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KEY TECHNOLOGICAL ISSUES IN LMFBR HIGH-TEMPERATURE STRUCTURAL DESIGN — THE U.S. PERSPECTIVE*

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Abstract — The purpose of this paper is (1) to review the key technological issues in LMFBR high-temperature structural design, particularly as they relate to cost reduction, and (2) to provide an overview of activities sponsored by the U.S. Department of Energy to resolve the issues and to establish stable, standardized, and defensible structural design methods and criteria. Specific areas of discussion include: weldments, structural validation tests, simplified design analysis procedures, design procedures for piping, validation of the methodology for notch-like geometries, improved life assessment procedures, thermal striping, extension of the methodology to new materials, and ASME high-temperature Code reform needs. The perceived problems and needs in each area are discussed, and the current status of related U.S. activities is given.

I. INTRODUCTION

Liquid-metal fast-breeder reactor components present unique structural design requirements. First, because of the good heat-transfer characteristics of the coolant and the relatively large temperature rise through the reactor core, reactor power changes can result in significant thermal transient loadings on system components. Second, the components operate at temperatures where creep effects and time-dependent failure mechanisms are significant.

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For the austenitic stainless and ferritic steels used in LMFBRs, these effects are implicitly assumed by the ASME Boiler and Pressure Vessel Code, Section III, to occur upon significant exposure to temperatures above 427°C (800°F) and 371°C (700°F), respectively [1].

In the late 1960s, it was recognized in the United States that the low-temperature structural design methodology developed and used for light-water reactors would not be adequate for LMFBRs. Consequently, an effort was mounted to develop a high-temperature structural design methodology that explicitly accounts for the effects of nonlinear material deformation and time-dependent damage mechanisms and failure modes. Both elastic and inelastic design analysis methods have been established, and these are specified in Department of Energy design guidelines. Likewide, criteria for guarding against structural failures have been developed and are given in ASME high-temperature Code Case N-47 [2]. The basic elements of this high-temperature structural design methodology have been experimentally validated, and the methodology has been successfully used in the United States in the design of the Fast Flux Test Facility (FFTF) and the Clinch River Breeder Reactor Plant (CRBRP) and in the development of high-temperature components and facilities.

Although the basic framework of the high-temperature structural design methodology is believed to be valid and sound, shortcomings and weaknesses remain. It is the purpose of this paper to review these key technological issues, or problem areas, and to outline current U.S. activities to resolve them.

The next two sections of this paper provide background; the unique LMFBR structural design problems and the importance of having a well-established, experimentally verified methodology are discussed, and the current methodology is briefly outlined. Section IV then discusses, in priority order, the critical-few key technological issues as identified by U.S. designers and investigators. Finally, Section V provides an overview of current U.S. activities and plans in the high-temperature structural design technology area.

II. THE NEED FOR A STABLE AND DEFENSIBLE STRUCTURAL DESIGN METHODOLOGY

As background, it will be useful at this point to review the potential structural effects that a typical repeated LMFBR thermal transient loading can have on a simple component — a straight pipe. The situation is depicted in Fig. 1. Assume that the sodium temperature drops 167°C (300°F) in several seconds (*a–b*), rises slowly (*b–c*), and then is constant for several hundred hours of normal operation (*c–d*), after which the cycle is repeated. The predicted response is shown in Fig. 1(c). Starting with point *a*, the inner surface of the pipe first yields in tension as it contracts, but as the outer surface subsequently begins to cool, the inner surface stress reverses sign and goes into compression. At *b*, the wall is uniformly at the lower temperature; slow heating from *b* to *c* causes the residual stress to decrease because of the decreasing yield condition with increasing temperature. At *c*, a compressive residual stress remains, which relaxes during the subsequent hold period. The response to subsequent cycles is depicted in the figure by dashed lines.

The behavior shown in Fig. 1 illustrates three key potential failure modes. First, creep-rupture damage is accumulated during the hold periods; second, the plastic cycles introduce fatigue damage which interacts with the creep to produce a creep-fatigue interaction damage mode; and third, ratchetting occurs, introducing the potential for failure due to excessive deformation. The LMFBR structural designer must have analysis methods for predicting, or conservatively estimating, the inelastic response, he must have criteria that guard against failure by time-dependent cracking or rupture and by excessive deformation, and he must be assured that enough residual strength remains at the end of a 30- or 40-yr life to withstand an accident. This is the task of the high-temperature structural design methodology.

Plant failure experiences indicate that concerns about the damaging effects of thermal transient loadings and creep are justified. Just two examples will be mentioned here. The first one is the French Phenix reactor, which, although it has been extremely successful overall, was initially plagued with several problems of structural cracking [3,4]. These included cracking at welds joining piping tees and valves to piping runs and cracking in intermediate heat exchanger welds. In each case the cause was identified as fatigue or creep-fatigue due to the repeated thermal transient loadings. It has been stated that these problems "cost the power station many months of unavailability and constituted a considerable loss of earning power" [4].

A second example is the Eddystone coal-fired generating plant operated by Philadelphia Electric Company in the United States. Unit 1 of that station went into operation in 1960 and has operated for most of the intervening period with steam temperatures of approximately 621°C (1150°F). In 1964 cracking was detected in the type 316 stainless steel main steam line junction headers, and in 1982-83 extensive cracking was detected in the main steam lines themselves, which were also of 316 stainless steel [5]. The plant was shut down, and much of the steam piping has been replaced. Again, the cause was diagnosed as classical creep-fatigue (dominated by creep damage) due to repeated thermal transient loadings (exactly the situation illustrated in Fig. 1).

These examples forcefully illustrate the key role that high-temperature structural design must play in maximizing LMFBR plant reliability and availability and thus in minimizing power costs. But high-temperature structural design has an equally large role to play in reducing construction costs. A recent study of light-water reactor nuclear plant projects in the United States revealed that escalation and interest make up an average of 62% of total plant cost. Thus, not only must the overnight costs be reduced, but lead times, which currently average 13 years (9 years for construction), must be drastically cut to reduce the costs of inflation and interest. A one-year construction delay can add hundreds of millions of dollars to the total cost of a project.

A recent study, sponsored by the Electric Power Research Institute [6,7], of 26 nuclear units that experienced an average of 43 months' construction-related delay, found that 78% of the delays were due to out-of-scope work. Redesign and rework due to regulatory ratchet and scope changes were significant factors. Clearly, an unstable structural design methodology with unresolved technological uncertainties invites regulatory delays, scope changes, and backfitting. Development of stable, standardized, and defensible design methods and criteria will contribute substantially to LMFBR cost reduction.

III. THE CURRENT HIGH-TEMPERATURE STRUCTURAL DESIGN METHODOLOGY

In the United States, the high-temperature structural design methodology centers on the rules and criteria of ASME Code Case N-47 for elevated-temperature Class 1 components [2]. The Code Case has two general categories of limits. The first consists of primary stress limits placed on elastically-calculated load-controlled quantities, such as the internal pressure stresses. The second consists of strain, creep-fatigue, and buckling limits. In meeting these latter limits, either inelastic analyses predictions or conservative estimates based on elastic analysis predictions must be used.

The primary stress limits are based on, in addition to the time-independent yield and ultimate strengths used at low temperatures, the minimum stress to cause rupture, the minimum stress to initiate tertiary creep, and the stress to produce 1% strain, all in a specified time t. The resulting allowable stresses, which are provided for types 304 and 316 stainless steels, 2-1/4 Cr-1 Mo steel, and nickel Alloy 800H, are thus time and temperature dependent; the allowable loads depend on the duration of the loading.

The strain limits in Code Case N-47 are not necessarily related quantitatively to specific failure modes. Rather, they are aimed primarily at limiting the accumulation of ratchetting strains. A number of very conservative checks, using elastically calculated quantities, are provided for satisfying the strain limits and avoiding inelastic analysis when the loading conditions are not too severe.

The creep-fatigue rules in Code Case N-47 are, by far, the most frequently limiting criteria, and they are perhaps also the most questionable. A linear time- and cycle-fraction damage accumulation rule, expressed as

$$\sum_j \left(\frac{n}{N_d}\right)_j + \sum_k \left(\frac{\Delta t}{T_d}\right)_k \leq D$$

is used by the Code along with von Mises effective quantities to represent multiaxial stresses and strains. The time fraction represents the time, Δt, at a given condition (stress and temperature) divided by the allowable time at that condition. The cycle fraction represents the number of cycles, n, at a given condition (strain range and temperature) divided by the allowable number of cycles at that condition. The quantity D, which is less than or equal to one, comes from an interaction diagram that is experimentally determined from creep-fatigue tests. Both the quantities N_d, which comes from a design fatigue curve, and T_D, which comes from a minimum creep-rupture curve, have design margins built into them. Although inelastic analyses are generally required for a creep-fatigue evaluation, procedures are given for estimating the creep and fatigue damage from elastically calculated quantities; use of these elastic analysis procedures is limited, however, to relatively mild loading conditions.

A major effort was mounted in the United States in the early 1970s to provide the constitutive equations (mathematical descriptions of inelastic material behavior) and inelastic analysis guidelines needed for performing consistent and valid design analyses as required by Code Case N-47. Extensive uniaxial and multiaxial exploratory deformation tests were carried out, and the results were used as the basis for developing inelastic analysis guidelines that are provided in a U.S. Department of Energy design guide for types 304 and 316 stainless steels and 2-1/4 Cr-1 Mo steel. The guide also provides some simplified analysis methods that have been developed. Extensive high-temperature structural test data have been generated to validate the analysis methods.

These analysis methods and the rules and criteria of Code Case N-47 were, as previously mentioned, used for the design of components for both FFTF and CRBRP. Forty major detailed inelastic design analyses were successfully performed on FFTF components.* Incidentally, the total elevated-temperature design/analysis cost was only about 2.3% of the total FFTF capital cost, and

*From data compiled by L. K. Severud, Westinghouse Hanford Company.

inelastic analysis accounted for just 13% of the cost of elevated-temperature design/analysis. These same relative cost figures are representative of the CRBRP experience as well.

IV. REMAINING PROBLEM AREAS AND NEEDS

Despite wide application of the existing high-temperature structural design methodology, it is recognized that significant problem areas and needs remain and that these must be resolved to assure the realization of a low cost and marketable LMFBR. The problem areas and needs are outlined in this section, in order of decreasing priority, in two categories: (1) problems with the technology and its validation and (2) perceived problems with the ASME Code. In each case the items discussed have been identified and prioritized by U.S. LMFBR program participants on the basis of the innovative low-cost design studies that are underway, the CRBRP licensing experience, and an awareness of the shortcomings in the underlying technology.

1. Technology Needs

a. *Weldment Structural Integrity*. Although explicit design criteria for weldments have been developed by the ASME Code elevated-temperature groups and are being considered by the higher-level Code groups, the current Code Case N-47 provides essentially no experimentally-based rules for assessing weldments. Yet, any failures generally occur at weldments, and during the CRBRP licensing process the U.S. Nuclear Regulatory Commission identified the possibility of early weldment cracking, particularly in components subjected to repeated thermal transient loadings, as the number one structural integrity concern. Thus, a verified design and life assurance procedure for weldments is considered to be the top priority need.

b. *Structural Validation Tests to Failure.* The ultimate defensible demonstration of the adequacy of the design analysis methods and design criteria to guard against structural failures can come only from structural tests. Simple and complex structural validation tests to failure (mostly under thermal transient loadings) are thus needed. And, although some results already exist, more are required to provide an adequate sample from which to draw meaningful conclusions, particularly with regard to design margins.

c. *Simplified Design Analysis Procedures.* Although inelastic design analyses have proven to be tractable and economically feasible, their use is still limited to the few most critical areas. For the majority of design evaluations, simplified elastic or inelastic procedures are required. Yet, these methods are either grossly overconservative or their demonstrated applicability is limited to axisymmetric geometries and loadings. A key need is for less conservative, more generally applicable procedures.

d. *Design Procedures for Piping.* Piping system design analysis procedures must generally be based on elastic approaches. The primary need here is to simply reach a consensus agreement on a single standardized method and to then carefully document that method. Although there is a need to expand the stress indices for piping components and to experimentally validate their extension to use for time-dependent failure modes at elevated temperatures, the key technological need is for a valid, experimentally verified, procedure for assessing elastic follow-up, which is the potential for a pipe line to act as a spring and to continue to load and cause inelastic strain accumulation in weaker regions of the line.

e. *Notch-Like Geometric Discontinuities.* Demonstrating adequate life at notch-like discontinuities poses the most difficult test of the high-temperature structural design methodology. Along with weldments, this was a major concern of the U.S. Nuclear Regulatory Commission during CRBRP licensing. The effects of inelastic behavior and of uncertainties in long-term cyclic material properties on creep and fatigue damage were key questions. Additional failure tests and analyses, particularly for bending loadings, are needed to demonstrate the adequacy of the methodology.

f. *Improved Material Failure Criteria.* Criteria for predicting when material cracking will occur under time-varying temperatures and multiaxial loadings underlies nearly all of the elevated-temperature design criteria. Yet, the current damage accumulation procedures and multiaxial strength theories, particularly those used for creep-fatigue, have known fundamental shortcomings and do not always correlate well with available experimental data. There is a major need for improvements in this area.

g. *Flawed and Cracked Component Evaluation Procedures.* Rules for design are currently predicated on crack prevention, but the need for simple engineering procedures to evaluate the structural integrity or remaining life of elevated-temperature nuclear components containing real or postulated crack-like flaws is becoming increasingly evident. Needs include flaw modeling guidance, methods for predicting slow incremental creep and fatigue crack growth, and finally experimentally verified methods for predicting ultimate component failure where failure modes in addition to crack growth can come into play.

h. *Thermal Striping.* The need for sound rules for design against failure by thermal striping, caused by the mixing of hot and cold sodium, is generally recognized. The problem is two-fold: (1) to develop/validate procedures for using isothermal fatigue data to predict cracking due to thermal striping where the metal temperature cycle is relatively well known, and (2) to develop procedures for characterizing the actual fluid and metal temperatures under realistic mixing conditions.

i. *Design Methodology for Modified 9 Cr–1 Mo Steel.* Modified 9 Cr–1 Mo steel has many attractive features promising both cost reduction and increased reliability, and it is being pursued in the United States as an alternative to the austenitic stainless steels and 2-1/4 Cr–1 Mo steel. However, the structural design methodology, which has been developed for these latter alloys, must be extended to the new alloy, which has some significantly different behavioral features.

j. *Tubesheet Analysis Procedures.* Tubesheets are complex three-dimensional structures that are difficult to analyze. Section III of the ASME Code provides a simplified method of analysis based on the equivalent solid plate concept, but it is not adequate at elevated temperatures where creep effects are significant and the dominant stress is due to thermal gradients and occurs in the vicinity of the boundary between the rim and hole regions. A practicable design and evaluation procedure, that is experimentally based, is needed for LMFBR application.

k. *Constitutive Equations.* Accurate models of the inelastic response of materials to time-varying multiaxial loadings are necessary not only for inelastic analyses but as a basis for simplified analyses as well. Although constitutive equations have been developed and widely used in the United States, they still have known shortcomings that need to be overcome, and additional experimental support for their validity is required.

2. Code Reform Needs

All but the last item in the following list deals with ASME high-temperature Code Case N-47 [2]. All of these items have been formally transmitted to the ASME Boiler and Pressure Vessel Code by the U.S. LMFBR program with the request that the items be addressed by the Code groups.

a. *Creep-Fatigue Rules.* It is felt by many that the creep-fatigue rules are not well based and are overly prescriptive relative to their experimental bases. The elastic rules, in particular, are excessively conservative and confusing to follow, and they should be revised, simplified, and clarified.

b. *Limits for Weldments.* Realistic, experimentally-based, and defensible limits should be provided for weldments. Also, meaningful design analyses, in which realistic weldment property variations are used, should be permitted, both for similar and dissimilar metal weldments.

c. *Strain Limits.* The current strain limits are not based quantitatively on any particular failure mode and do not specifically account for stress state or material ductility. Improvement is needed.

d. *Limited Materials of Construction.* The limited materials permitted in elevated-temperature construction hinders innovative LMFBR plant designs. The prompt addition of modified 9 Cr—1 Mo steel to Section III and the elevated-temperature Code Cases would significantly benefit the U.S. LMFBR effort.

e. *Buckling Limits.* Two key issues relative to the current buckling limits have been voiced. First, it is difficult to identify and account for imperfections in buckling analyses of very thin components, such as the vessel of a pool-type reactor, and, second, the load factor of 3 on time-independent buckling may be excessive when imperfections are properly accounted for in analyses.

f. *Need for Industrial Grade Code Rules for Nonsafety LMFBR Components.* The latest LMFBR designs limit safety functions to the primary system plus a few specific safety systems. The intermediate loop and balance-of-plant are nonsafety related and can therefore, it is hoped, be built to industrial standards. These codes do not, however, adequately address the cyclic thermal transient loadings and associated creep damage accumulation that occur in LMFBRs. An industrial type code or code case is thus needed for nonsafety-related LMFBR elevated-temperature components.

V. U.S. HIGH-TEMPERATURE STRUCTURAL DESIGN DEVELOPMENT AND VALIDATION ACTIVITIES

This section will briefly outline ongoing U.S. activities to resolve the previously identified technology issues and to support Code reform. Only current activities, or those planned for the near term, will be mentioned.

1. Design Assessment Procedures for Weldments

With the exception of the development of rules for the design of dissimilar metal welds, which is being carried out by General Electric, the current U.S. effort is concentrated on weldments in types 316 stainless steel using 16-8-2 filler metal. Tests and companion analyses at Oak Ridge National Laboratory (ORNL) are aimed at (1) providing further substantiation of creep-rupture and creep-fatigue strength reduction factors that are currently being considered by the ASME Code and (2) providing a more rigorous design life assessment approach for critical weldment locations.

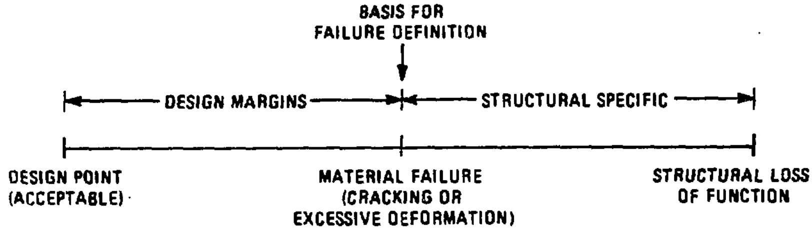
Creep-rupture tests and analyses of structural weldments are focused on uniaxially loaded welded plates and welded pipes. A typical cracked welded plate is shown in Fig. 2. Tests such as this are demonstrating the adequacy of the ASME Code Case N-47 primary stress limits, with the creep-rupture strength reduction factors currently being considered. Such tests are also showing that the failure time and location can be reasonably well predicted by an inelastic failure anaysis that properly accounts for the "metallurgical notch" by using the actual distribution of yield, creep deformation, and creep-rupture properties across the weldment. Figure 3 shows the good comparison between the measured and predicted axial strain and point of crack initiation that can be obtained. The weld metal in this case had a yield strength at 593°C (1100°F) that was more than twice that of the base metal; the creep rate in the weld metal was lower than in the base metal, and the creep strength was higher.

Fatigue tests are being performed on welded tubes. The tubes, which are subjected to axial or torsional cycling, have either axial or circumferential welds. These combinations of weld orientations and multiaxial loadings are providing data for validating the appropriateness of the pending Code weldment fatigue strength reduction factor of 2 on allowable cycles.

2. Structural Validation Tests

Approximately 60 high-temperature structural validation tests have been performed in the United States. In the past the emphasis was on deformation, and the results were used to assess inelastic analysis predictions. Now, the emphasis is on failure and comparison with failure predictions. Four test types will be mentioned here.

First, thermal transient creep-fatigue tests of thick-walled cylinders are being conducted at ORNL. In these tests an induction heating facility is used to impose an upshock on the outer surface of the cylinders. This leaves a residual tensile stress on the outer surface which relaxes during the subsequent hold period and eventually leads to creep cracking, which can take the form of "mud cracking" or of a few distinct and separate cracks, depending, perhaps, on the creep ductility of the material. The primary purpose of these tests is to validate failure prediction methods. Defining precisely when material failure or cracking occurs is, however, a problem. The following diagram helps to clarify the issues. The "material failure"



point must be defined and design margins established; likewise, "material failure" or initial cracking must be related to structural failure.

Nozzle-to-sphere specimens at ORNL, such as the one depicted in Fig. 4, are being subjected to cyclic nozzle moment loadings and to long-term internal pressure loading until failure occurs in the junction region. So far, the occurrence of visible cracking has been found to correlate reasonably well with failure predictions. As an example of the ability to predict deformations, typical comparisons of measured and predicted junction creep strains are shown in Fig. 5 for a repeated moment histogram.

Another ongoing series of tests, which are being planned and coordinated by ORNL but performed in the Thermal Transient Facility at the Energy Technology Engineering Center (ETEC), are thermal ratchetting tests to failure of 203-mm-(8-in.) diam pipes. Type 304 stainless steel tests have been completed, and tests of 2-1/4 Cr—1 Mo steel and circumferentially welded 316 stainless steel pipes are currently being initiated. Typical results for 304 stainless steel are shown in Figs. 6 and 7. The pipe in this case was subjected to an axial load and to periodic thermal downshocks from 590°C (1094°F), as was depicted schematically in Fig. 1. For this particular test, the life was somewhat over-predicted but the Code allowable life was still conservative.

The final test, which was conducted by Westinghouse and is still being analyzed, is depicted in Fig. 8. Here, a realistic vessel, with nozzles, was subjected to an internal pressure, and one of the nozzles was subjected to repeated thermal downshocks on the inner surface to provide ratchetting data. Interestingly, creep cracking occurred in several of the nozzle forgings near the welds to the vessel shell. Reasons for this early cracking are still being investigated, but a contributing factor was the low creep-rupture strength of the large-grain forging material. Analyses have shown that the weldment residual stresses played only a minor role.

3. Simplified Analysis Methods

Continuing efforts are underway at ORNL and Hanford Engineering Development Laboratory (HEDL) to develop and verify simplified methods for assessing the adequacy of a design without having to resort to cyclic inelastic analysis. As a near-term effort at ORNL, an attempt is being made to identify and recommend a procedure for using an elastic core concept for predicting ratchetting of three-dimensional structures in shakedown situations. As a longer-term ORNL effort, the state-variable method of Zarka [8] is being combined with creep bounding procedures to formulate a more general method for predicting ratchetting strains. Efforts are underway at HEDL to develop improved elastic analysis creep-fatigue evaluation procedures; plans are to also evaluate the use of various time-independent inelastic analysis procedures

4. Design Procedures for Piping

Rockwell International has the lead in developing piping rules and procedures. The use of low-temperature stress intensity factors and flexibility factors has been evaluated, and revised rules have been developed and submitted to the Code bodies. High-temperature tests of tees are planned to augment the information on indices. Elastic analysis recommendations are being prepared. Also, an elastic follow-up piping loop test is planned at ETEC, and the results will be utilized to develop and assess a simplified methodology for quantifying elastic follow-up in elevated-temperature piping lines.

In addition to the Rockwell International effort, piping work at Westinghouse has focused on inelastic tests of elbows, including creep deformation and buckling tests, and on assessing inelastic predictive capabilities for elbows. A final report on this work is currently being prepared; it will contain analysis guidance for elbows.

5. Validation of Procedures for Notch-Like Discontinuities

Notch effects are being evaluated in tests and analyses at ORNL. Notched bar results plus the results of monotonic and cyclic creep-rupture bending tests, which are currently being initiated on notched rectangular and circular plates, will be used to demonstrate, hopefully, the adequacy of the current design assessment methodology for notch-like discontinuities.

6. Life Assessment Procedures

The effort here, which is being conducted by ORNL and Argonne National Laboratory (ANL), is aimed at sound and reliable rules for precluding material failure through cracking or rupture. The focus is on both creep rupture and creep-fatigue and on the two necessary ingredients of failure criteria: (1) a damage accumulation rule for counting and limiting the cumulative damage under time-varying temperatures and loadings, and (2) a multiaxial strength theory for predicting failures under multiaxial loadings from uniaxial failure data.

For creep rupture, ORNL has just completed an assessment of the time-fraction damage accumulation rule used by Code Case N-47 on the basis of an extensive series of variable load and temperature creep-rupture tests. The results indicate that time fractions do an adequate job for loadings that do not involve inelastic load reversals. Both ANL and ORNL are working on improved damage accumulation rules for creep-fatigue. ANL is conducting exploratory uniaxial tests under complex loading histories, identifying damage mechanisms, and formulating an improved damage accumulation rule based on the damage rate approach. ORNL is focusing on cycles dominated by creep damage.

A new multiaxial creep-rupture strength theory has been formulated by ORNL based on multiaxial tubular test data for types 304 and 316 stainless steels and an Inconel alloy. The new model, which is based on an equivalent stress parameter containing the hydrostatic stress, the Mises effective stress, and the maximum deviatoric stress, provides a substantially better fit to experimental data than the Mises and Tresca (maximum shear stress) criteria currently used in Code Case N-47. This is illustrated in the isochronous plot of Fig. 9, which compares the locus of experimentally determined biaxial stress states that produce identical rupture times with the three criterion. The new criterion, which is being further evaluated for additional materials and is currently being considered by the Code groups, reduces the scatter in life predictions for various stress states by an order of magnitude.

Multiaxial strength criteria for fatigue and creep-fatigue are also being evaluated by ORNL. Tests of 304 stainless steel and 2-1/4 Cr—1 Mo steel tubes subjected to cyclic axial and torsional loads are complete and 316 stainless steel creep-fatigue tests are underway. The fatigue data shown in Fig. 10 for 2-1/4 Cr—1 Mo steel are typical. Uniaxial loadings give the shortest lives, while pure torsion gives the longest. Thus, design fatigue curves based on uniaxial data appear to be conservative.

7. Thermal Striping

Both Westinghouse and Rockwell International are doing thermal striping tests. The Westinghoue tests use a thin-walled rotating cylinder specimen that is alternatively subjected to hot and cold streams of sodium, as shown in Fig. 11, and they are aimed at correlating striping failure data with isothermal fatigue data and at developing life assessment procedures. The Rockwell tests use a 305-mm (12-in.)-long beam which either oscillates or remains stationary in two mixing streams of hot and cold sodium, as depicted in Fig. 12. Although some tests are taken to failure, to obtain data for correlation with the Westinghouse results, the main objective of the Rockwell tests is to provide data for characterizing the fluid film effect on heat transfer under the random conditions of fluid mixing.

The Westinghouse results for 316 stainless steel indicate that striping data for crack initiation generally fall at the upper bound of uniaxial isothermal data. By applying appropriate safety factors on strain range and cycles, thermal striping design fatigue curves have thus been developed from isothermal fatigue data. Tests on Alloy 718 indicate that, if the sensitivity to initial flaws is neglected, this alloy has a 100°C (180°F) advantage in fluid ΔT over type 316 stainless steel at 10^6 cycles. Likewise, modified 9 Cr—1 Mo steel has a 100°C advantage.

8. Design Methodology for Modified 9 Cr—1 Mo Steel

Currently a modest activity is underway at ORNL to assess the applicability of the existing high-temperature structural design methodology to modified 9 Cr—1 Mo steel. This effort is focused on two areas: (1) assessing constitutive equations (it is apparent that a viscoplastic model will be needed because of the indistinguishable nature of rate-dependent plastic strains and creep strains) and failure criteria, and (2) performing a select few preliminary structural tests and accompanying analysis to assess the applicability of the overall methodology.

9. Tubesheets

Rockwell International has recently issued a report summarizing U.S. tubesheet design methods and proposing a plan for developing a validated simplified methodology for analyzing high-temperature tubesheets, particularly where thermal loadings are significant. A development program, including thermal loading tests of tubesheets, is planned for future years.

10. Constitutive Equations

The U.S. LMFBR program has had, in the past, a strong emphasis on constitutive equation development. Out of this has come the classically-based constitutive equations widely used in design analyses as well as proposed viscoplastic, or unified, constitutive equations that do not distinguish between rate-dependent plasticity and creep. Current efforts, which are minimal, are focused on continued improvement of the classically-based equations and on fostering the use and validation of the improved unified equations.

VI. SUMMARY

Unique high-temperature structural design problems in LMFBRs arise primarily from the repeated thermal transient loadings and the fact that the components operate at temperatures where time-dependent effects are important. Over the past 15 years, the framework of a design methodology for dealing with these loadings and effects has been developed and widely applied in the United States. Nonetheless, it is recognized that there are significant fundamental problem areas and needs that remain, and as long as these are unresolved, the design methodology is, in a sense, unstable and questionable and will almost certainly lead to scope changes, regulatory delays, and backfitting in LMFBR plant projects. Stable and standardized methods and criteria must be available for safe and reliable LMFBR plants having minimal capital costs and power costs.

In the United States, the problem areas and needs have been identified and prioritized based on input from both plant designers and those responsible for developing and validating the methodology. Activities addressing the most important of these problem areas and needs are underway. These focus primarily on the development of procedures for assessing structural life with certainty, on the need for confirmatory structural tests that demonstrate that the methods, rules, and criteria provide adequate margins against failure, and on the need for simpler, more generally applicable, criteria and procedures.

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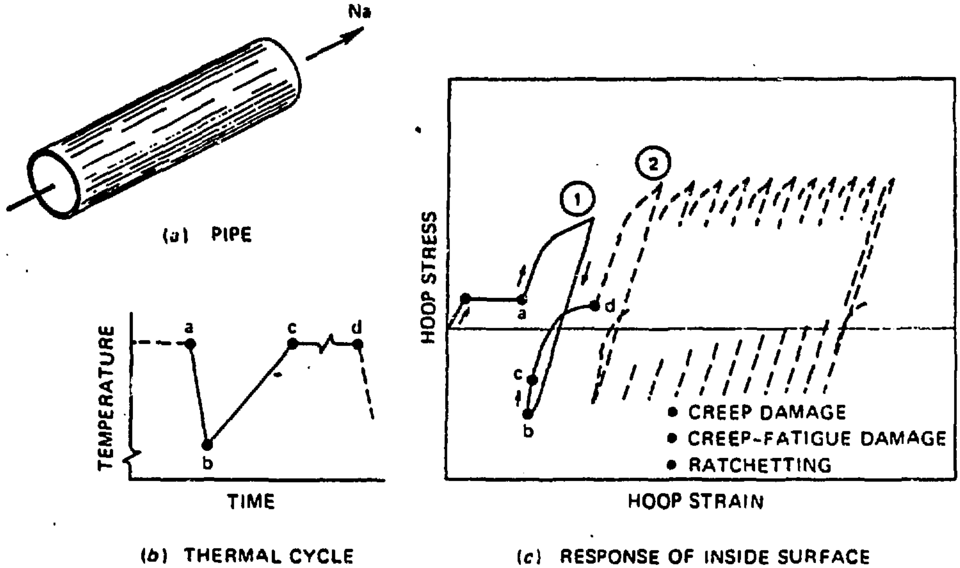

Fig. 1. Schematic representation of effects of repeated thermal transient loadings.

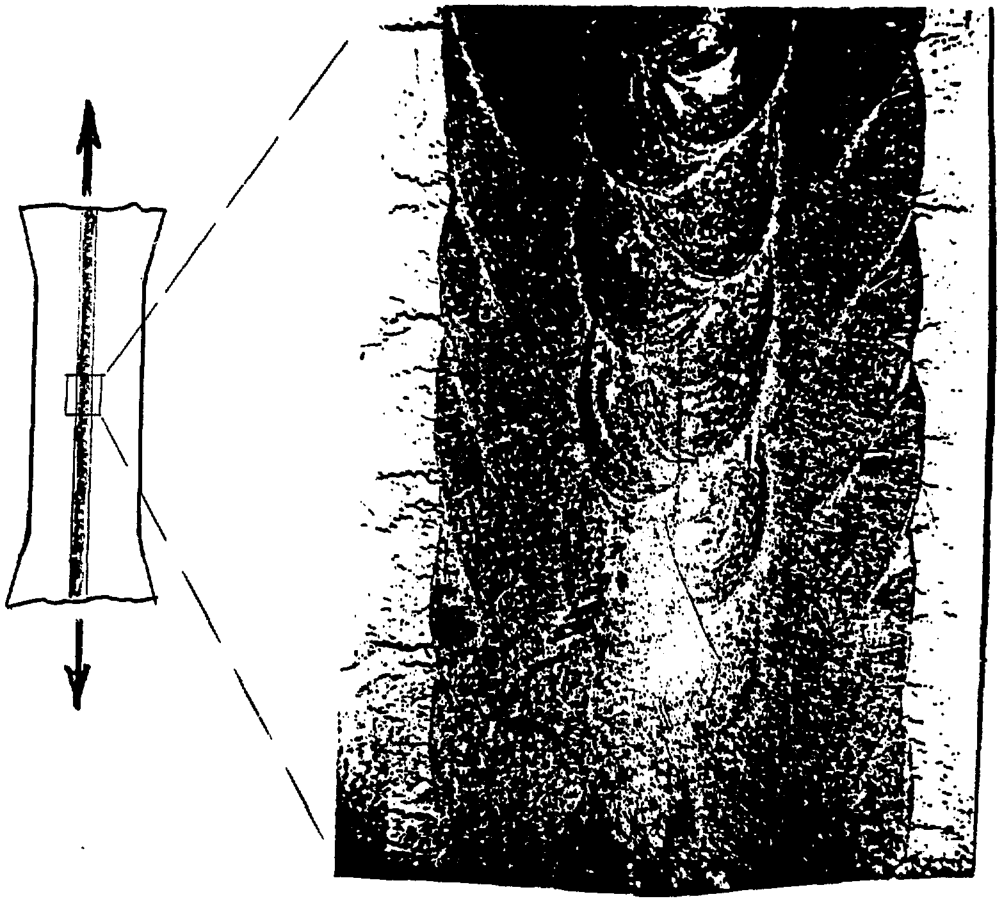

Fig. 2. Creep-rupture cracking in 316/16-8-2 plate weldment subjected to long-term axial load.

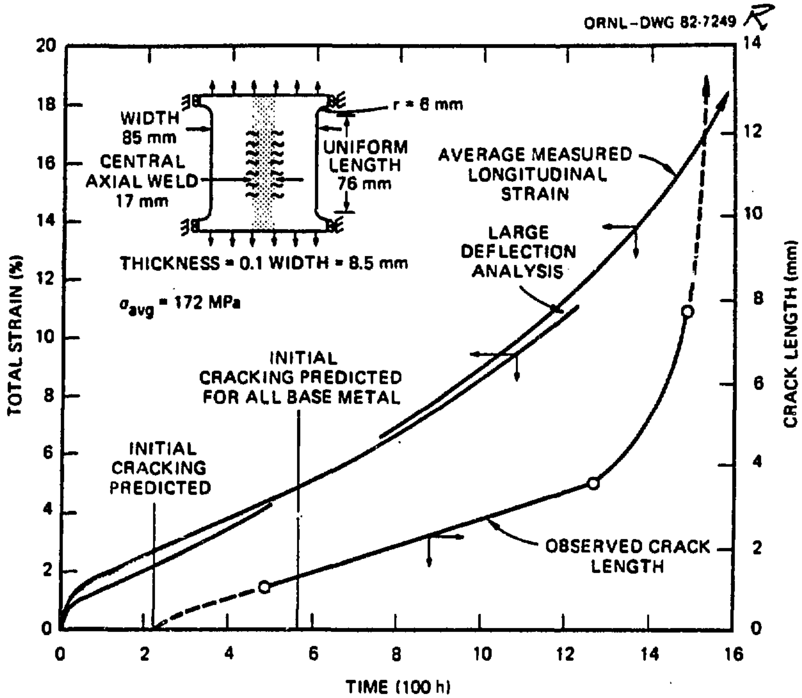

Fig. 3. Comparison of analytical predictions with experimental results for typical 304/308-CRE plate weldment creep-rupture test performed by Westinghouse.

Fig. 4. Instrumented nozzle-to-spherical shell specimen of type 304 stainless steel.

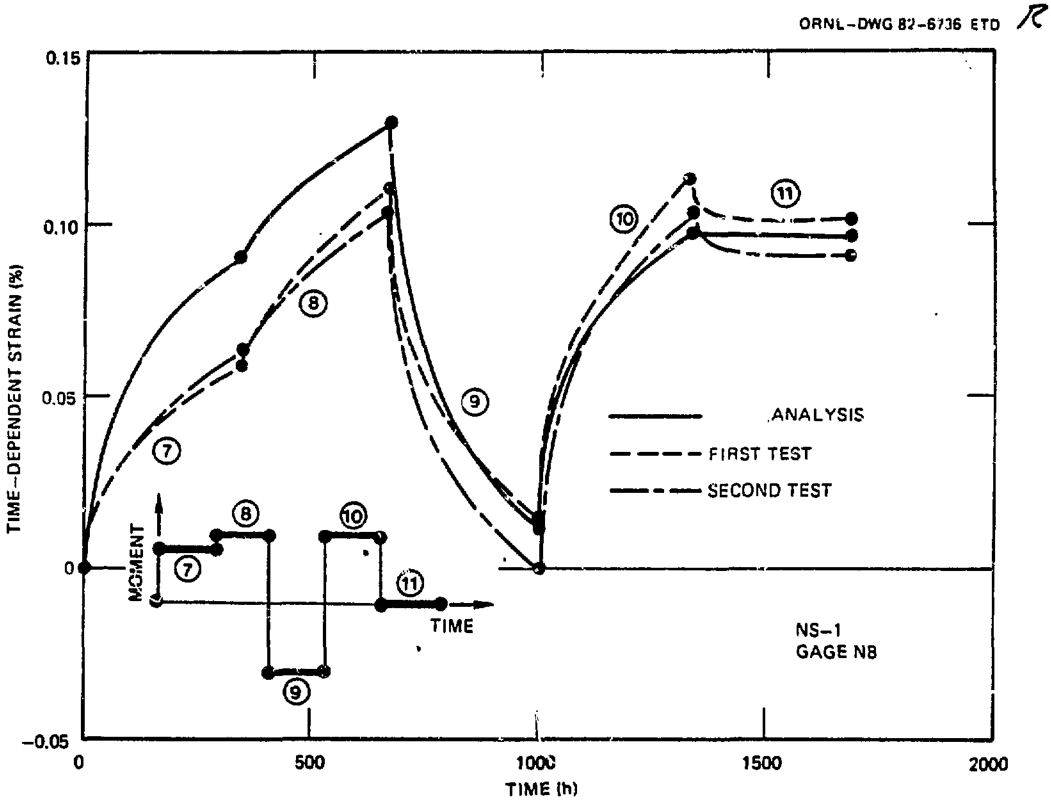

Fig. 5. Time-dependent circumferential strain measurements and predictions for two repeated moment-only tests of a nozzle-to-spherical shell specimen (transition region behavior).

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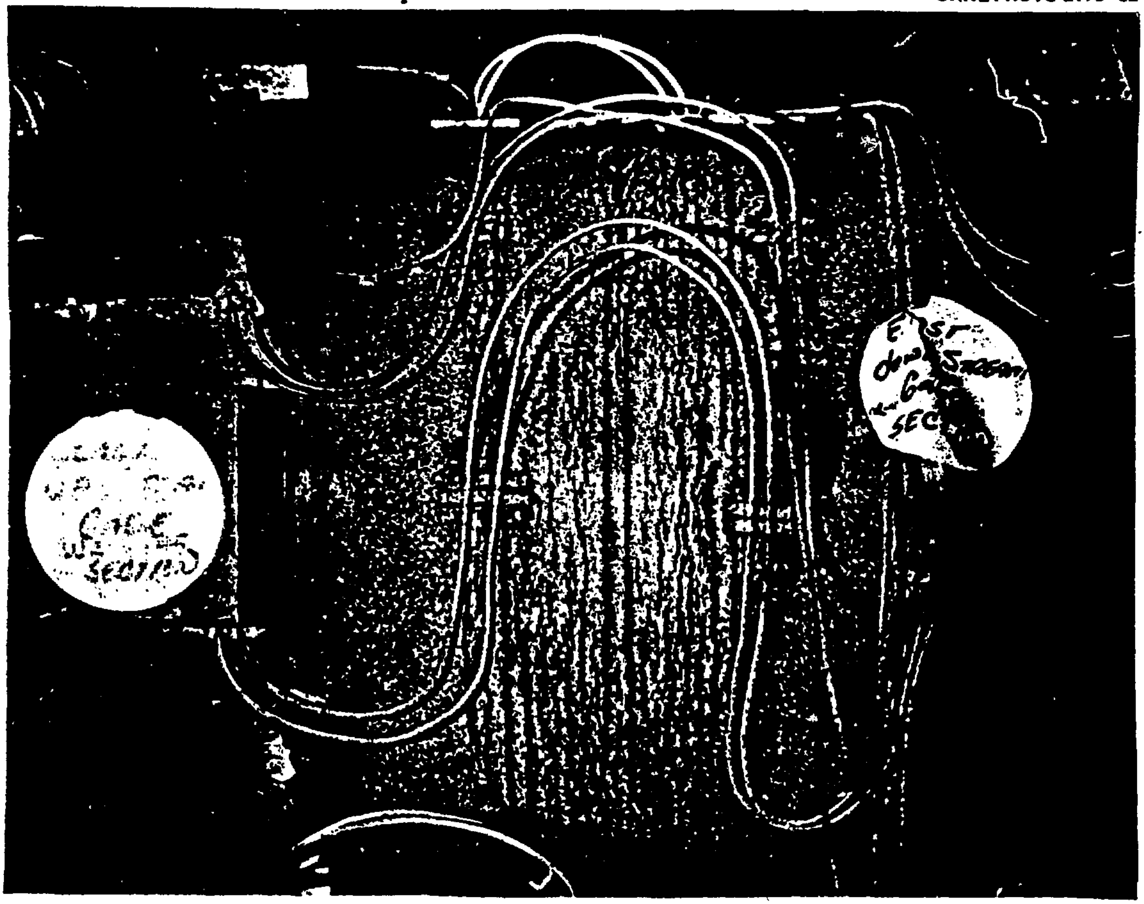

Fig. 6. Outer surface cracking due to creep damage in 203-mm-diam x 9.5-mm-wall (8 in. x 0.375 in.) type 304 stainless steel pipe thermal ratchetting specimen.

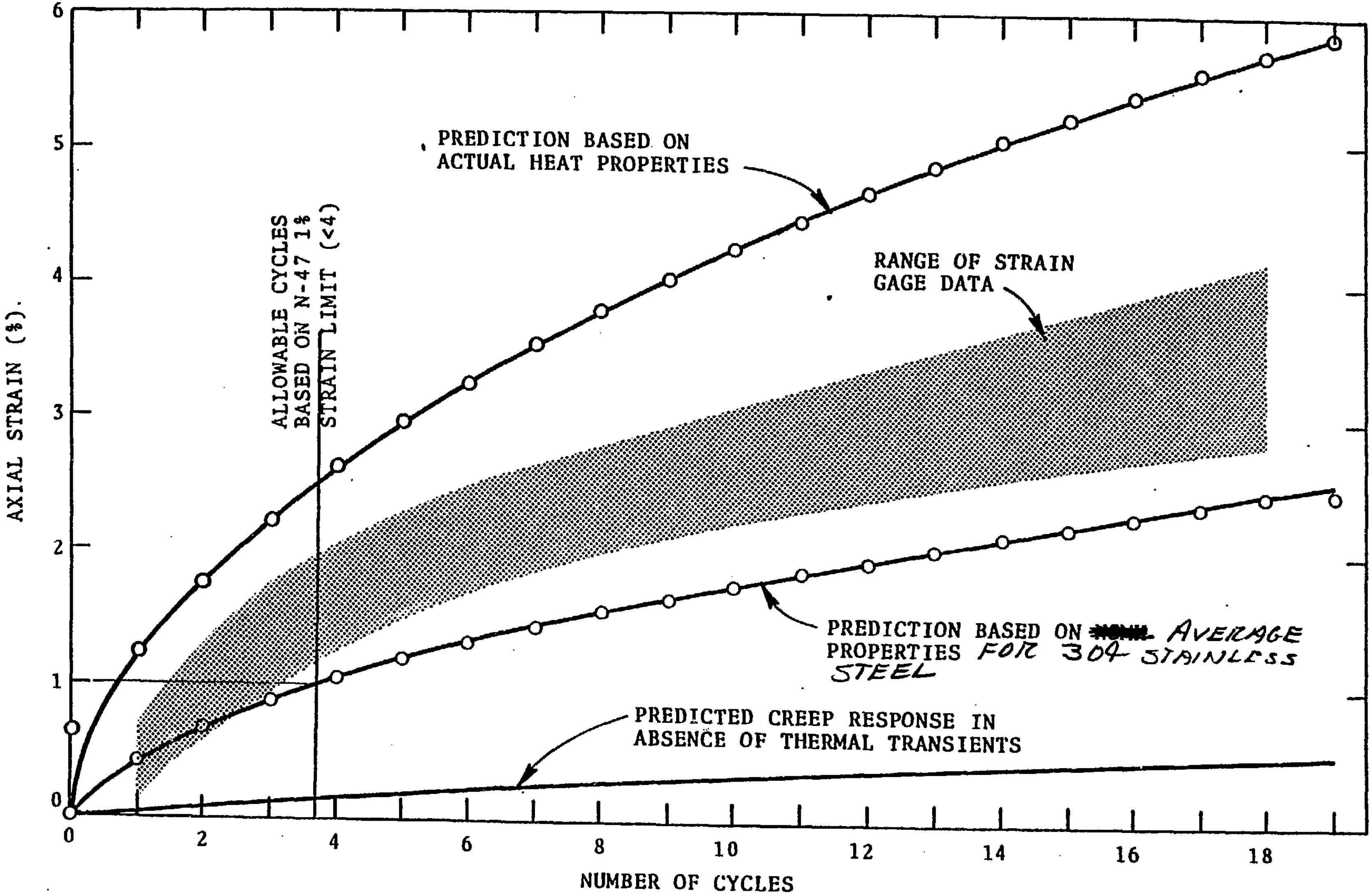

Fig. 7. Measured vs predicted axial ratchetting strain on outer surface of type 304 stainless steel pipe thermal ratchetting specimen.

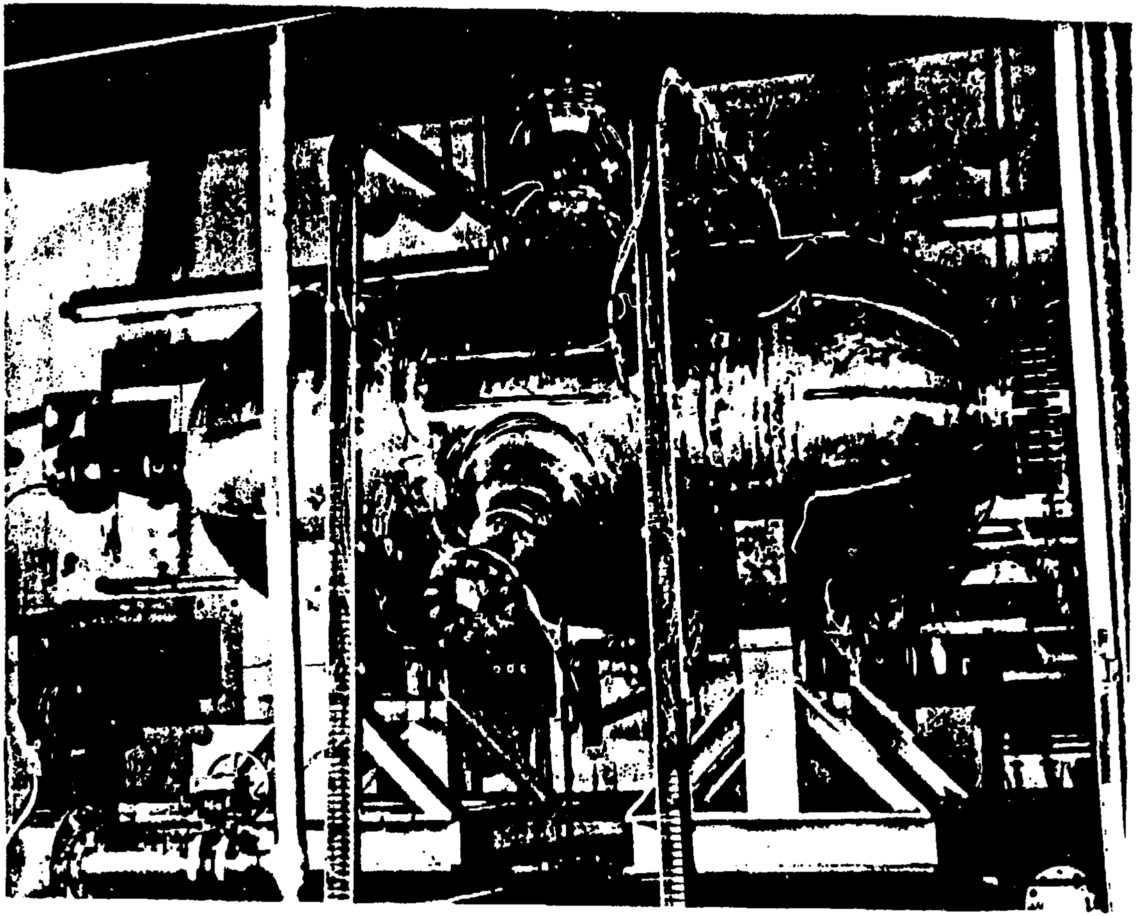

Fig. 8. Type 304 stainless steel pressure vessel being tested in Creep Ratchetting Test Facility.

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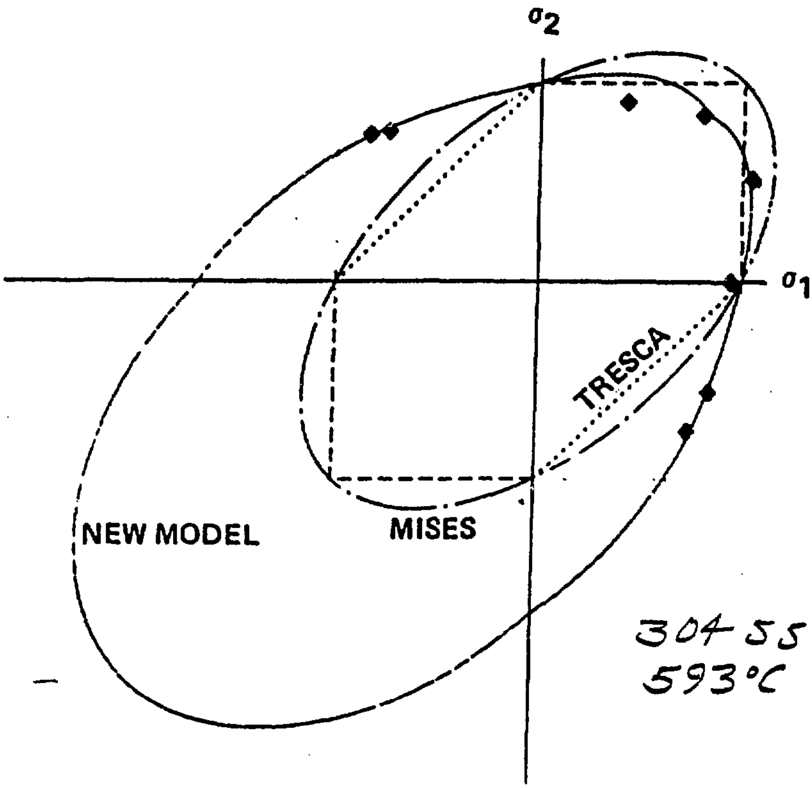

Fig. 9. Biaxial isochronous stress rupture contours showing that new creep-rupture criterion fits 304 stainless steel data much better than the classical criteria.

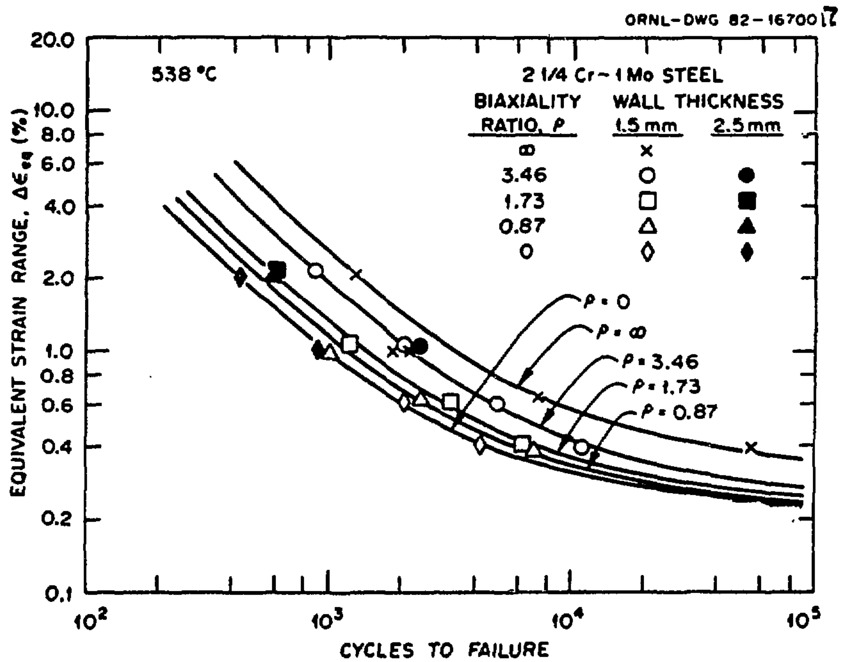

Fig. 10. Mises equivalent strain range vs cycles to failure for multiaxial fatigue tests of 2-1/4 Cr–1 Mo steel tubes at 538°C. ($\rho = 0$ corresponds to uniaxial straining; $\rho = \infty$, to pure torsional straining.)

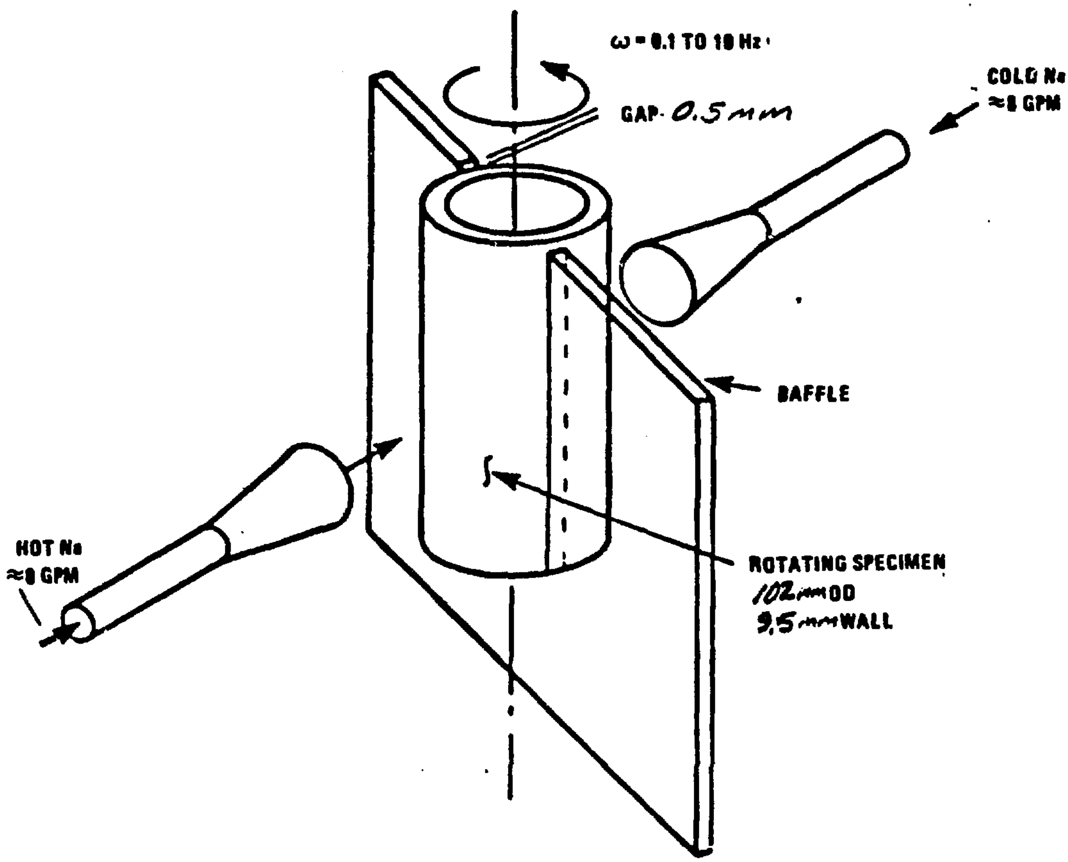

Fig. 11. Conceptual representation of Westinghouse thermal striping test concept, based on rotating cylinder specimen.

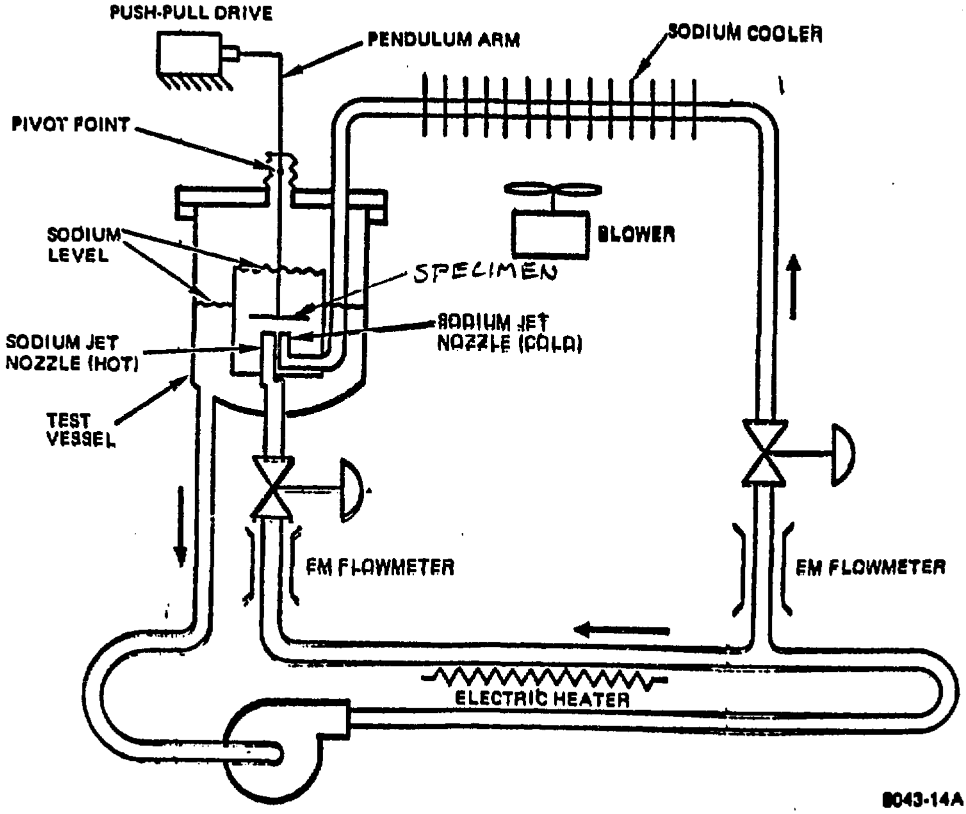

Fig. 12. Conceptual representation of Rockwell thermal striping test concept, based on oscillating beam specimen above parallel fluid streams.

OCT 15 1984

NE-53 (BTP:MS:106)

Request for Release of Applied Technology Information for Presentation at IAE International Symposium on LMFBR Development, Tokyo, 11/6-9/84

J. B. La Grone, Manager
Oak Ridge Operations Office

Reference: Letter, J. M. Corum (ORNL) to G. A. Newby (BMCD), dated 10/5/84, same subject

The paper submitted by the reference letter has been reviewed and is approved subject to the comments given in telecon between J. Corum and C. Bigelow of my staff being addressed.

The comments were related to clarifying certain technical terms in explaining the role HTSD plays in providing validated design methodology for advanced LMR designs that are highly reliable, safe, and are competitive in cost and explaining the need for continued development.

We would like a copy of the final version of this paper for our records.

Original signed by:
Glen A. Newby

Glen A. Newby, Director
Breeder Mechanical Component
Development Division
Office of Breeder Technology
Projects
Office of Nuclear Energy

CONCURRENCES	
RTG SYMBOL	NE-53
INITIALS/SIG	CBigelow
DATE	10/11/84
RTG. SYMBOL	NE-53
INITIALS/SIG	GNewby
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cc:
J. Corum, ORNL

Subject OR 1.1
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MS Rdr
CBigelow Rdr

S. Rosen, NE-75
D. Bunch, NE-53

NE-53:BTP:MS:106:CBigelow:jbn:353-4299:10/11/84

M/R: Paper reviewed and discussed at length with J. Corum by C. Bigelow in telecon of 10/10/84. Record of comments is in margin of C. Bigelow's copy which will be filed in the OR 1.1 division file. The paper submitted by the referenced letter is the basis for a lecture to be presented at the IAE International Symposium on LMFBR Development in Tokyo, 11/6-9/84. The request for a DOE lecture on this subject was accepted by S. Brewer for J. Corum, in his letter of 5/17/84 to Y. Yamamoto. J. Corum was requested to attend and give lecture.

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