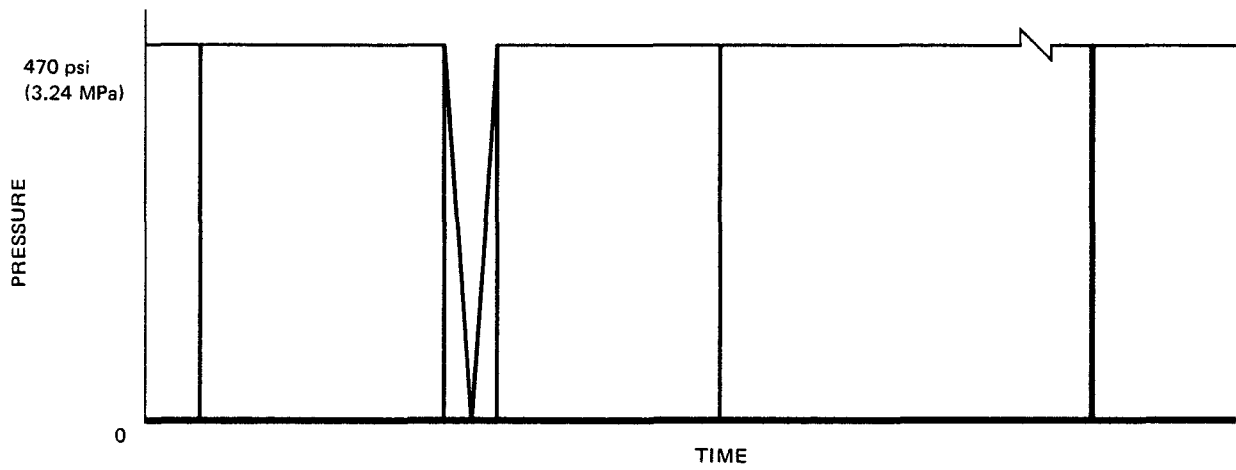


79-290-2

Figure 2. Pre-test Thermal and Pressure History



(a) TEMPERATURE HISTORY



(b) PRESSURE HISTORY

79-290-3

Figure 3. Thermal and Pressure History of Ratchetting and Creep Test

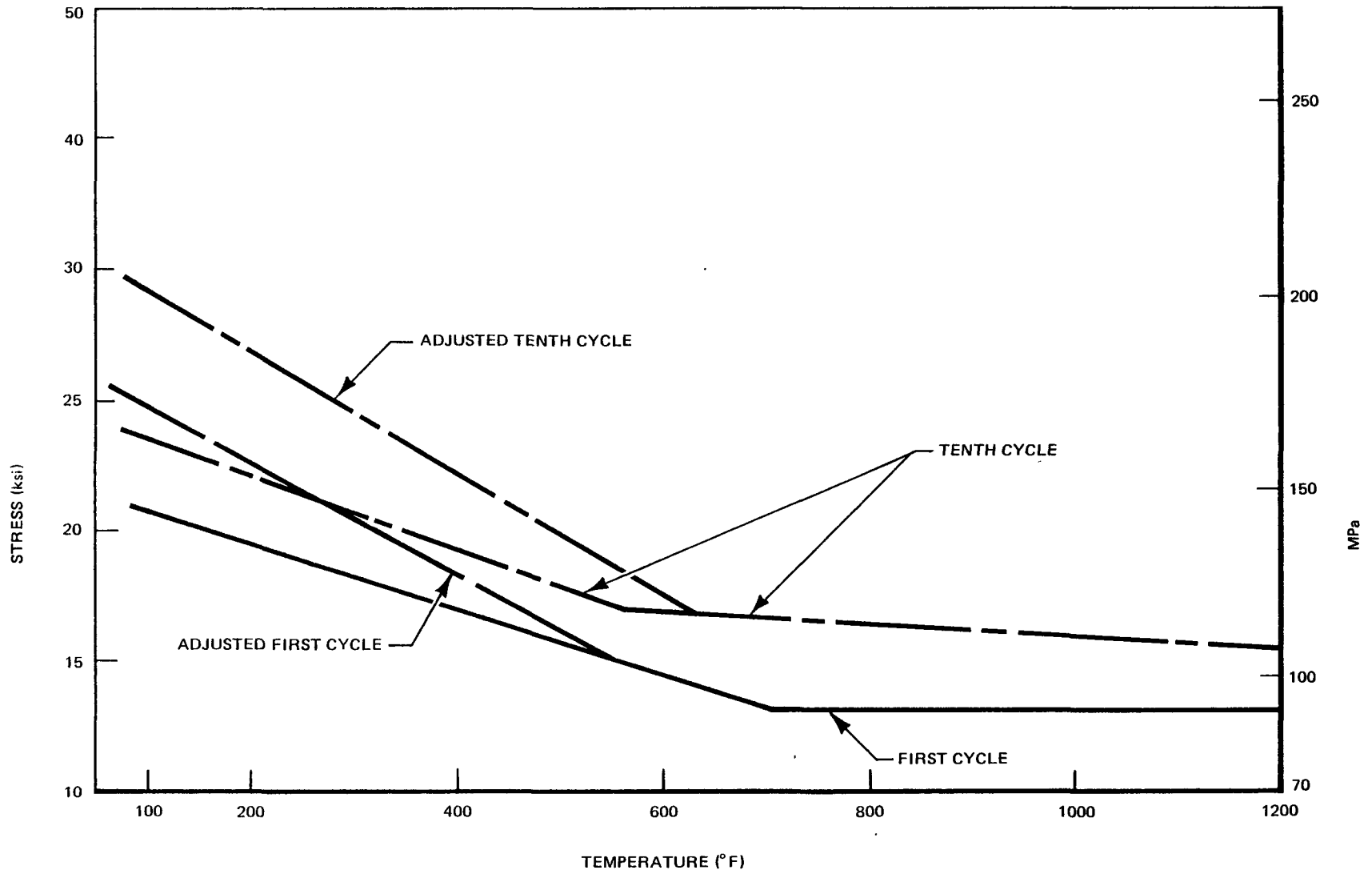


Figure 4. Yield Stress of SS 316

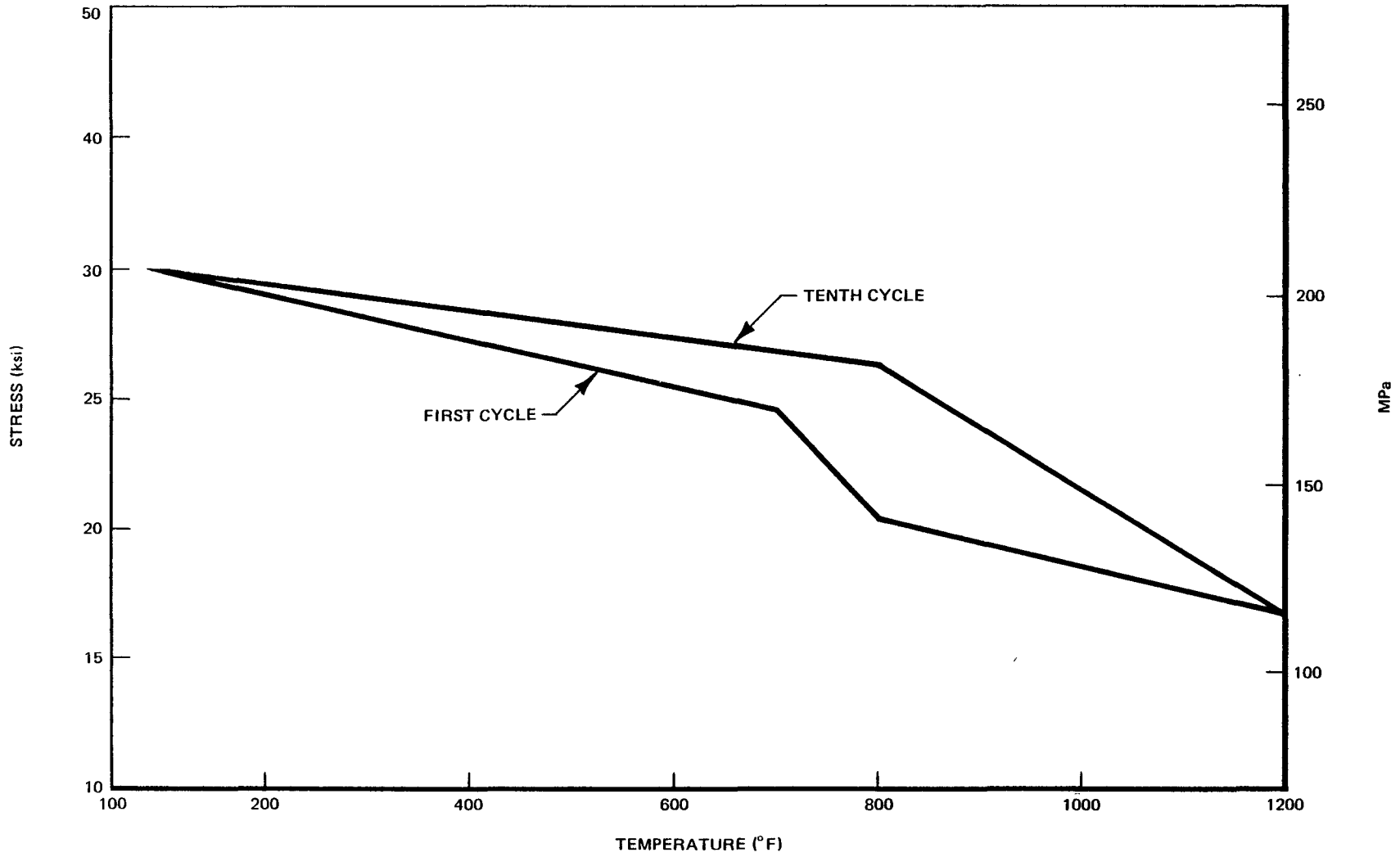


Figure 5. Yield Stress of 2-1/4Cr-1Mo

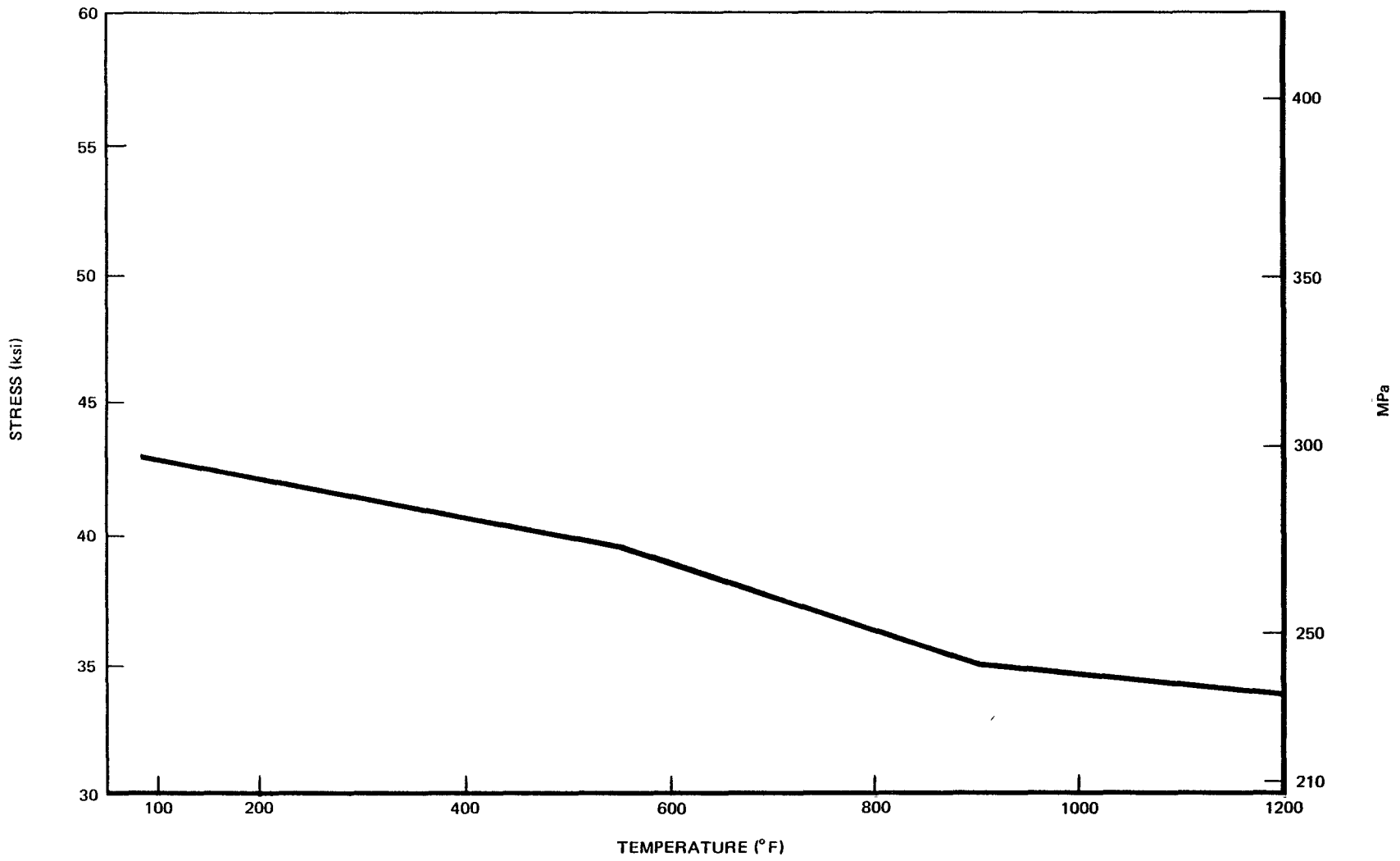
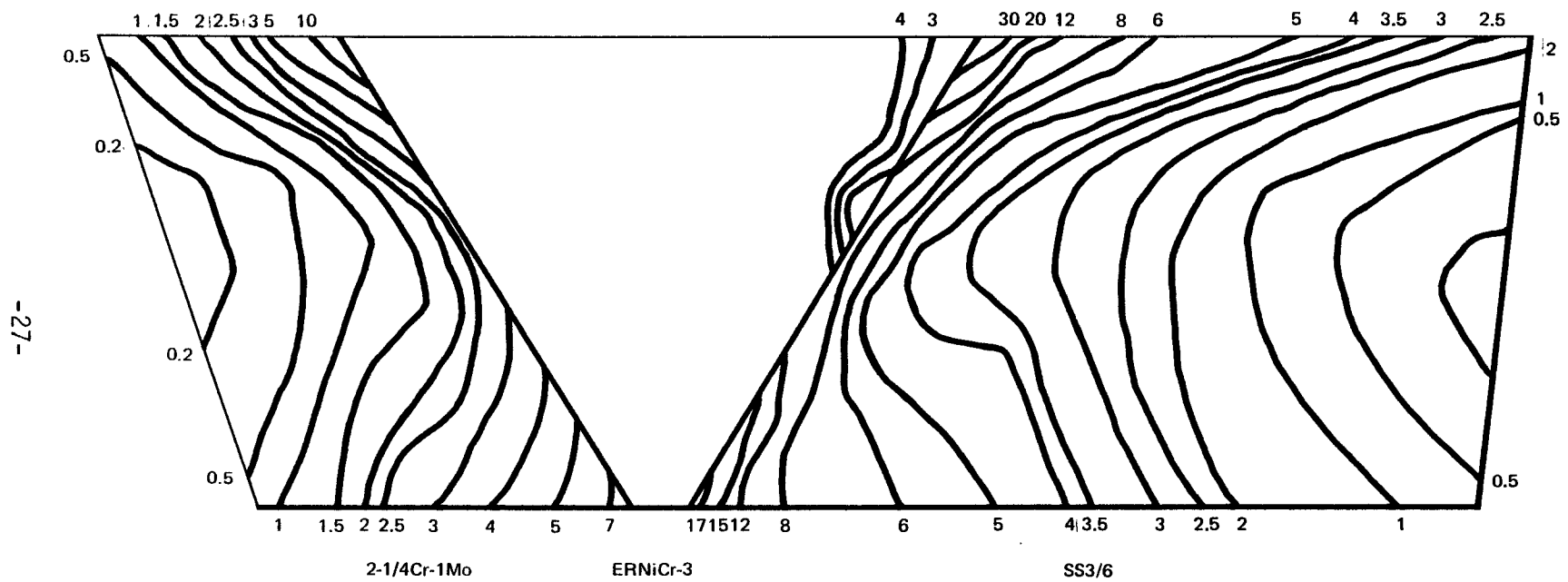


Figure 6. Yield Stress of ERNiCr-3

EFFECTIVE PLASTIC STRAIN ($\times 10^{-4}$)

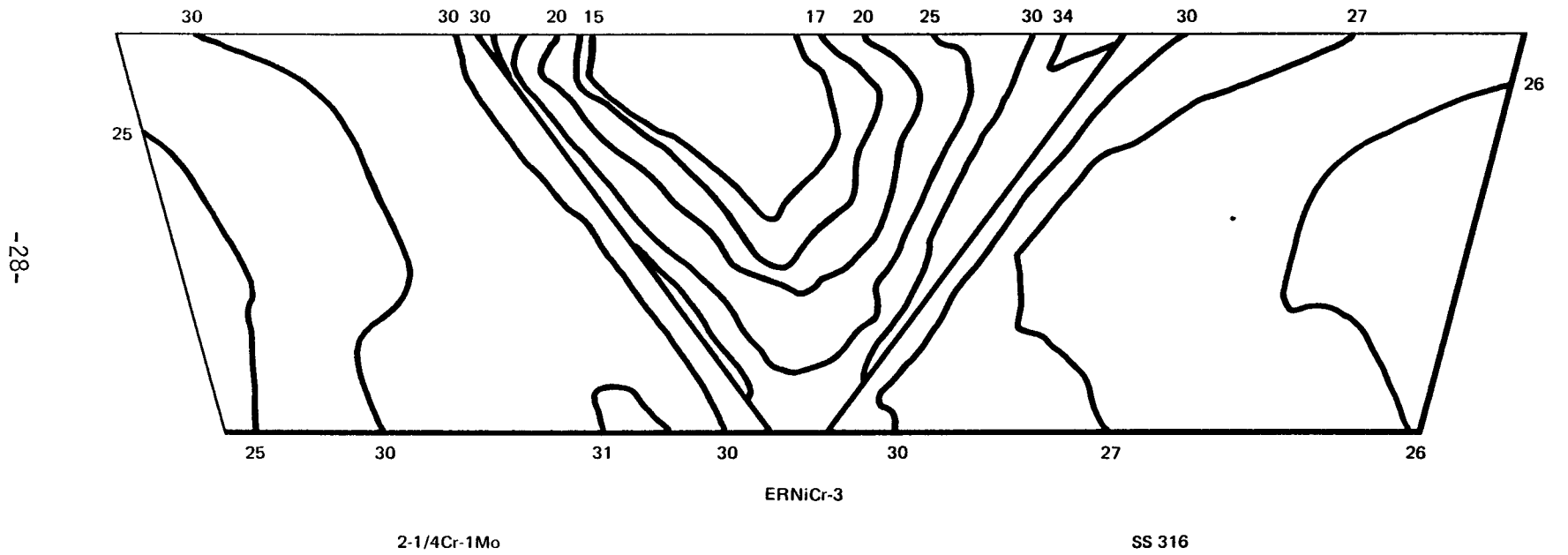


-27-

79-290-7

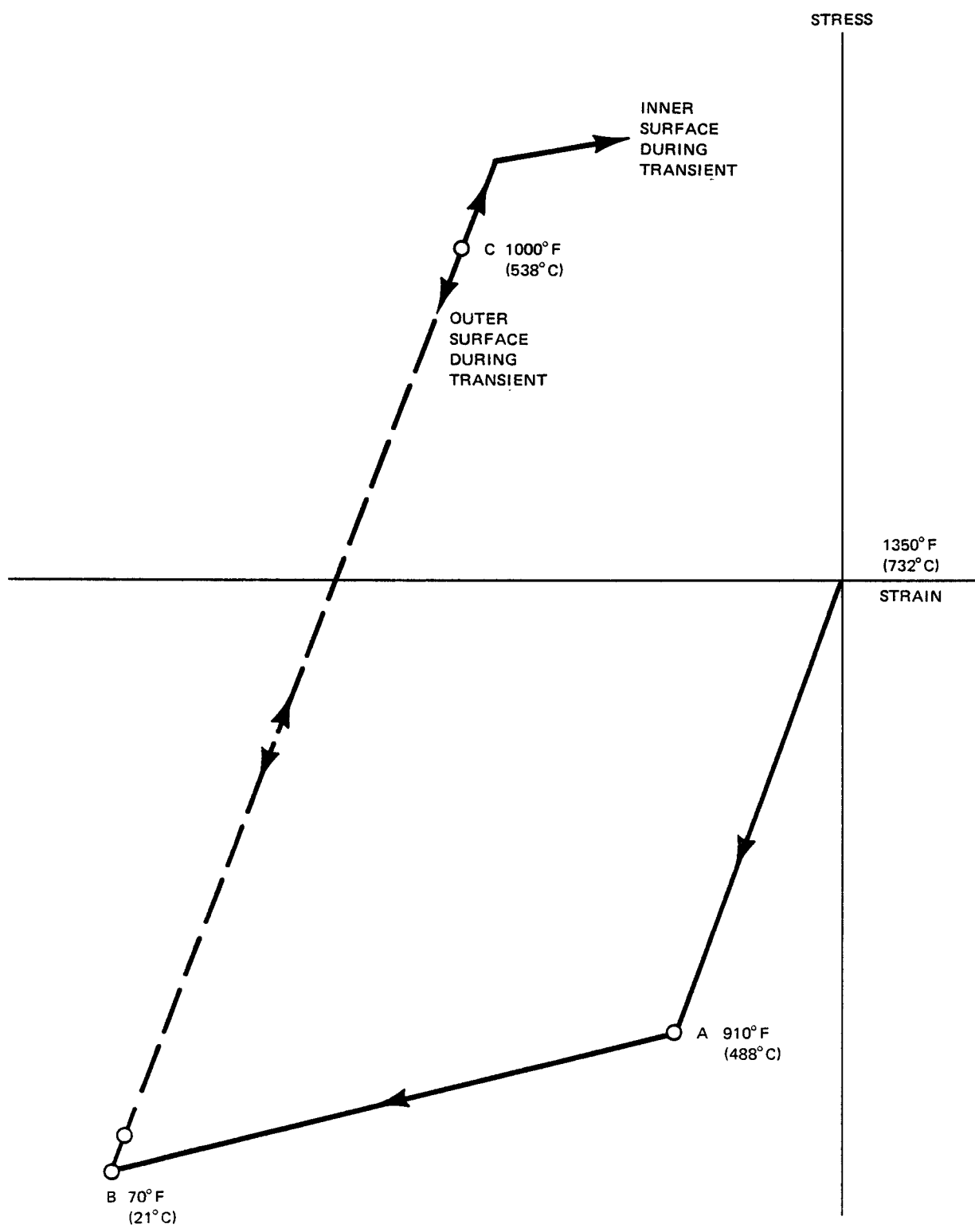
Figure 7. Plastic Strain at Room Temperature (No Applied Pressure)

EFFECTIVE STRESS (ksi)



79-290-8

Figure 8. Effective Stress at Room Temperature (No Applied Pressure).



(NOT TO SCALE)

79-290-9

Figure 9. Stress-Strain State of 2-1/4Cr-1Mo.

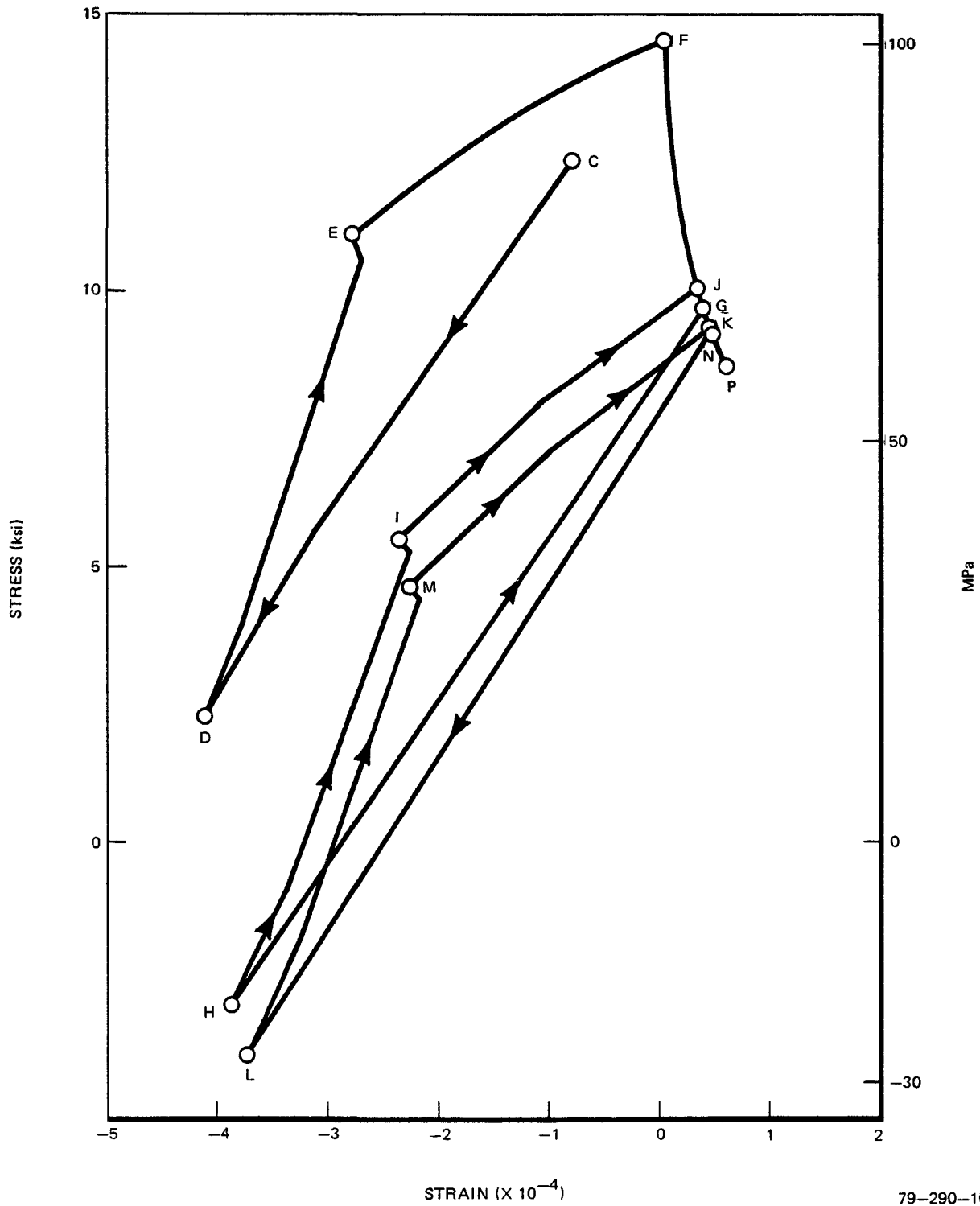


Figure 10. Circumferential Stress-Strain State of Outer Surface of 2-1/4CR-1Mo Pipe

79-290-10

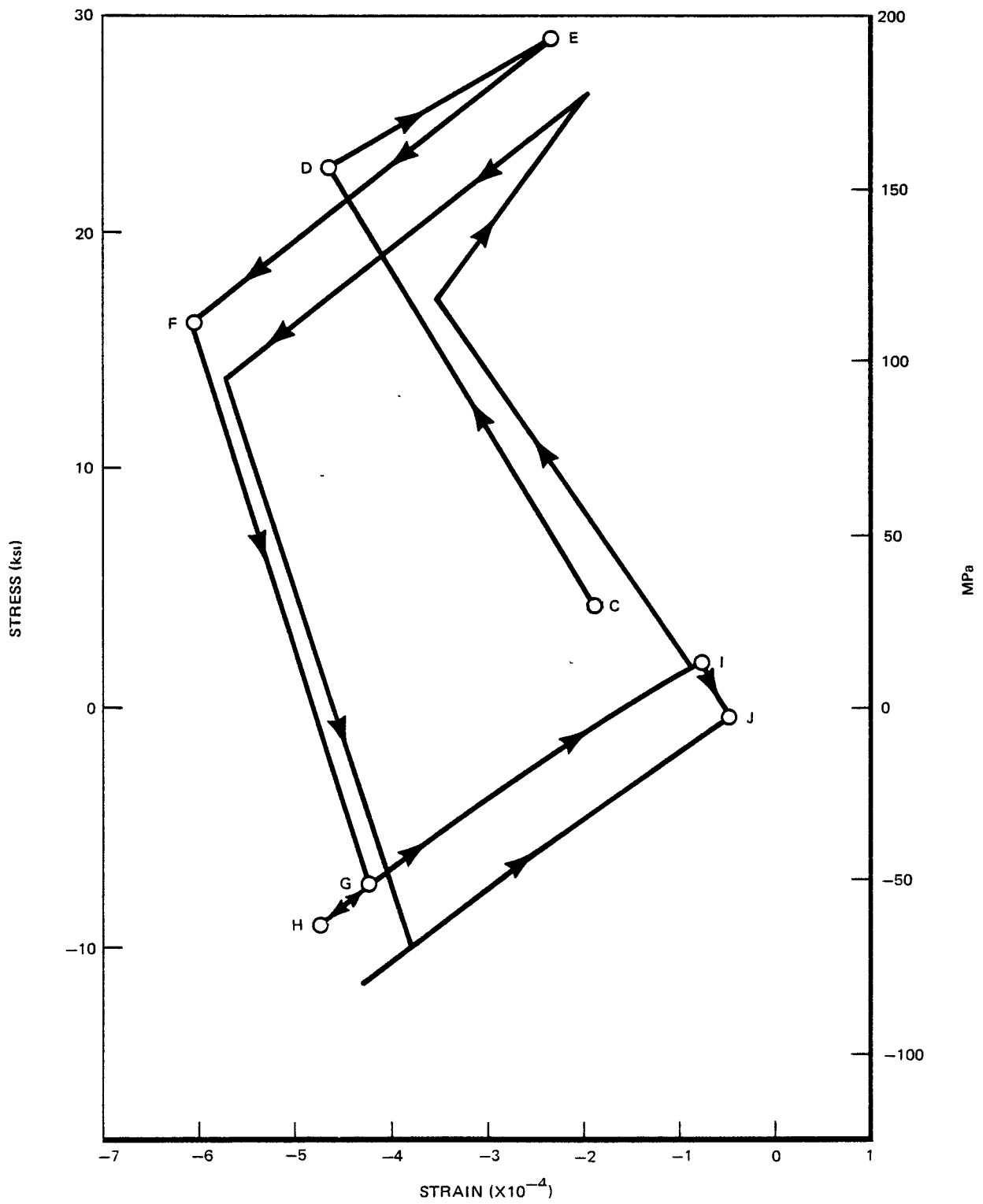


Figure 11. Circumferential Stress-Strain State of Inner Surface of 2-1/4Cr-1Mo Pipe

79-290-11

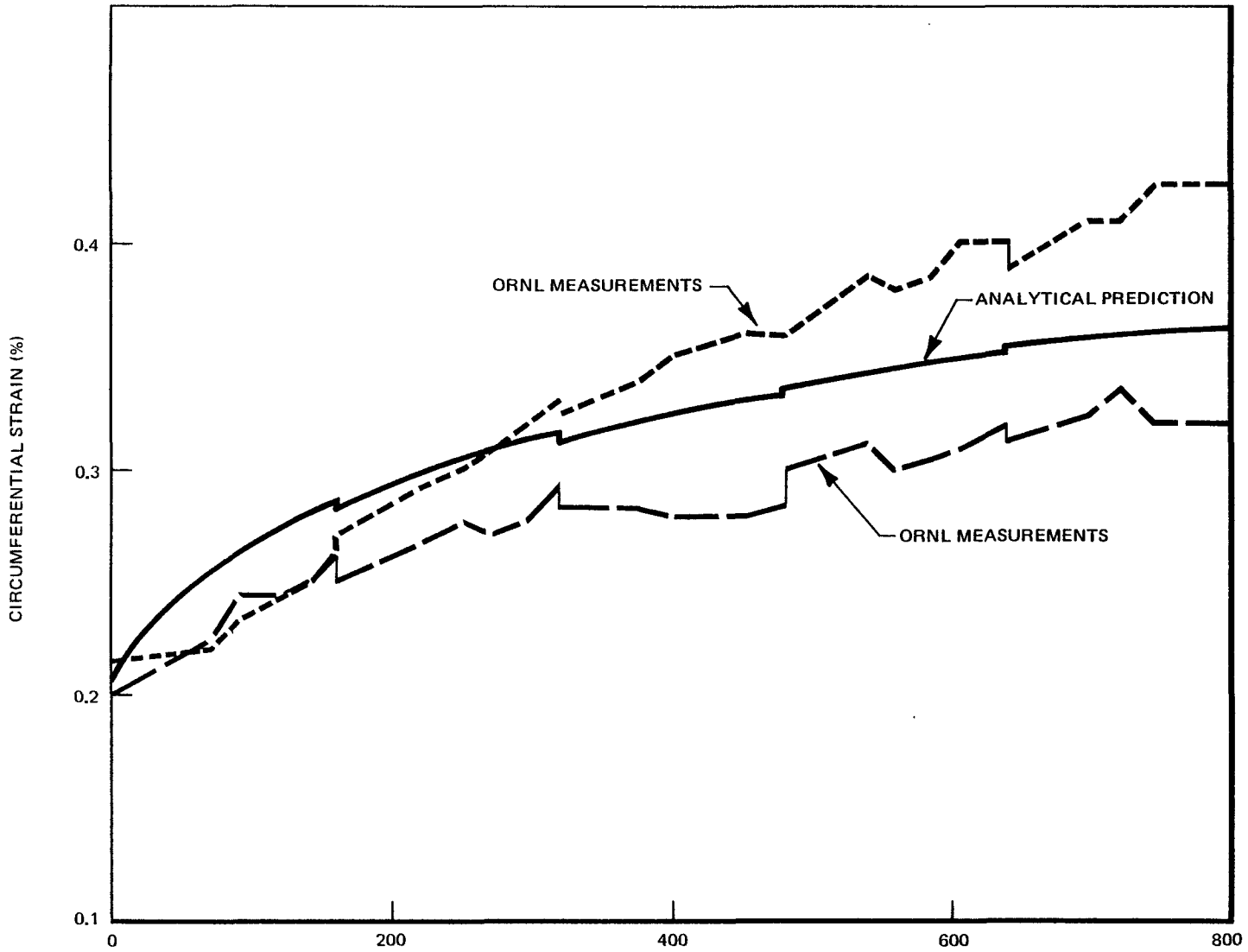


Figure 12. Comparison of Analytical Prediction and ORNL Measured Strain of 2-1/4Cr-1Mo

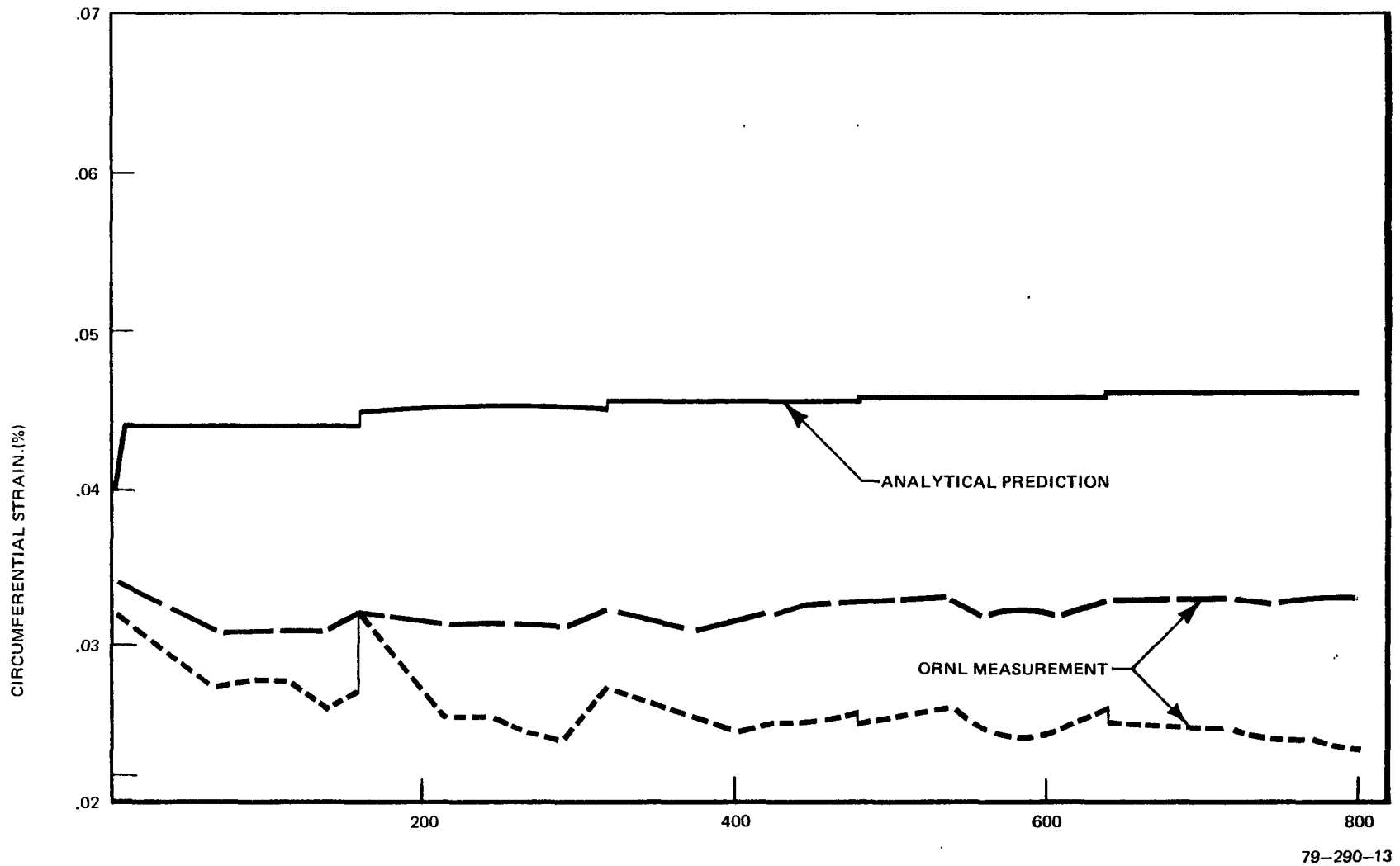
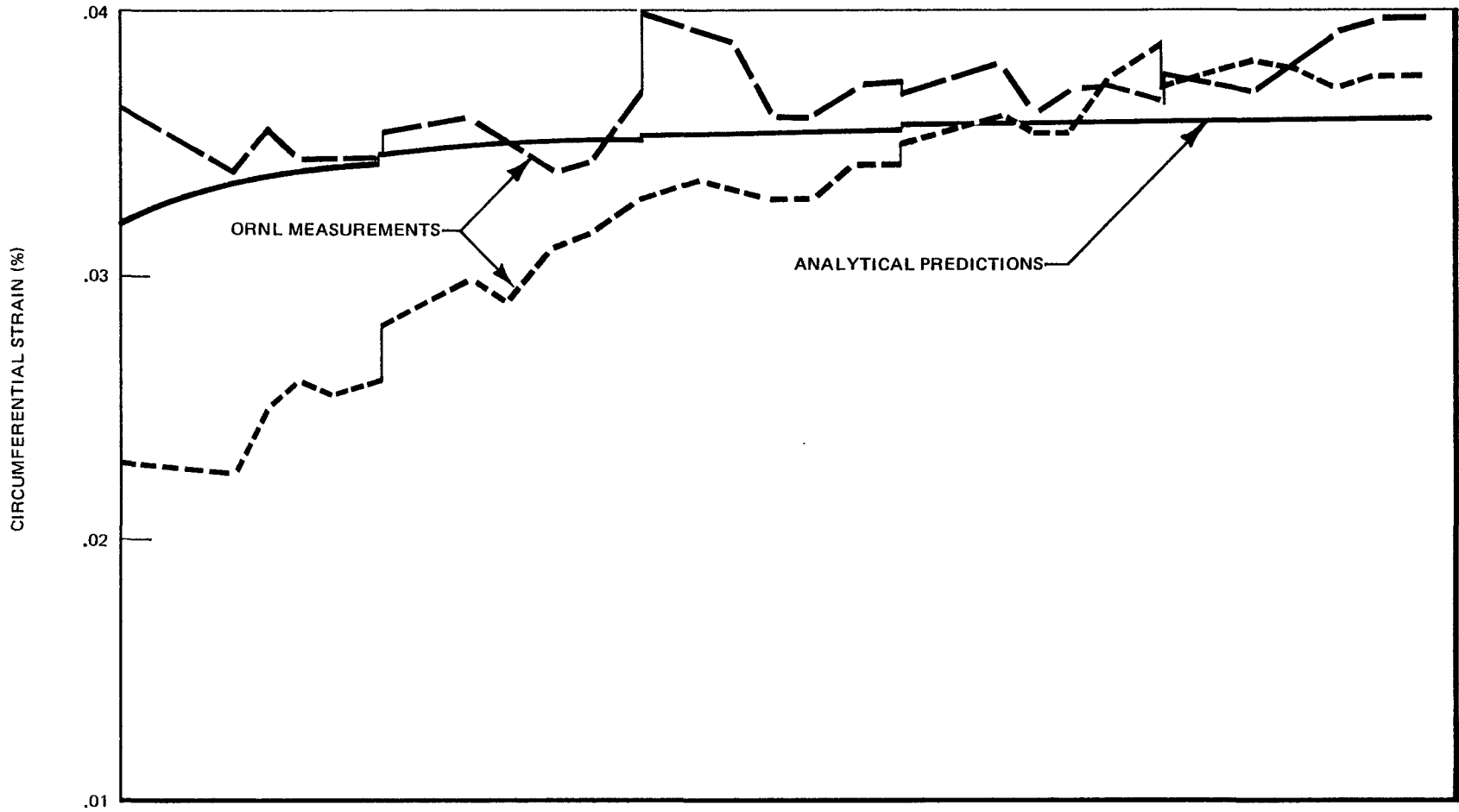


Figure 13. Comparison of Analytical Prediction and ORNL Measured Strain of SS 316



79-290-14

Figure 14. Comparison of Analytical Prediction and ORNL Measured Strain of ERNiCr-3