EVALUATION OF WELDMENT CREEP AND FATIGUE
STRENGTH-REDUCTION FACTORS FOR ELEVATED-
TEMPERATURE DESIGN*

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ABSTRACT

New explicit weldment strength criteria in the form of creep and fatigue strength-reduction factors were recently introduced into the American Society of Mechanical Engineers Code Case N-47, which governs the design of elevated-temperature nuclear plants components in the United States. This paper provides some of the background and logic for these factors and their use, and it describes the results of a series of long-term, confirmatory, creep-rupture and fatigue tests of simple welded structures. The structures (welded plates and tubes) were made of 316 stainless steel base metal and 16-8-2 weld filler metal. Overall, the results provide further substantiation of the validity of the strength-reduction factor approach for ensuring adequate life in elevated-temperature nuclear component weldments.

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1. INTRODUCTION

The structural integrity of weldments in elevated-temperature construction has long been a concern, particularly for nuclear components where a higher level of life assurance is required and the service life is long. Yet until 1987, the *American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Case N-47*, which governs construction of elevated-temperature Class 1 nuclear components, contained only minimal weldment design guidance based on actual weldment properties. In 1987, efforts of the Code groups and the Department of Energy's (DOE) advanced reactor materials and structures programs resulted in the inclusion of weld creep and fatigue strength-reduction factors in Case N-47-26 (1). These factors significantly improve the overall elevated-temperature design methodology for welded components.

Actual plant experience has shown that concern for the structural integrity of welded components subjected to elevated-temperature service is well founded. Thermal fatigue has led to weldment cracking in a number of liquid-metal reactor components. For example, the French Phenix liquid-metal fast breeder reactor (LMFBR), although extremely successful overall, was initially plagued with several problems of weldment cracking (2,3). In each case, the cause was identified as fatigue or creep-fatigue resulting from repeated thermal transient loadings. A second example is the British Dounreay Fast Reactor (DFR), which developed a fatigue crack in a primary circuit pipe weld (4). Liquid-metal reactors in the Soviet Union have reportedly also experienced weldment failures. Recently, elevated-temperature failures have begun to occur in some fossil plant welded pipe. These have appeared after many years of

elevated-temperature operation and have been associated with creep rupture.

Although lessons regarding such things as weld placement, composition, and procedures were learned from these incidents, the need for explicit, experimentally based design rules is clear. The Nuclear Regulatory Commission (NRC) recognized this deficiency during the licensing review of the Clinch River Breeder Reactor Plant for a construction permit (5). Early weldment cracking, particularly in components subjected to repeated thermal transient loadings, was identified by the NRC as the foremost structural integrity concern, and a confirmatory test program was to have been required to determine the safety margins of weldments in elevated-temperature components (6).

The purpose of this paper is to provide some of the background, logic, and experimental validation of the creep-rupture and fatigue strength-reduction factors that are used with the primary stress limits and creep-fatigue rules of Code Case N-47. The paper also summarizes the results of a series of creep-rupture and fatigue tests carried out at Oak Ridge National Laboratory (ORNL) on simple welded plate and tubular structures fabricated from 316 stainless steel welded with 16-8-2 filler metal. These tests provided (1) a better understanding of weldment failures and (2) additional validation of the Code design rules.

This paper is a follow-on to a previous one that addressed only the fatigue factor (7). In addition, the previous paper contained only a portion of the confirmatory fatigue test results. This paper provides all of the confirmatory test results and addresses both the creep-rupture and fatigue factors. More details can be found in Refs. (8) and (9).

The main body of the paper is divided into two sections - one providing the background of the Code factors, and the second summarizing the confirmatory tests. A final section briefly summarizes the factors and their bases, and it provides conclusions from the confirmatory tests relative to weldment failure behavior and the Code design rules.

2. WELDMENT STRENGTH REDUCTION FACTORS

2.1 Weldment Versus Base Metal Behavior

To understand the causes of early weldment failure requires that we view a weldment as a "metallurgical notch," in which the differing deformation response of the constituent materials through the weldment can result in nonuniform stresses across the weldment. Thus, even if the creep-rupture strength and fatigue strengths of the constituent materials are the same, early weldment failure, relative to that expected for the base metal alone, can occur because of the metallurgical notch.

Figure 1 illustrates typical observed property variations. The tensile test results on the left show an initial weld metal yield strength substantially higher than that of the base metal. Although this ratio decreases with temperature, weld metal yield, for both austenitic and ferritic steels, in the elevated-temperature design range of interest is usually about twice that of the corresponding base metal. As strain cycling occurs in a cyclic stress-strain or fatigue test, weld and base metals harden and/or soften, depending on the strain range and temperature. Although the weld metal may initially cyclically harden, it generally softens later to the point that its cyclic yield strength becomes fairly close to, or even less than, that of the base metal.

Thus, in a fatigue test of a specimen containing both base and weld metal, either could take a disproportionately large amount of the applied strain range, depending on the point in the cyclic life of the test. Failure time and location depend on the relative damage accumulation in each material.

Returning to the constant stress creep curves in Fig. 1, the weld metal is stronger than the base metal in the illustrated case. Usually, however, the weld metal becomes a little weaker with increasing temperatures and times. Creep-rupture failure in a weldment depends not only on this relative creep strength but, in many cases, on the relative yield strength and creep deformation, which affect the stress levels in the weld and base metal.

2.2 Weldment Creep-Rupture Factors

Considering the complexity of weldment behavior and the strong influence of relative material variability, the ASME high-temperature Code groups concluded that adequate weldment life can best be ensured through the basic safety margins on allowable stress and the use of simple weld strength-reduction factors. In Case N-47, the primary time- and temperature-dependent stress limit S_t is less than or equal to $2/3 \sigma_{rmin}$, where σ_{rmin} is the expected minimum creep-rupture strength of the base metal. At weldments, the allowable stress limit S_t is specified to be the lower of the tabulated values for the base metal or $0.8 \sigma_{rmin} \times R$, where R is the appropriate ratio of the weld metal creep-rupture strength to the base metal creep-rupture strength.

The appropriate R values for the various allowable weld filler metal/base metal combinations are listed in tables in Case N-47. As an

example, the R factor table for 316 stainless steel welded with 1 filler metal is reproduced below. For this example, the factors re

TABLE I-14.10 B-2 STRESS RUPTURE FACTORS FOR TYPE 316 STAINLESS STEEL W/ SFA 5.22 EXXT-C (16-8-2 CHEMISTRY); SFA 5.4 E 16-8-2; AND SFA 5.9 ER 1

Temp °F	10 hr	30 hr	100 hr	300 hr	1000 hr	3000 hr	10,000 hr	30,000 hr	100,000 hr
850	1.00	0.96	0.91	0.91	0.91	0.90	0.89	0.88	0.87
900	1.00	0.94	0.88	0.82	0.81	0.80	0.77	0.76	0.75
950	1.00	0.93	0.86	0.86	0.85	0.83	0.83	0.81	0.80
1000	1.00	0.93	0.90	0.90	0.90	0.89	0.87	0.87	0.86
1050	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.93	0.93
1100	0.91	0.91	0.93	0.94	0.94	0.96	0.96	0.96	0.96
1150	0.91	0.91	0.93	0.95	0.95	0.96	0.98	0.99	0.99
1200	0.89	0.89	0.90	0.92	0.93	0.97	0.99	1.00	1.00

relatively high over the entire time-temperature range. For an example, however, the factors for 316 welded with 316 drop below 0.1 at the higher temperatures and longer times.

Substantiation of the overall adequacy of the Code limits came from an ORNL compilation and examination of the results of creep-rupture tests of structural weldments. Data for three of the basic Case materials were collected: 304 and 316 stainless steels and 2 1/4 Mo steel. In addition to DOE-sponsored welded plate and tube tests performed at ORNL and welded plate tests performed at Westinghouse, data from the open literature from Sweden (10), the United Kingdom (11), and Japan (12) were used, as were some foreign exchange data that, because of agreements, cannot be referenced here. Altogether, 40 pertinent structural weldment creep-rupture test results were located and assessed. The various specimen types employed are depicted in Fig. 2.a. Several prototype weld metals and processes were used, and both as-welded and postweld heat-treated specimens were tested.

The structural weldment test results were compared with the Code Case N-47 expected minimum creep-rupture strengths of the corresponding base metals, and the results are plotted in Figs. 2.b. The base metal minimum stress to rupture appears to be the lower bound of the weldment data, and the margin between the data and this lower bound tends to increase with increasing rupture life.

These results are encouraging. However, the data points plotted in Fig. 2.b represent complete specimen rupture, whereas the Code rules are intended to guard against cracking. Plate weldment creep-rupture tests performed at Westinghouse provide some insight into initial cracking vs complete rupture (9). The nominal stress to produce initial cracking appears to be about 90% of that to produce rupture in a given time. For other structural configurations and materials, this factor could be different. However, it was concluded by the Code groups that the Case N-47 S_t allowables based on two-thirds of the expected minimum base metal creep-rupture strength, together with the R factors to account for lower weld metal creep-rupture strength, are adequate to guard against weldment cracking without excessively eroding the ability of the design margin to cover other uncertainties.

2.3 Weldment Fatigue Factor

Elevated-temperature fatigue data for both austenitic stainless steel (types 304 and 316) and ferritic steel (2 1/4 Cr-1 Mo and modified 9 Cr-1 Mo) weldments have been generated, both under the U.S. Department of Energy (DOE) reactor programs and under similar programs in the United Kingdom, France, Germany, The Netherlands, and Japan. The

foreign data are in restricted reports obtained under DOE's foreign exchange agreements. In all, 15 sources of data were studied. Data for 304 stainless steel weldments are available to 593°C (1100°F); 304 and 308 (with and without controlled residual elements) were used as filler metals; and several weld processes, heat treatments, and base metal product forms were employed. For 316 stainless steel weldments, data to 625°C (1157°F) are available with 16-8-2 and 316 filler metals, and, again, a number of different variables were used in preparing the weldments. Normalized and tempered 2 1/4 Cr-1 Mo steel weldment data are available at 482°C (900°F), and modified 9 Cr-1 Mo steel data are available to 593°C (1100°F). References (13-16) typify these available data.

Weldment fatigue data are usually generated by using three different types of uniaxial solid-bar specimens (Fig. 3.a). The general trend of the data studied from these three specimen types is depicted schematically in Fig. 3.b. Longitudinal weld metal fatigue data differ, if at all, only very slightly from fatigue data for the corresponding unaffected base metal. Weldment and transverse weld metal data, on the other hand, drop below the base metal fatigue curve in the midcycle region (14,15). In terms of strain range, the reduction factor varies generally between 1.5 and 1.8, although, depending on weld process, the factor can be somewhat larger for 2 1/4 Cr-1 Mo steel weldments. Although the data at high and low strain ranges are sparse, it appears, as depicted in Fig. 3.b, that at large strain ranges the weldment data approach the base metal data. Likewise, although high-cycle fatigue is very dependent on grain size, there is often little difference between weldment and base metal data at very low strain ranges.

The premise is that these observed differences are largely due to the metallurgical notch effect resulting from widely varying yield strengths in weld and base metal. At low strain ranges (high-cycle fatigue), little yielding is believed to occur; thus, the metallurgical notch effect is minimal. At large strain ranges, which are outside the normal design region, any hardening and softening occur quickly. During most of the life of a weldment fatigue specimen, the weld and base metal yield strengths are close so that, again, the metallurgical notch effect is minimal. In summary, it is believed that the behavioral trends illustrated in Fig. 3.b are explained by the yield strength variations. Any time there is a difference in yield strength across a weldment specimen, the fatigue life will be reduced.

How can this information be transformed into an elevated-temperature weldment fatigue design factor? Clearly, the case of a small weldment specimen, where a fixed cyclic deformation range is imposed across a gage length that is roughly one-half weld and one-half base metal, is an extreme situation. However, when welds are placed in a structure's deformation-controlled discontinuity region, a somewhat similar, though less extreme, situation does exist.

When the ASME Code Subgroup on Elevated Temperature Design considered the available data, as described above, and the possible structural ramifications, a reduced elevated-temperature factor of 1.2 on strain range was judged to be adequate for elevated-temperature design. In the midcycle range of the Code Case N-47 design fatigue curves, this corresponds approximately to a reduction factor of two on cyclic life. Thus, the actual rule reads:

In the vicinity of a weld (defined by ± 3 times the thickness to either side of the weld centerline) the fatigue evaluation shall utilize reduced values of the allowable number of design cycles, N_d . The N_d value shall be one-half the value permitted for the parent material.

In cases involving creep-fatigue, the previously described R factors are used to reduce the parent stress-to-rupture curves from which the creep damage is calculated.

3. CONFIRMATORY CREEP AND FATIGUE TESTS

The conclusions and understanding summarized in the previous section were based on limited data. The purpose of the tests described in this section was to obtain additional data, including material characterization and some analysis results, from carefully performed tests on a single weldment (316 stainless steel welded with 16-8-2 filler metal) of most current interest for liquid-metal reactors. The results strengthen the understanding of weldment creep-rupture and fatigue behavior and the validation of the Code factors.

3.1 Materials and Specimens

The weldment specimens used are depicted in Fig. 4. All specimens were fabricated from 316 stainless steel base metal (DOE reference heat 8092297) with 1.02-mm-dia (0.04 in.) 16-8-2 filler metal wire (Arcos Corporation heat Y3018R). Either the normal gas tungsten arc process or the hot-wire gas tungsten arc process was used to prepare the various weldments. The base metal for all the structures was solution annealed before welding, and no further heat treatment was performed after welding. Smooth specimens were machined from the weldments; thus there were no geometric discontinuities at the welds.

The plate creep-rupture specimens had a gage length cross section of 101.6 mm wide $\times$ 9.53 mm thick (4.0 $\times$ 0.375 in.). For the cylinder

creep-rupture specimens the nominal outside diameter in the gage length was 102 mm (4 in.) and the thickness was 5.1 mm (0.20 in.). The cylindrical specimens had a total length of 1.02 m (40 in.), and each contained three circumferential welds 203 mm (8.0 in.) apart. The length of both the plate and cylinder specimens was sufficient to provide a sizable gage length free of end effects. Reference (9) contains the specimen details.

The tubular fatigue specimens had an outside diameter and thickness within the gage length of 20.7 mm (0.815 in.) and 2.54 mm (0.100 in.), respectively. The gage length was 25.4 mm (1.00 in.). Reference (8) contains the specimen details.

Mechanical properties specimens were cut from identical weldments, as shown in Fig. 5, and tensile and creep-rupture tests were performed at 566°C (1050°F), which was the temperature of the weldment creep tests. The relative values of the measured properties are summarized below.

	Yield and flow stress	Creep strain	Creep-rupture time*
Lowest	BM	FL	BM
↓	HAZ	W	HAZ
	FL	HAZ	W
Highest	W	BM	FL

As a specific example, the yield strength of the weld metal was 255 MPa (37.0 ksi), while the base metal yield strength was just 113 MPa (16.4 ksi).

*The creep-rupture curves cross at a stress level of about 276 MPa (40 ksi). The order shown is for stresses below that level.

3.2 Creep Test Results

The test results, as well as the loadings, for the four weldment creep-rupture tests are depicted in Fig. 6. Except for one of the plates (WPCT-7), which was subjected to a step increase in applied load partway through the test, each specimen was subjected to a constant axial load. The tests were interrupted periodically and the welds were microscopically inspected for cracking. The points at which microcracks had grown to visible cracks [defined as cracks having a length of 790 μm (1/32 in.)] are denoted in Fig. 6. The rupture points refer to complete separation. Note that WPCT-7 was not tested to complete rupture.

Cracking in the plate specimens initiated in the FL/HAZ perpendicular to the weld (and to the applied stress). Cracking in the cylinders occurred in the HAZ, and the cracks were oriented circumferentially (again perpendicular to the applied stress). Although not well monitored, cracking occurred at about the same time in the base metal portion of the cylinders.

The creep-rupture curves of stress vs time for the base metal, HAZ, fusion line, and weld metal for the test specimen welds are plotted in Fig. 6, along with the Code Case N-47 minimum expected base-metal creep-rupture strength (σ_{rmin}); weld-metal strength ($\sigma_{\text{rmin}} \times R$); and allowable stress, S_t . Note that all of the visible cracking points and one of the rupture points fall below the curves for the individual component materials, illustrating the metallurgical notch effect of the weld.

The Code S_t curve is well below the observed points of initial cracking. In this case, the R ratios are not sufficiently low to affect the S_t curve in the region shown. Thus the S_t curve shown in Fig. 6 would govern both base metal and weldment.

An inelastic failure analysis using multi-property zones was performed for each of the four structural weldment tests, and the predicted deformations and failures were compared with the test observations. Details of these comparisons, including high-temperature strain gage results for each specimen, can be found in Ref. (9). Taken as a whole, the inelastic loading and creep strains in the weldments were fairly well predicted. Likewise, visible cracking in both plates correlated well with the calculation, via time fractions, of a damage $D=1$ in the HAZ of the specimens. For example, for WPCT-5, visible cracking occurred at about 860 h versus a prediction of 1300 h; for WPCT-7, visible cracking existed at the conclusion of the test (10,400 h), while $D=1$ was predicted at 13,000 h. In the case of the cylinders, predicted damage was somewhat higher in the base metal than in the HAZ. Visible HAZ cracking occurred at 776 h and 2015 h, while the corresponding predicted times to $D=1$ in the base metal were 1525 h and 5000 h, respectively.

3.3 Fatigue Test Results

All of the tubular fatigue tests were performed at 550°C (1022°F). To understand the weldment results, it will help to first look at base metal test results.

Figure 7 shows a comparison of uniaxial solid bar data, obtained at Argonne National Laboratory, with axial and torsional tubular specimen results. At high strain ranges the sets of axial data are nearly identical, but at lower strain ranges the solid bar data show longer life than the tubular axial fatigue specimens. This is at least partly explained by the fact that failure was taken as complete fracture for the solid-bar specimens versus a 50% reduction in the strain-hardened load for the tubular specimen.

Two torsional fatigue tests were also conducted on the 316 base metal and compared in Fig. 7 with the axial fatigue data to determine how life depends on the loading mode. As has been repeatedly found by other investigators, torsionally fatigued specimens tested at the same equivalent strain ranges had considerably longer lives than axially fatigued specimens. Since the von Mises effective strain range value is used in Code Case N-47 for design, torsional fatigue design based on the design curves in the Code would be more conservative than design for axial fatigue. Because the axial fatigue case is the less conservative of the two test schemes, the axial fatigue base metal data were used to investigate the applicability and appropriateness of the proposed design factor for failure of weldments.

Thus, longitudinal and circumferential weldment specimen data for axial and torsional fatigue were compared with the axial 316 stainless steel tubular base line curve. Figure 8 shows the 316 stainless steel base metal curve and both longitudinal and circumferential weldment data points. Figure 8(a) shows the torsional fatigue data for both longitudinal and circumferential weldment specimens relative to the axial fatigue 316 base metal curve. Although the weldment data are below the torsional base metal data (by a factor of 1.7 to 1.8), the data fall very nearly on the base metal curve. In particular, the weldment data show no unique weakness arising from the shear along the fusion zone.

Figure 8(b) shows the axial fatigue data relative to the base metal curve. As expected, the longitudinal weldment axial fatigue data fall very nearly on the base metal curve because both base metal and weld metal experience the same axial strain range. However, the

circumferential weldment axial fatigue data fall below the baseline curve. The solid-bar specimen tests described earlier showed a 1.5 to 1.8 reduction in strain range from base metal to weldments. Likewise, these data show a reduction of 1.5 on strain range from the base metal to circumferential weldment. Also shown in Fig. 8(b) are the Code Case N-47 316 stainless steel design curve for the temperature range 539 to 699°C (1000 to 1200°F) and the Code curve with the weldment design factor of 2 on cycles applied.

From Fig. 8(b) it becomes obvious that the weldment data use up much of the safety factor of 2 on strain range or 20 on cycles put in the Code to cover factors affecting life other than the presence of a weld. These factors include such considerations as surface finish, size effects, material variability, environmental considerations, and residual stresses caused by fabrication (except for welds). If the safety factor of 20 on cycles to failure were applied to the circumferential weldment data, these "design" points would fall slightly below the proposed weldment design curve for fatigue. However, welds do not normally compose almost one-half of a region experiencing a fixed cyclic deformation such as our test specimens experienced. Thus, it is believed that the tubular weldment data support the suitability of the Code factor for the fatigue of welded joints at elevated temperature.

4. SUMMARY AND CONCLUSIONS

The latest revision of the *ASME Boiler and Pressure Vessel Code Case N-47* (Ref. 1), which governs the design of elevated-temperature nuclear components, contains explicit creep-rupture and fatigue

strength-reduction factors for weldments. The purpose of this paper was to describe the background and bases for these factors and to further substantiate their adequacy through a series of creep-rupture and fatigue tests of simple plate and tube structural weldments.

The Code creep-rupture strength-reduction factors are given as time- and temperature-dependent tables of the ratio of weld metal creep-rupture strength to the corresponding base metal creep-rupture strength. The ratios are used to reduce both the primary stress allowances at weldments and the allowable creep damage in creep-fatigue assessments. Usually the reductions are relatively small, which is consistent with the fact that of the results of some 40 creep-rupture tests found in the literature, none were below the Code expected minimum creep-rupture strengths of the respective base metals. The factors do add some additional design margin at weldments, and in addition, the tables, which are for specific weld filler metals and processes, limit the weld metals and processes that are allowed.

The Code fatigue strength-reduction factor was based on an ORNL review of fatigue data available at elevated temperatures on weldment materials used in nuclear components. These data were generated from solid-bar specimens, and it was determined from them that a reduction factor of 2 on the number of design cycles relative to the base-metal curve would be an effective design approach for welded joints.

The specific purpose of the four creep-rupture tests described in this paper was to substantiate the logic of the Code creep-rupture factors and to enhance understanding of what leads to early creep-rupture cracking in weldments. Key observations from the creep-rupture tests and companion inelastic failure analysis are listed below.

- The inelastic loading and creep strains in the weldments were fairly well predicted.
- The predicted time to failure for both plates agreed closely with the observed times to visible (1/32-in.) cracking.
- Cracking in the cylinders was overpredicted by a factor of about 2 (3 or 4 if it is considered that observed initial cracking was in the HAZ). Although larger than for the plates, the differences between measured and predicted lives for the cylinders are not considered to be unreasonable. The safety margin on life in Code Case N-47 is much larger than 3 or 4.
- Like the results of the 40 tests from the literature, the results of the four tests reported here support the adequacy of the Code Case N-47 allowables and weld strength-reduction factors for handling weldments.

The specific purpose of the welded tube fatigue tests was to gain additional confidence in the Code fatigue strength-reduction factor and to provide an increased understanding of the metallurgical notch effect in fatigue. The torsional fatigue tests of both longitudinal and circumferential weldments produced nearly identical results that were below the base metal torsional fatigue data by a factor of 1.7 to 1.8 on strain range. On the other hand, the torsional weldment data fell very close to the axial base metal fatigue curve. In the case of the axial fatigue tests, the longitudinal weldment data fell, as expected, close to the base metal curve, but the circumferential data fell significantly lower (below the base metal curve by a factor of about 1.5 on strain range). This reduced life can be explained by the differences in cyclic

strain across the weldment produced by different yield strengths in the constituent materials.

Two key conclusions were drawn from the tubular fatigue tests. First, the Code Case N-47 design factor of 2 on cyclic life is appropriate, and, second, cyclic shear strain on the fusion zone of a weldment is not as detrimental as cyclic normal strain. This latter observation helps to allay a common concern about weldment fatigue.

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REFERENCES

1. Case N-47-26, *Class 1 Components in Elevated Temperature Service, Section III, Division 1, Cases of ASME Boiler and Pressure Vessel Code*, American Society of Mechanical Engineers, New York, February 1987.
2. *The Phenix Nuclear Plant After Three Years of Operation*, Centrale Phenix, Bagnols sur Ceze, France, July 14, 1977.
3. F. Conte, M. Sauvage, and J.-F. Roumailhac, "The Intermediate Heat Exchanger Leak on Phenix Plant and Their Report," pp. 291-96 in *Optimization of Sodium-Cooled Fast Reactors*, Proceedings of the International Conference in London, Nov. 28-Dec. 1, 1977, British Nuclear Energy Society, London, 1978.
4. R. R. Matthews and K. J. Henry, "Location and Repair of the DFR Leak," *Nucl. Eng.* 13(149), 840-44 (October 1968).
5. *Safety Evaluation Report Related to the Construction of the Clinch River Breeder Reactor Plant*, NUREG-0968, Vol. 1, U.S. Nuclear Regulatory Commission, March 1983.
6. D. S. Griffin, "Elevated-Temperature Structural Design Evaluation Issues in LMFBR Licensing," *Proceedings of Eighth International Conference on Structural Mechanics in Reactor Technology*, Vol. L, Paper L9/1, Brussels, August 1985.
7. D. G. O'Connor and J. M. Corum, "Design Rule for Fatigue of Welded Joints in Elevated-Temperature Nuclear Components," *ASME Codes and Recent Advances in PVP and Valve Technology*, PVP Vol. 109, pp. 75-81, American Society of Mechanical Engineers, 1986.
8. D. G. O'Connor and J. M. Corum, *Design Rule for Fatigue of Welded Joints in Elevated-Temperature Nuclear Components and Its Experimental Confirmation*, ORNL-6333, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., January 1987.
9. J. M. Corum et al., *Experimental and Analytical Evaluation of Weldment Creep Strength Reduction Factors for Elevated-Temperature Structural Design*, ORNL-6500, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., September 1988.
10. R. Sandström and B. Ivarsson, "Creep in Butt-Welded Tubes of Cold Worked AISI 316 With Internal Pressure," pp. 223-31 in *Proceedings of Third International Conference on Mechanical Behavior of Materials*, Vol. 2, Cambridge, England, Aug. 20-24, 1979, ed. K. J. Miller and R. F. Smith, Pergamon, Oxford, 1980.

11. M. C. Coleman, J. D. Parker, and D. J. Walters, *The Behavior of Ferritic Weldments in Thick Section 1/2 Cr-1/2 Mo-1/4 V Pipe at Elevated Temperature*, Central Electricity Generating Board Report RD/M/1204R81, CEGB Research Division, Marchwood, England, December 1981.
12. Isao Okane and Koji Osumi, "Creep Rupture Properties of Welded Joints of Type AISI 304 and 316 Austenitic Stainless Steels," *Trans. of National Research Inst. for Metals* (Japan) 14(2), 67-74 (1972).
13. S. Usami, Y. Fukuda, and S. Shida, *Microcrack Initiation, Propagation, and Threshold in Elevated Temperature Inelastic Fatigue*, Preprint 83-PVP-94, American Society of Mechanical Engineers, New York, 1983.
14. G. E. Korth and M. D. Harper, "Fatigue and Creep-Fatigue Behavior of Irradiated and Unirradiated Type 308 Stainless Steel Weld Metal at Elevated Temperatures," pp. 172-90 in *Properties of Reactor Structural Alloys after Neutron or Particle Irradiation: A Symposium, Philadelphia*, STP-570, American Society of Testing and Materials, Philadelphia, 1976.
15. C. R. Brinkman, G. E. Korth, and J. M. Beeston, "Comparison of the Strain-Controlled Low Cycle Fatigue Behavior of Stainless Type 304/308 Weld and Base Material," *Proceedings of International Conference on Creep and Fatigue in Elevated Temperature Applications*, Institution of Mechanical Engineers, London, 1973.
16. R. W. Swindeman and E. C. Williams, *Fatigue of Bainitic 2 1/4 Cr-1 Mo Steel Weldments at 482°C*, Preprint 84-PVP-57, American Society of Mechanical Engineers, New York, 1984.

CAPTIONS

Fig. 1. Typical variation of tensile and creep properties through a weldment.

Fig. 2. Results of creep-rupture tests of structural weldments compared with minimum stress to rupture of base metal. (a) Test specimens and loadings, (b) test results.

Fig. 3. Trends of available weldment fatigue data. (a) Specimen orientation, (b) schematic of test results.

Fig. 4. Confirmatory weldment creep and fatigue test specimens. (a) Creep-rupture specimens, (b) tubular fatigue specimens.

Fig. 5. Mechanical properties specimen locations relative to 316/16-8-2 weldment.

Fig. 6. Comparison of four sets of structural weldment test results with material rupture curves and Code Case N-47 allowables (1 ksi = 6.895 MPa).

Fig. 7. Base-metal fatigue data for 316 stainless steel (heat 8092297). All tests were conducted at effective strain rates of $1 \times 10^3/s$.

Fig. 8. Comparison of tubular weldment fatigue data with tubular base-metal axial fatigue curve. (a) Torsional fatigue data vs axial fatigue base-metal curve, (b) axial fatigue data.

Figure 1

(a)

(b)

Figure 2

Figure 3

(a)

(b)

Figure 4

HAZ = HEAT-AFFECTED ZONE
BM = BASE METAL
FL = FUSION LINE
W = WELD

Figure 5

Figure 6

Figure

(a)

(b)

Figure 8