AREVA

ANP-10326Q3NP
Revision 0

Response to Third Request for Additional Information

ANP-10326P

Environmentally Assisted Fatigue: Modified Effective Correction Factor for Austenitic Stainless Steels

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AREVA Inc.

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Nomenclature

(If applicable)

Acronym	Definition
F_{en}	Environmental Fatigue Correction Factor
F^{exp}_{en}	Modified Environmental Fatigue Correction Factor
LWR	Light Water Reactor
N_{25}	Number of cycles when a fatigue test specimen exhibits a load decrease of 25%
N_r	Number of cycles when a fatigue test specimen exhibits a rupture
PWR	Pressurized Water Reactor
RF	Reduction Factor
RMS	Root-Mean-Square
R_q	RMS Roughness
R_t	Total Roughness
R^2	Coefficient of Determination or Square of Pearson Correlation Coefficient

Question 1

[

]

Table 5-2 of ANP-10326P provides a summary of the all RF values as a function of strain amplitude for polished and ground specimens for each of the transient types (complex and triangular). [

] The table below, which summarizes the ground specimen data in two groups (one for each loading type) indicates RF values scatter between [ ] for complex loading, and between [ ] tests for triangular loading.

Provide a data analysis of the information in the table below that supports the final RF values shown in Table 6-1 of ANP-10326P and address the large amount of scatter observed in the RF values.

Response 1

The method used to calculate the RF is provided in Section 2.4 of ANP-10326 and is based entirely on the experimental data. This indicates that scatter in the RF values is a direct result of scatter in the experimental data. Therefore, the data analysis will focus on the experimental data.

Data scatter in fatigue testing is impacted by a number of factors, such as peak strain, strain rate, loading signal and surface finish, as well as variations in chemical composition and mechanical properties. The data scatter seen in fatigue testing is often significant, as illustrated in ANP-10326 and in NUREG/CR-6909, Rev. 0, Figure 55.

Figure 55 of the NUREG provides a plot of predicted fatigue life vs. experimental fatigue life in an LWR environment for various austenitic stainless steels with similar loading signals and surface finishes but varying strain amplitudes. In that figure, the data is compared to a line with slope of unity and two boundary lines are provided that represent multiples of the comparison line slope. As shown in the figure, most of the data points lay between the boundary lines, but there are some values that lay outside the boundaries, with both greater than three times the predicted life and less than one-third the predicted life. No measures of the accuracy of the data fit are provided in the NUREG.

To adequately compare the AREVA experimental data to the data provided in Figure 55 of the NUREG, the polished and roughened specimen test data must be considered together and separately. Figure 1-1 provides a plot of the NUREG/CR-6909 calculated mean In-PWR fatigue life versus the experimental In-PWR fatigue life for the complete AREVA data set, including polished and roughened test specimens. Figures 1-2 and 1-3 provide the same plot for the AREVA polished and roughened test specimens, respectively. [

]. As expected, the R^2 value for the roughened test specimens is lower than for the polished test specimens due to the greater variation in surface finish. As shown in each of the figures, all of the data remains within the factor of three boundary lines.

Considering that the trend line provides an average of the data, that the R^2 value is as expected and the data lay within the factor of three boundaries, it is concluded that the scatter is acceptable and that use of the average RF is acceptable and in keeping with the methods used in the NUREG.

Additionally, the two data points representing fatigue tests 36 and 37 of Table 3-9 of ANP-10326 are being removed from ANP-10326 as they do not provide useful data for a low cycle fatigue evaluation. Markups illustrating the changes are provided in the enclosed mark-up.

Figure 1-1
AREVA Test Specimen Data – Polished and Roughened

[ ]

Figure 1-2
AREVA Polished Test Specimen Data

[ ]

Figure 1-3
AREVA Roughened Test Specimen Data

Question 2

Table 4-3 of ANP-10326P provides experimental F_{en} factor values for polished and ground specimens for four different complex loading types, and indicates a large variation in the F_{en} values. Section 4.4 of ANP-10326P states that the results in Table 4-3 show that the F^{exp}_{en} factors [

] approximately constant value of six evaluated according to NUREG/CR-6909. Provide an appropriate data analysis of the experimental F_{en} values in Table 4-3 that address this data scatter.

Response 2

The experimental F_{en} factor values listed in Table 4-3 of ANP-10326 are based on the experimental data and represent the ranges and averages for the values, sorted by loading signal and surface finish. Sorting this data reduces the number of data points in each group, which has the effect of making the data appear to have a greater degree of scatter.

The scatter in the AREVA In-PWR fatigue test data discussed in the Response to Question 1 is similar to the In-Air data measured against the proposed mean fatigue curve considered in NUREG/CR-6909, Rev. 0, as measured by the R^2 value of 0.851 provided in Section 5.1.7 of that document. Additional R^2 values are provided in the NUREG in Section 5.1.7, which represent measurements of In-Air data against the mean curves of Tsusumi et al. (R^2 = 0.839), Jaske and O'Donnell (R^2 = 0.826) and the ASME Code (R^2 = 0.568).

Considering the AREVA polished samples and roughened samples separately, plotted against the expected mean fatigue life calculated using the NUREG, [

] respectively, as provided in the Response to Question 1. The increased scatter in the roughened sample test data is due to the variability in the process used to create the surface finish as well as increased variability in the number of cycles required for crack initiation for a given measured roughness.

Question 3

Table 3-6 of ANP-10326-P states that NUREG/CR-6909 tested specimens have roughness (R_t) values of [ ] and representative components and piping are [ ]

Section 3.1.9 of the draft of NUREG/CR-6909, Revision 1 states that the R_q of a smooth polished specimen is approximately 0.0075 μm. Section 5.3 of the draft of NUREG/CR-6909, Revision 1 states that industrial-grade surface finishes range from 0.2 μm to 6.0 μm, and that the fatigue lives of components with such surface roughness values can be a factor of 2 to 3.5 lower than those of smooth specimens. Therefore, the representative components and piping with [ ] surface roughness may lead to significantly shorter fatigue lives compared to the fatigue lives of smooth specimens. Also, the RF values in Table 6-1 of ANP-10326P are derived from [ ] of which have surface finishes that are significantly less than [ ]

Provide an explanation for the differences observed in the surface roughness values listed in Table 3-6 of ANP-10326P, including the [ ] specimens with surface finishes that are significantly less than [ ], and the values described in the draft of NUREG/CR-6909, Revision 1.

Response 3

As stated in Section 3.2.1 of ANP-10326, the maximum allowable R_t value specified for the as-manufactured surfaces of certain AREVA components is [ ] R_t is the maximum peak-to-valley distance measured normal to the surface. R_q is the Root-Mean-Square roughness of the surface and is calculated using a profile of the surface.

A comparison of R_t and R_q values for the surfaces of a sampling of roughened test specimens is provided in Table 3-5 of ANP-10326. As shown in the table, the average ratio, [ ] for the surfaces evaluated, but this ratio may differ for actual components, depending on the manufacturing methods employed. However, using this ratio, an R_t value of [ ] would lead to an average R_q value of [ ] which is only slightly greater than the upper bound of 6.0 μm for R_q for the industrial-grade surface finishes referenced in the NUREG.

The average R_t of the AREVA roughened test samples is [ ] with a [ ] Using Equation 12 of NUREG/CR-6909, Rev. 0, the percent difference in cycles required for crack initiation between surface finishes of [ ] While this difference may slightly impact the cycles required for crack initiation, the impact on the fatigue life of the specimen is less significant, as cycles required for crack growth are not affected. Therefore, while grinding the surface of the fatigue test specimens adds a degree of variability in the fatigue lives of the individual specimens, the variation in surface roughness found in the AREVA test specimens does not significantly impact the mean fatigue lives of the specimens.

Question 4

The staff reviewed Table 3-8 of ANP-10326-P and compared the data in that table with the data in Table 5-1. Table 3-8 includes strain amplitude and N_{25} values for in-air testing of 2 polished specimens as [ ] Similarly, Table 5-1 includes strain amplitude and N_{25} values for in-PWR testing of 2 polished specimens as [ ] While Specimen No. 71QS7 has a different strain amplitude than the other specimens, the fatigue lives of the specimens tested in the PWR environment seem considerably longer than that of Specimen No. 71QS7.

Explain why the fatigue lives for the same strain amplitudes are much longer in a PWR environment compared to an air environment, and why Specimen No. 2 seems to have a considerably shorter fatigue life than those tested in a PWR environment.

Response 4

Of the [ ] In-PWR fatigue tests documented in the Revision 1 of ANP-10326, two of the In-PWR test specimens were found to have fatigue lives greater than an In-Air test specimen tested at high temperature, but with similar strain amplitude. The two In-PWR test specimens [ ] and the one In-Air test specimen (In-Air Specimen 1 of Table 3-8) each demonstrated fatigue lives in the high cycle regime. In other words, each of these test specimens achieved fatigue lives that were greater than the low cycle fatigue cutoff of 16,000 cycles. This value is approximately the point where the NUREG/CR-6909, Rev. 0, In-Air design fatigue curve transitions from dividing the number of cycles by a factor of 12 to dividing the strain by a factor of 2. The strain amplitude for the other In-Air test specimen (In-Air Specimen 2) is significantly higher than the two In-PWR test specimens and cannot be compared directly.

In the high cycle fatigue regime, which is outside the range of focus for ANP-10326, minor variations in chemical composition and mechanical properties can have a significant impact on fatigue life. The extended life displayed by the two In-PWR specimens coincides with a threshold strain value and supports the idea that the effects of environmentally assisted fatigue are less pronounced at low strain values as discussed in Section 5.2.2 of the NUREG.

As discussed in the Response to Question 1, the two data points representing fatigue tests [ ] of Table 3-9 of ANP-10326 are being removed from ANP-10326 as they do not provide useful data for a low cycle fatigue evaluation. Markups illustrating the changes are provided in the enclosed mark-up.

Question 5

Table 3-7 of ANP-10326P includes strain amplitude and N_{25} values for in-air testing of 2 polished specimens as [ ] Similarly, Table 3-8 includes strain amplitude and N_{25} values for in-air testing of 1 polished specimen as [ ]

Explain why the fatigue life is significantly higher for the two polished specimens tested at strain amplitudes of [ ] compared to the fatigue life of the polished specimen tested at a strain amplitude of [ ]

Response 5

Specimens listed in Table 3-8 of ANP-10326 are tested at 572 °F while those listed in Table 3-7 are tested at room temperature. The yield strength of austenitic stainless steel at 572 °F is approximately 37% lower than it is at room temperature, based on ASME Code minimum yield strength values [ ] This affects the fatigue life of the test specimen because a greater percentage of the strain is in the plastic range for the material tested at high temperature.

In addition, these test specimens exhibit fatigue lives in the high cycle regime, which is outside the range of focus for ANP-10326. This portion of the fatigue curve is much flatter and, therefore, small differences in strain and mechanical properties have a significant impact on fatigue life.

Question 6

Table 3-8 of ANP-10326-P summarizes the fatigue lives in air at 572°F for both polished and ground specimens. The fatigue lives are specified in terms of N_{25} (i.e., the number of cycles until a 25% reduction of σ_{max}). The staff also reviewed a 2009 ASME PVP paper published by AREVA (PVP2009-78129, Reference 1) that describes the same fatigue testing and noted that most of the N_{25} values in Tables 2 and 3 of that paper do not agree with the N_{25} values listed in Table 3-8 of ANP-10326-P. Instead, some of the values in Table 3-8 of ANP-10326-P agree with the values specified for N_r (the number of cycles at fracture) in PVP2009-78129.

Explain the discrepancies in the reported values of N_{25} and N_r between ANP-10326P and PVP2009-78129 and discuss any potential impact of those discrepancies on the results documented in ANP-10326-P.

Reference:

1. PVP2009-78129, "Effects of Surface Finish and Loading Conditions on the Low Cycle Fatigue Behavior of Austenitic Stainless Steel in PWR Environment for Various Strain Amplitude Levels," Proceedings of the ASME 2009 Pressure Vessels and Piping Division Conference, July 26-30, 2009, Prague, Czech Republic.

Response 6

After further review of the data used to develop Table 3-8 of ANP-10326, AREVA has determined that N_r values were incorrectly tabulated for tests 3 through 7 instead of the N_{25} values. Review of the report indicates that the corrected values do not impact the calculations or conclusions of the report. Table 6-1 provides the corrected data as taken from Reference 1 with the revised values in **bold**.

Table 6-1
In-Air AREVA Tests at 572° F

[ ]

References for Response 6:

1 PVP2009-78129, "Effects of Surface Finish and Loading Conditions on the Low Cycle Fatigue Behavior of Austenitic Stainless Steel in PWR Environment for Various Strain Amplitude Levels," Proceedings of the ASME 2009 Pressure Vessels and Piping Division Conference, July 26-30, 2009, Prague, Czech Republic.

Question 7

In the staff's review of the data contained in Table 5-1 of ANP-10326P, Items 8, 9, 19, and 31 all possess the same strain amplitude [ ] and the same strain rate (variable B loading), but they have different roughness and fatigue life (N_{25}) values:

[

] The data indicate a roughness factor of as much as [ ] which is consistent with ANL's range of surface finish factors of 2.0 to 3.5, as listed in Table 2-1 of ANP-10326-P. These results do not support the statement made on page 3-11 of ANP-10326-P that, " [

]

Explain how the data in Table 2-1 of ANP-10326P support the statement made on page 3-11 of ANP-10326P.

Response 7

The roughness factor is the ratio of mean fatigue life for polished specimens to the mean fatigue life for roughened specimens. The fatigue life of individual test specimens cannot be used to make this comparison. Section 4.2 of ANP-10326 states the following:

[

]

This indicates that the cycle reduction factor of 3.0 attributed to surface finish in NUREG/CR-6909, Rev. 0 In-Air design fatigue curve and the factor of 4.0 attributed to surface finish in the ASME Code In-Air design fatigue curve are conservative relative to the results of the AREVA experimental data. In addition, the factors are conservative relative to the results of Eqn 12 from the NUREG, which provides a comparison of cycles required for crack initiation. Considering the average R_q values for the polished and roughened test specimens from ANP-10326 of [ ], respectively, the equation provides a cycle reduction factor for crack initiation of [ ] This ignores the additional cycles required for crack growth which would be equivalent between the two specimens and would reduce the final roughness factor. Section 7.3 of the NUREG provides the following:

> Limited data in LWR environments on specimens that were intentionally roughened indicate that the effects of surface roughness on fatigue life is the same in air and water environments for austenitic SSs...

Therefore, it can be concluded that the cycle reduction factor of 3.0 attributed to surface finish in the development of the design In-Air fatigue curve is conservative. While greater surface roughness could provide roughness factors that achieve the values considered in the NUREG or the ASME Code, typical nuclear power plant component surface finishes and, in particular, surface finishes in fatigue critical areas of the system do not approach these levels.

ANP-10326P—Environmentally Assisted Fatigue: Modified Effective Correction Factor for Austenitic Stainless Steels

Topical Report Markups

1.0 INTRODUCTION

The ASME Boiler and Pressure Vessel (B&PV) Code 2004 (Reference 1) does not consider the effects of the light water reactor (LWR) environment on the fatigue evaluation of components. Different methods have been proposed to account for the environmental effects on the fatigue evaluation; the "Fen methodology," demonstrated in NUREG/CR-6909 (Reference 2), is accepted by the U.S. NRC (References 3 and 4).

[

]

AREVA performed thirty-~~seven~~ five experiments with polished and ground specimens made of austenitic SS Type 304L in a controlled pressurized water reactor (PWR) simulated environment. The specimens were loaded with triangular and complex shape signals corresponding to hot and cold shock transients representative of PWR plants. The report presents the tests and details on the material and loading signals used, as well as the influence of the surface finish, strain rate, and strain amplitude on the fatigue strength of specimens. A comparison is made with the NUREG/CR-6909 testing procedure, specimens, and parameters.

[

] This report uses both United States Customary System and International System of Units.

2) NUREG/CR-6909 (Section 7.2) states that especially for rough surface finish the effect of specimen size may not be considered in the margin of 20 on life.

3) The values in parentheses correspond to ranges and values in bold to respective mean values.

4) AREVA does not intend to produce a new design curve, but examines the available experimental margin identified for SS Type 304L.

Figure 2-1 presents the derivation of the design in-air NUREG/CR-6909 fatigue curve.

[

]

Figure 2-1 Derivation of the NUREG/CR-6909 In-Air Design Curves for SS

[

]

Figure 2-2 provides a graph comparing the austenitic SS mean in-air fatigue curve of NUREG/CR-6909 to the design in-air fatigue curves of the ASME B&PV Code and NUREG/CR-6909. The AREVA tests in a controlled PWR-simulated environment are shown as scattered data. The stress amplitude for each data point is obtained by multiplying the experimental strain amplitude with the modulus of elasticity of 28.3 ksi, reported in the ASME fatigue curve of Fig. I-9.2.1. ~~The two tests with fatigue life of ≈100,000 cycles are excluded from the figure.~~ [

]

Table 3-1 Tests Performed in PWR Conditions per Calendar Year

Calendar year	Number of tests	Specimen ID
2005	2	471QS2B 271QS7
2006	3	371QS6A 471QI18 471QI18A
2007	7	471QI11B 471QI14A 471QSI11A 471QS1B 7QI4 471QI15B 7Q12B
2008	7	8QS1A 7QI5 8QS9A 8QI13A 10QS5 7QI3 8QI16A
2009	~~8~~6	10QI7 10QS1 10QI3 10QS6 10QI2 8QI10A ~~10QI1~~ ~~10QS2~~
2010	4	11QI1 11QS10 11QI4 11QI3
2011	6	11QI6 11QI8 11QS9 12QI3 12QI4 12QI7
Total number of tests	~~37~~35	

Table 3-3 Parameters of AREVA Tests in-PWR Environment

[ ]

3.2.1 Roughness

The cylindrical test specimens were cut off at the lower and upper parts of the 304L plate at a quarter thickness distance from surfaces, in the rolling direction. Then, they were machined and mechanically polished or ground. Details of the grinding operations performed on LCF test specimens are as follows:

- The lathe used is a conventional one, type Hernault-Somua Cholet J 350.
- The grinding wheel used is a cutoff disk, type Norton BDA-24 of 230 mm x 2.5 mm.
- Before grinding, specimens are turned on a conventional lathe with a low moving speed and a high speed of rotation. For these turning conditions, a low surface roughness is obtained that allows the application of constant speed and pressure on the specimen during grinding operations.
- The grinding wheel is positioned tangent to the surface; one or two passes of 0.3 mm depth are performed on the specimen gauge length and on the shoulders.

Figure 3-5 Roughness Versus Cycles to Failure

3.2.2 Medium

AREVA fatigue testing was performed both in air and in a controlled PWR-simulated environment.

3.2.2.1 In-Air Tests

Low cycle fatigue (LCF) tests in air were performed at room temperature and at 572°F (300°C) under strain control by using an extensometer located outside the furnace and two ceramic rods located inside the furnace between the test specimen and the material testing system (MTS) extensometer. The distance between the two ceramic rods in contact with the specimen is ≈0.38 in. Figure 3-6 shows the specimens' geometry and equipment used for the AREVA in-air fatigue testing.

Table 3-7 In-Air AREVA Tests at Room Temperature

[ ]

Table 3-8 In-Air AREVA Tests at 572°F

[ ]

[ ]

3.2.3 Strain Amplitude

[ ]

Figure 3-10 AREVA In-PWR Tests

[ ]

Figure 3-12 Strain Rate Versus Cycles to Failure for AREVA Polished Specimens

Figure 3-13 shows data for AREVA specimens with ground surface finish and tested with triangular loading signal. An increase of the strain amplitude with the same strain rate results in a decrease of the fatigue life for PWR environmental conditions for these specimens, too. The impact of the strain rate on fatigue life seems to be monotonic and independent from other parameters.

3.2.5 Loading Signal

The complex signal A was obtained by using the cold and hot thermal shock of the safety injection system (SIS) nozzle shown in Figure 3-14, which corresponds to the stress amplitude obtained by the temperature variation on the inner surface of the nozzle. In the figure, only a part of the hot thermal shock is shown. First, the loading signal with the strain amplitude of 0.3 percent was obtained by removing strain variations versus time close to zero and from 600 sec to 1000 sec and having a total duration of 1200 sec, as Figure 3-15 shows. Then, the long duration signal A was obtained by doubling the strain amplitude and time period of maximum strain. Therefore, the total duration of this signal is 2400 sec with maximum strain amplitude of 0.6 percent. Because only the tensile portions of the strain history that have a positive strain rate contribute to the reduction of the fatigue life of components in PWR environment, the decreasing phase of the cold thermal shock of the long signal A was removed as well as strains near to zero during the hot thermal shock. The short loading signal A with maximum strain amplitude of 0.6 percent with a total duration of approximately 840 sec was applied. The short loading signal A is shown in Figure 3-16.

Twelve out of thirty-~~seven~~ five specimens that were tested in PWR conditions were tested with complex signal A. Signal C was used only to test two polished specimens. Table 3-10 provides the signals and number of polished or ground specimens tested with each one of them. Signals B, C, and D are generated by rearranging the parts of the short Signal A. Long complex signal A was used only for testing specimen 471QI18A. For loading signal B and D, short signals with duration of 420 sec and strain amplitude 0.3 percent were used, as Table 3-10 shows.

Figure 4-7 Comparison of AREVA and ANL[9] Testing of Polished Specimens in PWR

4.4 *Loading Signal*

The cycling loading conditions for ANL testing were simulated by using the signal shown in Figure 4-8a. AREVA tests were performed with the triangular loading signal shown in Figure 4-8b and for the complex signals listed in Table 3-10. The latter signals are representative of component thermal transients in PWR plants.

where,

N = cycles to failure per the mean in-air fatigue curve

N_{25} = cycles to failure as evaluated from test in a PWR-simulated environment

Table 4-2 F_{en} Factors per NUREG/CR-6909 for AREVA Loading Signals

Signal	Theoretical [1] Strain Amplitude (%)	Tensile Strain Rate (%/s)		Temperature °C (°F)	F_{en}
Triangular	0.3 & 0.6	0.01		300 (572)	5.07
~~Triangular~~	~~0.2~~	~~0.1~~		~~300 (572)~~	~~2.91~~
Triangular	0.6	0.4		300 (572)	2.08
A	0.3 (Short SIS)	variable	Min = 0.000034 Max = 0.088739	300 (572)	5.88[2]
A	0.6 (Long SIS)	variable	Min = 0.000034 Max = 0.088739	300 (572)	5.88[2]
A	0.6 (Short SIS)	variable	Min = 0.00014 Max = 0.07923	300 (572)	5.97[2]
B	0.6 (Short SIS)	variable	Min = 0.00014 Max = 0.16969	300 (572)	5.98[2]
B	0.3 (Short SIS)	variable	Min = 0 Max = 0.051298	300 (572)	6.01[2]
C	0.6 (Short SIS)	variable	Min = 0.00014 Max = 0.02450	300 (572)	6.37[2]
D	0.6 (Short SIS)	variable	Min = 0.00012 Max = 0.07923	300 (572)	6.02[2]
D	0.3 (Short SIS)	variable	Min = 0.000026 Max =0.065892	300 (572)	6.02[2]

1) Theoretical strain amplitude applied on the shoulders of the specimen.

2) The modified rate approach in NUREG/CR-6909 was used for this evaluation.

Steel	Specimen	Strain rate tension (%/s)	Strain range (%)	Strain amplitude (%)	N_{25}
	1423	0.05	0.5	0.25	17812
	1425	0.0049	0.49	0.245	13684
	1431	0.29	0.29	0.145	116754
	1434	0.029	0.29	0.145	40643
	1436	0.025	0.25	0.125	1719851
	1512	0.24	0.24	0.12	2633954

~~4.7 Strain Amplitude Threshold~~

~~NUREG/CR-6909 provides a strain amplitude threshold of 0.1 percent below which there are no significant environmental effects on fatigue life of austenitic SSs. Although AREVA performed two tests with strain amplitude ≈0.21 percent, higher than the NUREG/CR-6909 threshold of 0.1 percent; no environmental impact on the fatigue life of these specimens (circled in Figure 2-1) was noticed because the data points for these tests are near the mean fatigue curve for SS. This is also an indication of the existence of the strain threshold for SSs as provided in NUREG/CR-6909.~~

Table 5-2 Summary of RF values with respect to strain amplitude

7.0 CONCLUSIONS

AREVA performed environmentally assisted fatigue testing on thirty-five ~~-seven~~ austenitic SS Type 304L specimens in a controlled PWR simulated environment. The specimens had different degrees of roughness. The ground specimens had a severe degree of roughness (40 μm ≤ R_t ≤ 80 μm). Triangular and complex shape loading signals representative of hot and thermal shocks occurring during the operation of the PWR plants were applied in these tests.

The AREVA tests confirmed that the life of ground specimens is lower than that of polished specimens, but the impact of the roughness is not as significant as suggested in NUREG/CR-6909; the fatigue life of these specimens may be dependent on other properties (e.g., the strain amplitude).

The shape of the loading signal has a significant effect on the fatigue life of specimens. Specimens tested with complex signals, representative of thermal shocks in PWR plants, have significantly higher life than those tested with triangular (ramp shape) transients. NUREG/CR-6909 has only limited results for these realistic loading conditions and specimen properties.

[ ]