## APPENDIX IV. COMPARISON OF LOW CYCLE FATIGUE RESULTS WITH DESIGN CURVES IN ASME CC 1592

Results reported in papers 15, 16, 27, 29, and 30 (see App. III) of this meeting were obtained with hourglass shaped specimens under axial strain control. To achieve proper comparibility of the data with design curves in ASME CC 1592 that have been derived from tests with diametral strain measurement and control appropriate correction factors should therefore be applied.



# An Overview of the U.S. Programs on Properties of Primary Circuit Materials*

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ABSTRACT

The objective of U.S. Breeder Reactor Programs associated with primary circuit structural materials is to develop the design data base and associated design technology on existing commercially available materials as well as new alloys. This will permit economic operation of components at acceptable levels of plant availability and at up to 40-yr lifetimes for inacccessible components. Long-term component reliability, elevated-temperature service within the creep range, and resistance to sodium attack and irradiation damage, along with design in compliance with ASME Codes and RDT Specifications, have required that the U.S. Programs be directed toward contributing knowledge in a number of areas. These areas, relating to material deformation, failure modes, compatibility, fabrication, long-term behavior, irradiation damage, and availability will be discussed. The U.S. Structural Material Programs concerned with primary-circuit components will be reviewed, and their current and future contributions to knowledge of these areas will be explained.

The objective of U.S. Breeder Reactor Programs associated with primary circuit structural materials is to develop the design data base and associated design technology on existing commercially available materials as well as for new alloys. This development will permit economic operation of components at acceptable levels of plant availability and at up to 40-yr lifetimes for inaccessible components.

The requirements of long-term component reliability, elevated-temperature service within the creep range, and resistance to sodium attack and irradiation damage, along with design in compliance with ASME Codes and RDT Specifications, have dictated that U.S. Programs be directed towards contributing knowledge in a number of areas. These areas, which

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are not necessarily unique to breeder reactor primary circuit systems, are as follows:

1. Limited Code-Approved Materials;
2. Reduction in Need for Large Amounts of Chromium and Nickel;
3. Heat-to-Heat Variations;
4. Product Form Selection;
5. Thermal Stability, Creep-Rupture Ductility, and Strain Limits;
6. Tertiary Creep;
7. Long-Term Data;
8. Time-Dependent Fatigue;
9. Damage Law Formulation;
10. Weldment Behavior;
11. Mass Transfer;
12. Fabrication Procedure;
13. Irradiation Effects; and
14. Constitutive Equations for Inelastic Analysis.

The objective of this paper is to review U.S. Primary Circuit Structural Material Programs and show how they will contribute knowledge in the areas defined above. Work under way at the following U.S. Laboratories will be briefly described: Argonne National Laboratory (ANL), Hanford Engineering Development Laboratory (HEDL), Idaho National Engineering Laboratory (INEL), Naval Research Laboratory (NRL), Oak Ridge National Laboratory (ORNL), and Westinghouse-Advanced Reactor Division (W-ARD).

1. Limited Code-Approved Materials for Elevated-Temperature Service.

ASME Code Case 1592 provides design rules for components fabricated to high-temperature Sect. III, Div. 1, Class 1 requirements. This Code Case contains stress limits for certain high-alloy steels up to 816°C and must be used for nuclear Class 1 components design. Currently, however, only four structural steels are covered by this Code Case. These materials include types 304 and 316 stainless steel, alloy 800H, and 2 1/4 Cr-1 Mo steel. Comparison plots of $S_{mt}$ — the allowable primary membrane stress limit that prevents failure from gross yielding, tensile instability, stress rupture, tertiary creep, and excessive strain — are shown as a function of temperature for the four Code-approved materials in Fig. 1. Two additional alloys, alloy 718 and 9 Cr-1 Mo steel, which are currently receiving attention for possible future addition to the Code Case, are shown for comparison as well. The plots given in Fig. 1 indicate that conventional 9 Cr-1 Mo steel has about the same strength as 2 1/4 Cr-1 Mo steel; however, as will be shown in the following section, certain alloy element additions can considerably strengthen this material. The high allowable stress limits and excellent high-cycle fatigue resistance[1] (Fig. 2) make alloy 718 a prime candidate for certain upper core internal nonwelded structural applications, especially in view of the expected thermal fatigue (up to $10^9$ cycles) that occurs when adjacent streams of greatly differing temperature alternately impinge on portions of the upper internal structure. Product forms of interest include bars, forgings, and forging stock in accordance with ASTM specification A 637, grade 718, and plate [(thickness to 76 mm (3.0 in.)] in accordance with ASTM A 670. The material is conventionally heat-treated as follows: held at 954°C for 1 hr, air cooled to below 621°C, heated to 718°C and held for 8 hr, furnace cooled at 55°C/hr to 621°C, and held for a total aging time of 18 hr, followed by an air cool.



The utilization of alloy 718 for core upper internal structural applications requires generation of design allowable stresses and ASME Code approval for high-temperature, nonwelded, non-pressure-boundary applications. Accordingly, comprehensive mechanical and physical property test programs are under way at HEDL, INEL, NRL, ORNL, and W-ARD to obtain data required for Code approval.[2] Property variations due to heat-to-heat and product form effects are also being studied. Thermal stability, heat treatment modifications, and sodium compatibility are also being assessed.

2. Reduction in Need for Large Amounts of Chromium and Nickel.

Currently the U.S. imports essentially all of its chromium (91%) and about 71% of its nickel. If a large number of breeder reactors, or for that matter light-water reactors, are constructed, extensive use will be made of the austenitic stainless steels (8–14% Ni and 16–20% Cr). For example, a 1000-MWe scale-up of the CRBRP design would require roughly 1600 metric tons of chromium and 1000 metric tons of nickel. Forty such breeder additions per year would be equivalent to 30% of today's U.S. nickel use and 6% of chromium use. To minimize the need for these critical elements, as well as for other reasons (such as development of breeder reactor systems with lower reactor outlet temperatures), current programs at Combustion Engineering Company and ORNL are concerned with the development of a stabilized 9 Cr-1 Mo ferritic steel. This alloy is a slight modification of commercial 9 Cr-1 Mo and is stronger in creep-rupture (Fig. 3), weldable, and stress-corrosion resistant.[3,4] Development of this alloy has proceeded through a screening phase aimed at finding suitable base material compositions and electroslag-melted ingot compositions for suitable welding materials. Current and future efforts will include microstructural stability studies. Design data gathering — including tensile, creep, fatigue, creep-fatigue, and toughness — is in progress to qualify this material as acceptable under ASME criteria for elevated-temperature service. Other representative large heats in needed product forms will be procured and characterized.

3. Heat-to-Heat Variations.

It has long been recognized that the ranges of composition and thermomechanical processing history permitted by applicable material procurement specifications results in considerable variation in certain important mechanical properties. It is important in setting allowable stresses, depicting stress-strain response in terms of constitutive equations, and modeling of long-term potential failure mechanisms such as creep-rupture and time-dependent fatigue to be able to know the effect of heat-to-heat variations on properties. Accordingly, several of the U.S. structural materials programs are investigating heat-to-heat variations.

One of the purposes of the materials program at ORNL is to determine[5] the variations in mechanical properties of 20 heats of type 304 and eight heats of type 316 stainless steel. The ORNL program emphasizes determining variations in tensile and creep properties of unaged and aged material, whereas an ANL program[6] concentrates similar work on fatigue and creep-fatigue properties. Wide variations in the tensile and creep properties of types 304 and 316 stainless steel have been found as reported elsewhere.[7,8] These variations were attributed to variations in thermomechanical

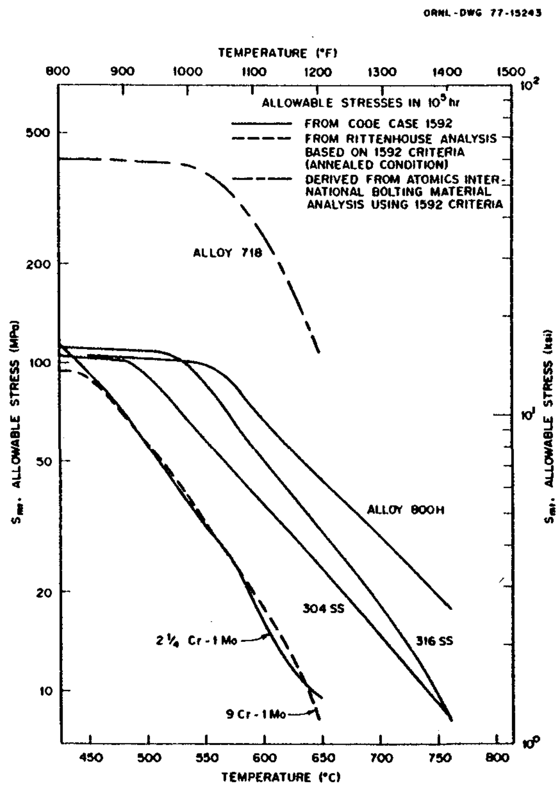


Fig. 1.

Comparison of ASME Allowable Stress Levels For Various Alloys in (Solid Lines) or Under Consideration for ASME Code Case 1592.

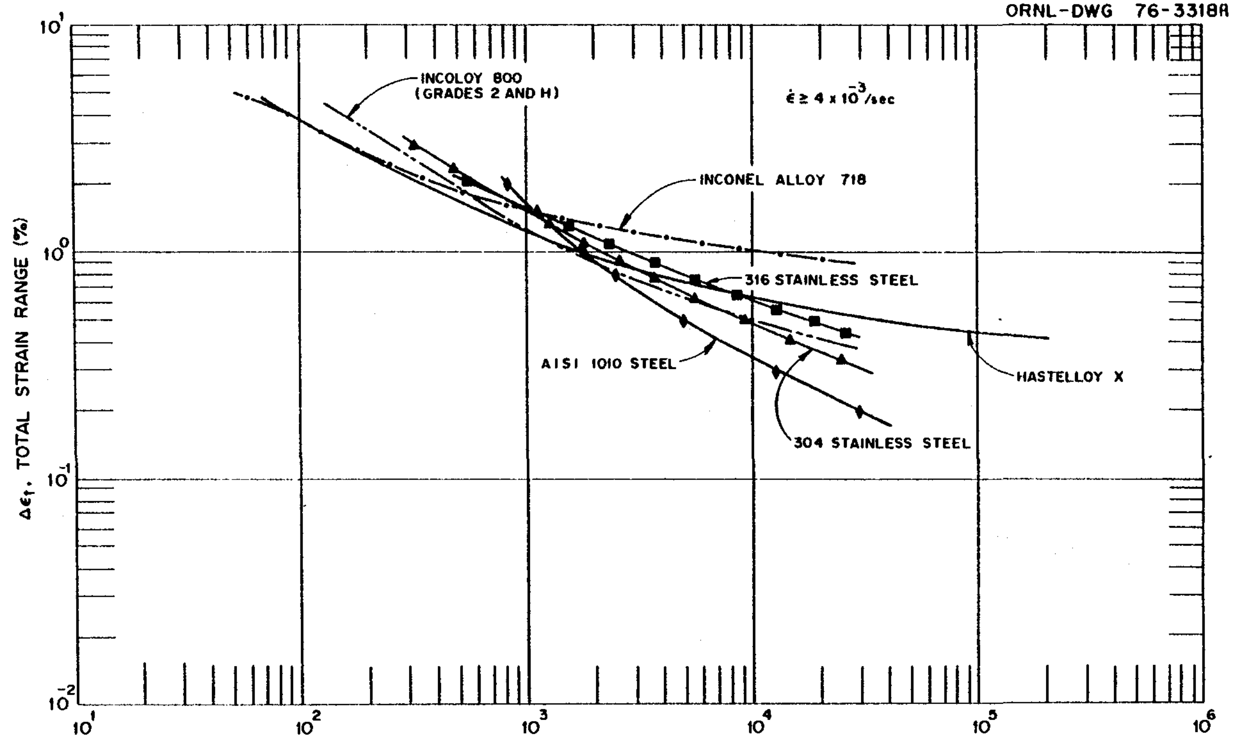


Fig. 2. Comparison of the Fatigue Behavior of Several Materials at 649°C. Lines represent best-fit values of actual data. Advantage of use of alloy 718 for high-cycle fatigue resistance are apparent.

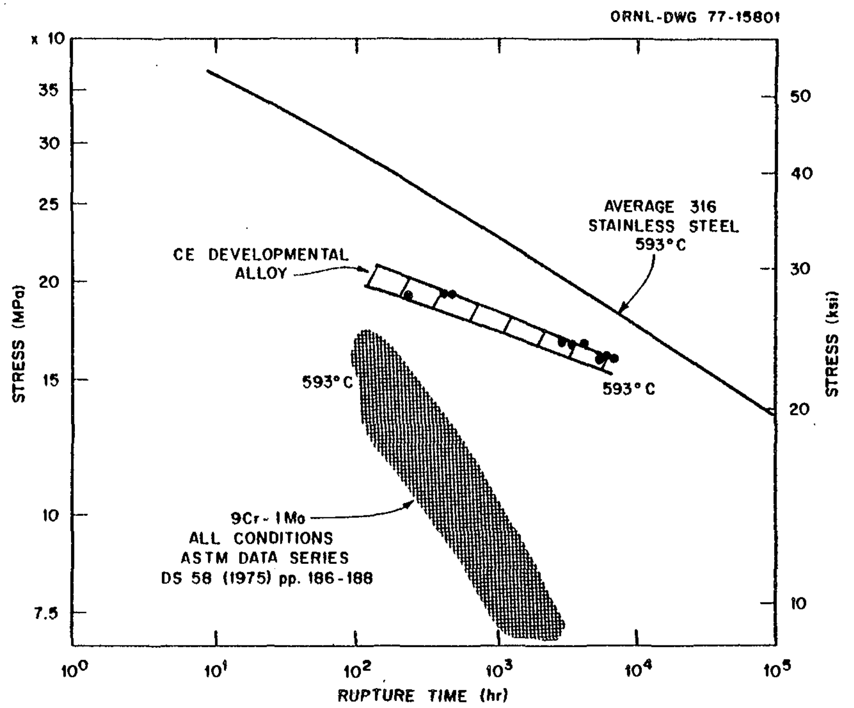


Fig. 3. Comparison of Stress-Rupture Behavior of Combustion Engineering Developmental 9 Cr-1 Mo (Low C, -W, -Nb, -B, -N) steel in the Normalized-and-Tempered Condition With Commercial 9 Cr-1 Mo and Type 316 Stainless Steel.

processing history, grain size differences, and variations in carbon, nitrogen, and residual element chemistry. Relationships between short-term elevated-temperature tensile strengths and long-term creep and creep-rupture behavior have been found. Confirmatory uniaxial creep tests in air scheduled to run up to $10^5$ hr are in progress.

Similar heat-to-heat variation and product form studies in fatigue crack propagation behavior using the techniques of linear elastic fracture mechanics are under way at HEDL. Five heats of annealed type 304 and three heats of annealed type 316 stainless steel have been tested in air at 538°C. Also included as a variable in this study was the influence of melt practice: air melt, vacuum-arc melt, and double-vacuum melt. Contrary to the tensile and creep property variations discussed above, no apparent effect of melt practice or heat-to-heat variation was found on crack propagation rates.

4. Product Form Selection.

Product form selection can be an important consideration, not only in terms of economics, dimensional requirements and control, and fabricability, but also in terms of mechanical property variations. The ORNL material testing programs have involved complete characterization[8-10] of various product forms of single reference heats of types 304 and 316 stainless steels. Typical product forms studied included plates, bars, and pipes of various sizes. This work has shown that tensile and creep strength variations can be expected between products of a single heat, even after the material has been cold worked. Similar studies will be made on product forms from a reference heat of alloy 718 currently being procured by INEL.

5. Thermal Stability.

In programs under way at nearly all the previously mentioned laboratories, environments of primary circuit materials and associated weld metals and weldments are thermally aged in air and/or sodium. The ORNL materials program involves aging[11,12] types 304 and 316 stainless steel with and without stress at 482, 593, and 649°C. Aging times have exceeded 35,000 hr for type 304 and 15,000 hr for type 316 stainless steel. Material is removed from the aging furnace at intervals and subjected to tensile and creep testing. Some toughness tests are also planned. Specimens exposed to prior creep have been tensile tested at the creep test temperature.

A program at ANL involves pre-exposure of type 304 stainless steel fatigue, stress-rupture, creep-fatigue, and tensile specimens to sodium for periods up to 10,000 hr. The exposure and test temperatures are in the range 550 to 700°C. After complete testing of these specimens, modifications to Code allowables will be made if required.

Similar aging studies are under way on alloy 718 at W-ARD. The environments are argon (up to 8000 hr) and sodium (up to 8000 hr), with aging and test temperatures set at either 649 or 704°C. The W-ARD program also includes aging of types 304, 316 stainless steel and alloy 718 in argon and sodium over the range of 482 to 732°C. Aging times are to 10,000 hr with sodium containing 1.5 to 2.0 ppm oxygen.

6. Tertiary Creep, Creep-Rupture Ductility, and Strain Limits.

Current elevated-temperature design rules include prevention of the onset of tertiary creep as a principal consideration in the establishment of time-dependent allowable stress levels. U.S. work has concentrated on prediction of the onset of tertiary creep for design use, rather than on fundamental studies of its cause and significance. Further, the retention of the tertiary creep criterion as a design limit has become increasingly more controversial as other materials, which tend to show nonclassical creep behavior, are evaluated for potential inclusion in the Code. One reason for this controversy is that for many materials it becomes somewhat difficult to determine where the onset of tertiary creep occurs and its significance. A schematic diagram is given in Fig. 4 showing examples of a classical creep curve (A) and a nonclassical creep curve (B). The strain to tertiary creep tends to decrease at a constant temperature as the rupture life is increased (or stress is decreased), as shown for several materials of interest at a test temperature of 593°C (Fig. 5).

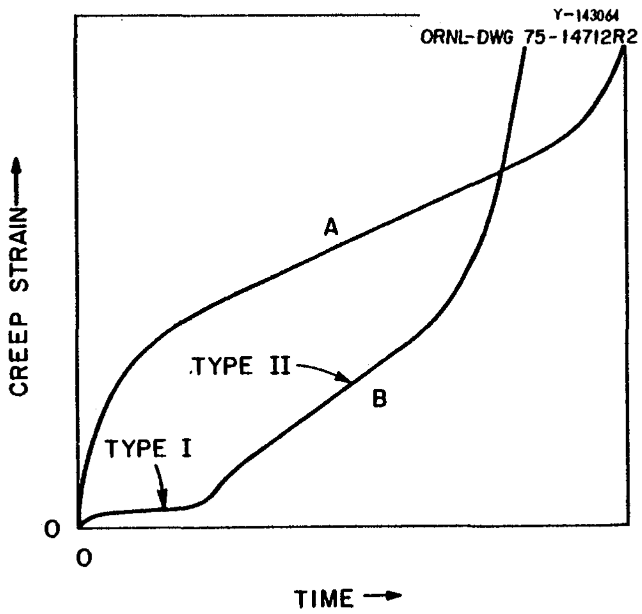


Fig. 4. Schematic Diagram Comparing Classical (A) and Nonclassical (B) Creep Curves.

The trend lines and regions are only approximate and were established by parametric extrapolations.[13,14] Wide variations occur in the data; however, the plot does show material differences and trends.

Strain limits for structural integrity are essentially a new type of design limit. The rationale for these has been given elsewhere[2]; however, the intent among other things is to limit the maximum value of accumulated inelastic strain to values such that creep tensile instability or creep rupture due to low ductility does not occur. Accordingly, long-term elevated-temperature tests are necessary to define both tertiary creep and creep-rupture ductility trends as well as low-stress inelastic deformation. A typical example of creep rupture ductility as affected by temperature and strain rate for type 304 stainless steel is presented in Fig. 6. Regions showing ductility minima with decreasing strain rate and increasing amounts of grain boundary sliding with resultant intergranular failure are apparent from this figure.

The possibility of very low ductility due to prolonged elevated-temperature exposure, mass transfer, or other environmental interactions in base as well as weldment materials is being addressed by a number of programs in the U.S.

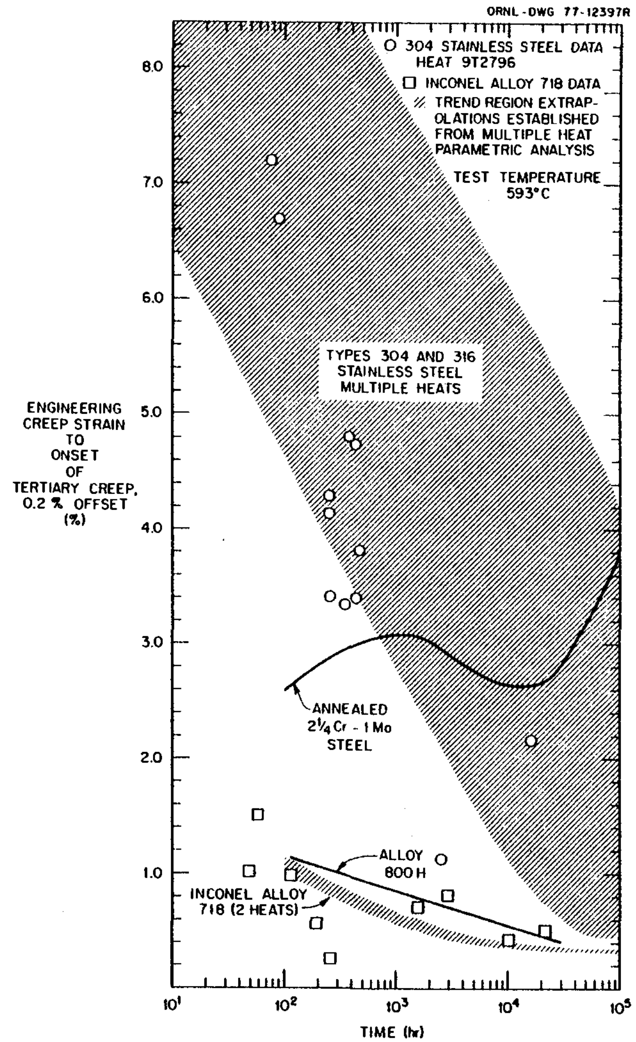


Fig. 5. Comparisons of Tertiary Creep Strain Trends for Several Materials at 593°C. Trend regions are only approximate.

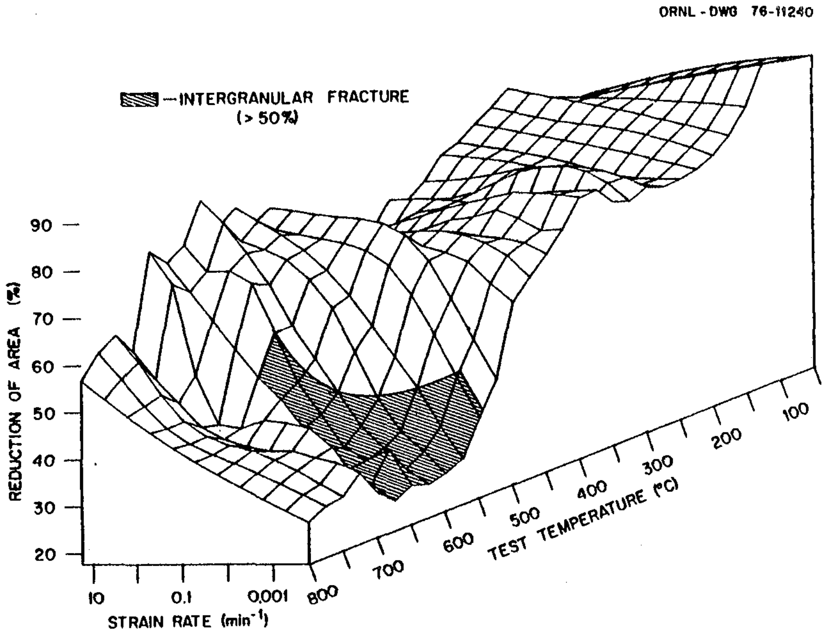


Fig. 6. Creep-Rupture Ductility, Measured as Reduction of Area, as a Function of Temperature and Strain Rate for Type 304 Stainless Steel.

## 7. Long-Term Data.

Long-term uniaxial tests (>50,000 hr) are being conducted at ORNL[15] on types 304 and 316 stainless steel in air. The most important part of the ORNL creep program is the tests being conducted at prototypic operating temperatures. For example, tests on type 304 are in progress at as low as 427 and 482°C and on type 316 at 538°C and higher temperatures. Data from these tests will provide information concerning low-stress deformation and failure behavior. *Similar creep-rupture tests* for periods in excess of 10,000 hr over the temperature range 538 to 760°C are also under way on alloy 718.

Long-term time-dependent fatigue data are also needed, as will be discussed in the following section.

## 8. Time-Dependent Fatigue.

Time-dependent fatigue, or interaction among fatigue, creep damage, and the environment, has been shown to be a failure mode when materials are cyclically deformed at temperatures within the creep range. Accordingly, a number of U.S. programs are studying this phenomenon and obtaining design data on materials of interest to breeder construction. Both initially defect-free uniaxial and precracked crack propagation specimens are being tested.

Fatigue studies in the U.S. on unirradiated austenitic stainless steels employing initially defect-free specimens are centered at Argonne National Laboratory (ANL). Several aspects of the fatigue behavior of type 304 stainless steel are examined. An early review[16] describes much of the ANL activity. Figure 7 shows data obtained to date for type 304 stainless steel in air, in terms of a time to failure versus cycles to failure. Completed test times extend only to three to six months, but current plans include longer term tests to perhaps three years. These tests will be conducted at low strain ranges (i.e., $\Delta\epsilon_t$ = 0.35 to 0.4%), which are appropriate to design, and at primarily a temperature of 593°C. Other fatigue tests at ANL will include notch tests with the stress concentration factor, $K_t$, varying from 1.5 to 4.0, crack growth, cyclic stress-strain deformation characterization of both types 304 and 316 stainless steel, tests under ultra high vacuum, and testing of both weldments and weld metal fabricated with types 308 and 16-8-2 filler metal.

Primary responsibility for fatigue studies on alloy 718 is centered at INEL, where low- and high-cycle time-dependent and -independent fatigue and notched fatigue behavior are being examined. Westinghouse-Advanced Reactor Division is conducting similar tests on this material in sodium.

In order to conduct design and safety analyses on components in terms of fracture mechanics techniques, it is necessary to know the effect of various operating parameters upon the fatigue crack propagation behavior

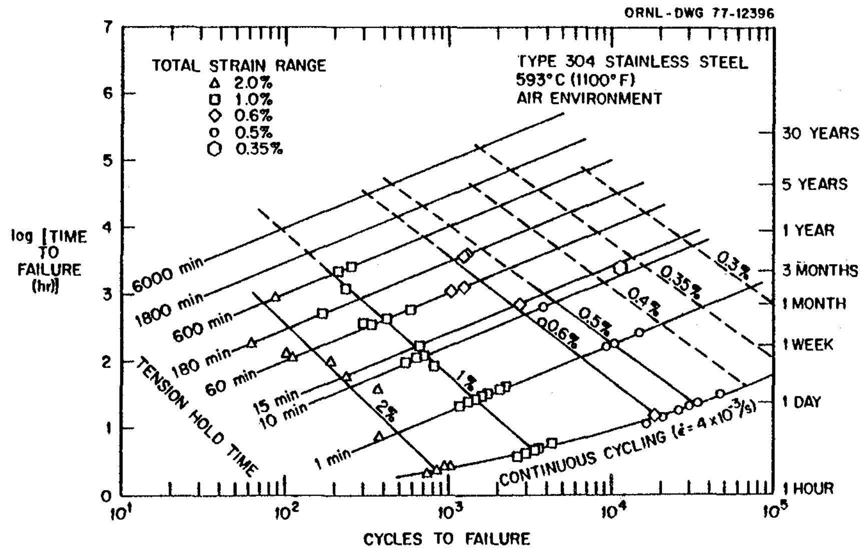


Fig. 7. Time to Failure Versus Cycles to Failure Diagram Showing That Only Data From Essentially Short-Term Tests Are Available for Characterizing Time-Dependent Fatigue of This Material.

of component materials. Hence, the objective of a HEDL study is to characterize the effect of temperature, cyclic frequency, environment, neutron irradiation, etc. on the crack propagation properties of breeder structural materials. Materials included in this investigation include both austenitic and ferritic alloys, a complete listing of which can be found elsewhere.[17]

## 9. Damage Law Formulation.

Most design situations involve exposure to loading conditions that are somewhat more complicated than those seen in simple base-line laboratory tests. In particular, to provide assurance against failure, one needs to be able to predict the amount of damage incurred in situations such as creep under variable load and/or temperature or mixed creep and fatigue loading.

Experimental data obtained[18] at ORNL have substantiated the use of the strain-hardening rule[19] to predict the creep behavior of austenitic stainless steels under variable load and variable temperature. In evaluating variable-load creep-rupture tests,[20] ORNL workers[21] found that a time-fraction life summation rule yielded slightly better results than a strain fraction rule for type 304 stainless steel. Westinghouse-Advanced Reactor Division is studying creep behavior of type 304 stainless steel under complex stress, and variable-load creep tests for alloy 718 are now underway at ORNL. Table 1 lists some common methods[22-26] for evaluation of creep damage accumulation.

When cyclic loading is interspersed with creep, the problem of damage evaluation becomes even more complicated. Current U.S. design rules[2] specify use of a simple linear summation[27,28] of time fractions and cycle fractions to evaluate creep-fatigue damage. Other possibilities include evaluation of the creep damage portion by any of the other methods listed in Table 1 and a nonlinear summation of creep and fatigue damage. Table 2 lists some commonly used forms[29-33] currently under examination, including an equation recently developed by ANL investigators[32] for type 304 stainless steel. A recent report[33] compiled at ORNL summarizes many current U.S. views on the treatment of creep-fatigue data. Full verification of any method (including effects such as environment, multiaxial, and complex loading conditions) awaits the availability of more long-term experimental data.

Table 1. Proposed Creep Damage Laws

| Law | Formulation | Author |
|---|---|---|
| Time Fraction | $\Sigma \frac{t}{t_r} = 1$ | Robinson |
| Nonlinear Time Fraction | $\Sigma \left[\frac{t}{t_r}\right]^a = 1$ | Oding |
| Strain Fraction | $\Sigma \frac{\varepsilon}{\varepsilon_r} = 1$ | Liberman |
| Geometric Time-Strain Fraction | $\Sigma \left(\frac{t}{t_r} \cdot \frac{\varepsilon}{\varepsilon_r}\right)^{1/2} = 1$ | Voorhees and Freeman |
| Combined Time-Strain Fraction | $K\Sigma \frac{t}{t_r} + (1-K)\,\Sigma \frac{\varepsilon}{\varepsilon_r} = 1$ | Abo el Ata and Finnie |

Table 2. Creep-Fatigue Damage Laws

| Law | Source |
|---|---|
| $\sum_{j=1}^{p}\left(\frac{n}{N_d}\right)_j + \sum_{k=1}^{q}\left(\frac{t}{T_d}\right) \le D$ | Taira (Code Case 1592) |
| $A\Sigma\left(\frac{\Delta t_i}{t_r}\right) + B\Sigma\left(\frac{\Delta\varepsilon_i}{\varepsilon_L}\right)_{\dot{\varepsilon},\sigma_{ij}} + C\Sigma\left(\frac{N_{\Delta\sigma}}{N_f}\right)_{\dot{\varepsilon},\sigma_{ij}} + E\Sigma\left(\frac{N_{\Delta\varepsilon}}{N_f}\right)_{\dot{\varepsilon},\sigma_{ij}} = D_{(T,E_n,MS)}$ | Manjoine |
| PHASE I: $da/dN = \Delta\varepsilon_p \sec\left[\left(\frac{\pi\sigma_t}{2T}\right) - 1\right]$ <br> PHASE II: $da/dN = \Delta\varepsilon_p(\omega - 1)$ | Tomkins and Wareing |
| $\Delta\varepsilon_t = \frac{AC_2^{n'}}{E} N_f^{-\beta n'_\nu}[K_1 + (1-K)\beta n'] + C_2 N_f^{-\beta_\nu(1-K)\beta}$ | Coffin |
| $\frac{f_{pp}}{N_{pp}} + \frac{f_{pc}}{N_{pc}} + \frac{f_{cc}}{N_{cc}} + \frac{f_{cp}}{N_{cp}} = 1$ | Manson and Halford |
| $\int_{a_0}^{a_c} \frac{da}{a} = N_f\left[2(T + C)\int_0^{\tau/4} \lvert\dot{\varepsilon}_p t\rvert^m \lvert k_{dt}\right]$ | Majumdar and Maiya |

## 10. Weldment Behavior.

A number of factors[7] can be important in determining the mechanical behavior of weldments. These include section thickness, degree of restraint during preparation, joint geometry, heat input (related to travel speed, current, and voltage), the number of passes, ferrite content and morphology, and chemical composition, including residual elements. Several characteristics, such as complex microstructure and heterogeneity, can result in anisotropic and varying mechanical properties. An example of such behavior is shown for stress-rupture properties in Fig. 8. For the particular as-deposited 16-8-2 weld metal shown, the stress-rupture properties tended to be slightly inferior to the average behavior of type 316 stainless steel.

Recognizing the importance of weldment behavior in primary loop containment applications, a number of U.S. Laboratories are studying the mechanical properties of weldments prepared according to prototype procedures with types 308, 316, and 16-8-2 weld metal.

11. Mass Transfer.

Exposure of materials to sodium environments can cause in-service changes in both surface and bulk properties arising from such effects as carburization, decarburization, formation of ferritic layers, and localized attack. However, depending upon the specific reactor component involved, these changes as determined from fairly short-time tests are

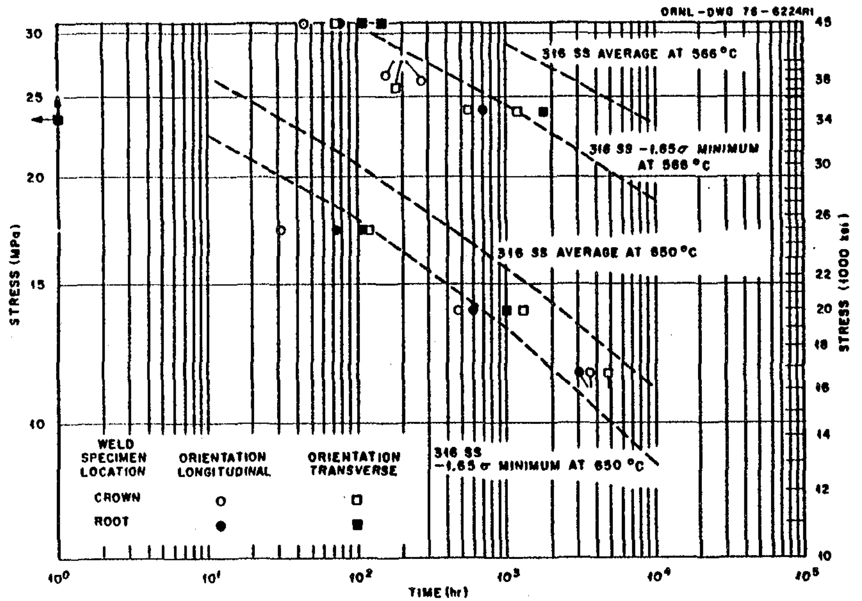


Fig. 8. Comparison of Creep-Rupture Properties of Type 16-8-2 Stainless Steel Submerged-Arc-Weld Specimens With Type 316 Stainless Steel Base Metal.

not expected to result in large deleterious effects on the mechanical properties of primary circuit materials. In the case of high-temperature fatigue response, the crack growth resistance of type 304 stainless steel is likely to actually increase as a consequence of exclusion of oxygen from any small flaws or defects that may be present. Adequate resistance to cyclic crack nucleation is likely to depend upon whether the surface areas are weakened or strengthened and the extent to which intergranular attack occurs. However, detailed mechanical property characterization of materials in sodium environments is a difficult and expensive task, and, therefore, the data presently available are somewhat limited. Therefore, the following areas requiring additional efforts have been identified:

1. Tests in sodium seldom exceed 10,000 hr, and, in the case of the fatigue studies reported, the test times were much shorter. Additional long-term data taken under prototypic breeder operating conditons are needed to develop correlations accounting for environmental interaction so as to supplement currently employed design rules and methods. Base materials, weld metals, and weldments need to be studied.

2. Component behavior of particular concern is the long-term response of the intermediate heat exchanger tubing, which must operate for times up to 230,000 hr while exposed to sodium that has been in contact with unstabilized ferritic steel in the steam generator. Short-term diffusion, physical, and mechanical property data are currently extrapolated with some uncertainty.

3. The ASME Code bodies currently concerned with formulating design rules for breeder systems have long recognized that fatigue and creep-fatigue interaction are potential failure modes, and, therefore, design rules protecting high-temperature energy-conversion systems have been and continue to be formulated. Environmental interaction, which must be accounted for, is not covered by the Code, and, therefore, an adequate data base and resultant models are needed to give the designer guidance in this area. Data defining strain rate and waveform or hold-time effects are therefore also needed. Recognizing these needs, work at ANL and W-ARD involves tensile, biaxial tube creep, fatigue, and crack growth tests in sodium. Materials of interest include types 304, 316, and Ti-modified 316 stainless steel and alloy 718. Facilities include sodium loops in which the sodium purity can be controlled and monitored. These loops permit pre-exposure of tensile, creep, and fatigue specimens for subsequent testing within the system.

12. Fabrication Procedure.

Fabrication procedure, particularly as it relates to piping, is another area receiving attention in U.S. programs. The relatively large-diameter, thin-wall piping of current U.S. design is unusual in today's technology, and some scaling up or modifications of industrial practice may be required. While the Fast Flux Test Facility primary sodium loop uses costly seamless piping and fittings to ensure high reliability, more economical methods for fabricating piping and fittings are desirable in subsequent systems. Accordingly, a program is under way at ORNL to develop optimum fabrication methods for large-diameter austenitic stainless piping. Factors such as weld methods, tolerance control, economics, and mechanical behavior are under consideration. A program at INEL focuses on pipe welding procedure development.

13. Irradiation Effects.

Design confirmation, safety analyses, and operations support of breeder systems require detailed descriptions of tensile, fatigue, toughness, and creep-rupture behavior of structural materials used in these systems. Of special significance is the effect of neutron irradiation on these properties. To provide the desired data a series of irradiation experiments, which are in progress, contain a wide variety of breeder structural materials including welds. Data from these experiments will provide necessary mechanical properties information relative to breeder operating conditions.

Materials of interest are shown in Fig. 9 and include annealed types 304 and 316 stainless steel and weldments, cold-worked stainless steel, alloy 600 (nickel base), alloy 718 (nickel base) and weldments, A 286 (13–16 wt % Cr, 24–27 wt % Ni, 1 wt % Mo), CF-8 (type 304 stainless steel castings, SA-351), tungsten, TZM (0.5 Ti, 0.08 Zr, 0.015 C, bal Mo, wt %), and some ferritic materials such as 2 1/4 Cr-1 Mo steel. Irradiation temperatures range from 370 to 650°C and fluences from $10^{25}$ to $10^{27}$ n/m$^2$ (>0.1 MeV). The test laboratories involved are HEDL and NRL.

One of the criteria for useful life is based on residual ductility as measured in a conventional tension test. Residual total elongation (RTE) of either 10% or 5% is used as an index. When the 10% RTE criterion is met, there is no need to account for irradiation effects and conventional design procedures are employed. However, when the RTE is expected to be between 5 and 10% the design analysis must consider the possibility of brittle failure and fracture mechanics analysis is considered. An example of current stress-rupture experiments in relation to irradiation temperature, neutron fluence, and the RTE fluence limit is shown in Fig. 10.

ORNL-DWG 77-15244

REACTOR STRUCTURAL MATERIALS

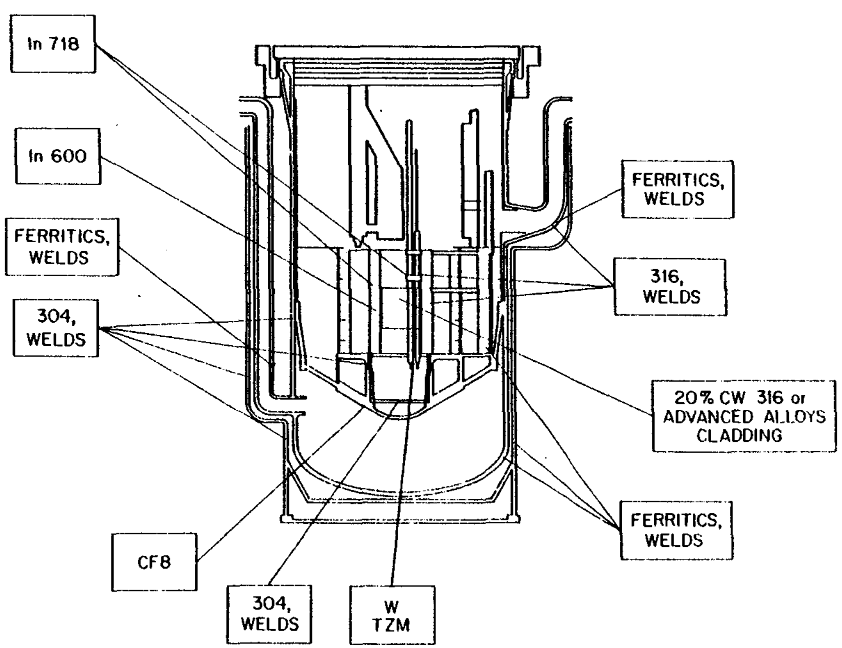


Fig. 9. Schematic Drawing Showing Reactor Structural Materials Undergoing Irradiation Exposure for Mechanical Properties Tests.

14. Constitutive Equation Needs for Inelastic Analysis.

It has long been recognized that operating temperatures of breeder components are within the creep range. Also because of such events as power changes, shutdowns, and scrams, rapid temperature drops throughout the coolant system are possible. These changes lead to the necessity of being able to characterize such phenomena as ratchetting and time-dependent fatigue. Programs at ORNL, W-ARD, Babcock and Wilcox Co., and several universities are currently collecting data helping to both confirm and improve existing constitutive relations as well as develop new equations as additional materials become of interest. Specific needs will be discussed in a paper by Pugh et al. of ORNL at this Conference.

## CURRENT EXPERIMENTS: STRESS RUPTURE

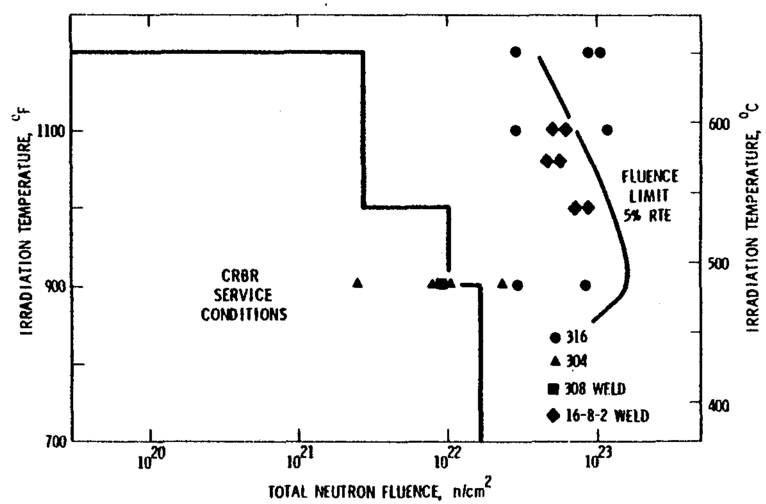


Fig. 10. Irradiation Conditions for Current Experiments on Stress Rupture of Austenitic Stainless Steel.

SUMMARY

A brief overview was presented of the U.S. mechanical property generation programs for structural materials of interest to the breeder primary circuit. The programs are being conducted in support of ASME Codes and RDT specifications, and, accordingly, the review was presented in terms of a number of areas of concern to U.S. engineers and designers. A more detailed overview of specific programs can be found elsewhere.[17]

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