AREVA

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Revision 1

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

Topical Report

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AREVA NP Inc.

Nature of Changes

Item	Section(s) or Page(s)	Description and Justification
0	N/A	Original Issue
1		
	vi, vii, viii, 1-1	Additions and editorial changes
	2.0	Explanation of the division of the overall factor of 12 in sub-factors was added and Table 2-1 changed
	2.3	Figure 2-4 was revised and explanation about the NUREG/CR-6909 methodology for the derivation of the factor of 12 was added
	2.4	Figure 2.4 was revised
	2.4, 3.1, 3.2, 3.2.2.1	Clarification about the type of steel and area of applicability was added
	3.2.3	Figure 3-11 was revised
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	7.0	Editorial changes

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Nomenclature

Symbol	Definition
A	Constant of mean fatigue curve
a	Reduction factor accounting for the material variability and data scatter
B	Constant of mean fatigue curve [2]
b	Reduction factor accounting for the size effect
C	Constant of mean fatigue curve [2]
c	Reduction factor accounting for the loading history
d	Available identified margin in the NUREG/CR-6909 prediction for environmental effects
ε_a	Strain amplitude (percent)
ε'	Strain rate (sec^{-1})
ε'^*	Transformed strain rate
F_{en}	Effective environmental fatigue correction factor [2]
F^*_{en}	Modified effective environmental fatigue correction factor
F^{exp}_{en}	Experimental F_{en} factor
N	Cycles to failure per the mean in-air fatigue curve for stainless steel [2]
N_{25}	Fatigue life (cycles at 25 percent maximum load drop)
N_{RTair}	In-air design cycles evaluated according to NUREG/CR-6909
N_f	Cycles to failure
N_o	Cycles for the initiation of a crack
N_p	Cycles for the propagation of a crack
N^{exp}_{water}	Estimated design cycles in-PWR that correspond to N_{25}
N_{water}	In-PWR design cycles
O^*	Transformed oxygen
R_a	Measure of roughness
RF	Environmental fatigue correction factor that reduces F_{en} – Reduction Factor
R_q	Measure of roughness
R_t	Measure of roughness
T	Water temperature
T^*	Transformed temperature
U_{envi}	Usage factor of a stress cycle or load pair set in PWR environment
U^*_i	Usage factor of a stress cycle or load pair set in PWR per NUREG/CR-6909

Acronym	Definition
ANL	Argonne National Laboratory
AREVA	AREVA NP SAS - An AREVA NP company with offices in France
ASME	American Society of Mechanical Engineers
B&PV	Boiler and Pressure Vessel
DO	Dissolved Oxygen
EAF	Environmentally Assisted Fatigue
LCF	Low Cycle Fatigue
LVDT	Linear Variable Differential Transformer
LWR	Light Water Reactor
MTS	Material Testing System
NRC	Nuclear Regulatory Commission
PWR	Pressurized Water Reactor
RDP	RDP Electronics Ltd
RPV	Reactor Pressure Vessel
SG	Steam Generator
SS	Stainless Steel
STP	Standard Temperature and Pressure

ABSTRACT

This report provides data and justification for the possible reduction of the effective environmental correction factor, Fen, which considers the impact of the light water reactor (LWR) environment on the fatigue life of components. The ASME Boiler and Pressure Vessel (B&PV) Code 2004 (Reference 1) does not consider the effects of the LWR environment on the fatigue evaluation of components. Although other methods have been proposed to account for the environmental effects on the fatigue evaluation, e.g., fatigue curves, etc., the "Fen methodology" presented in NUREG/CR-6909 (Reference 2), is accepted by the U.S. NRC (References 3 and 4).

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This report is based on experimental tests performed by AREVA NP SAS (AREVA). [

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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).

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AREVA performed thirty-seven 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.

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

2.0 ANALYTICAL METHODOLOGY

2.1 *Background*

The NUREG/CR-6909 in-air design fatigue curve for SS is obtained from the corresponding mean curve by first considering the Goodman mean stress correction and then applying a factor of 12 on the cycles or 2 on the stress, whichever is more conservative. The NUREG/CR-6909 design in-air fatigue curve for SS is different from the corresponding fatigue curve in the 2004 ASME B&PV Code, which is obtained from Langer's (Reference 5) mean fatigue curve, because the NUREG/CR-6909 is based on additional experimental data, different assumptions and methods. The factor of 20 on cycles as applied in the ASME Code was reduced to 12 in the NUREG/CR-6909 while the factor of 2 on stress is unchanged.

The mean NUREG/CR-6909 in-air fatigue curve for SS for Types 304, 304L, 316L, 316, and 316NG up to temperature 752°F (400°C) is shown in Equation 1.

$$ln(N) = A - B\ ln(\varepsilon_a - C) \qquad \text{Equation 1}$$

where,

A, B, and C are constants:

A is the intercept of the fatigue curve,

B is the slope of the log-log plot of fatigue $\varepsilon_a - N$ data,

C represents the fatigue limit of the material.

ε_a is the applied strain amplitude (percent).

N is the number of cycles to failure for the in-air conditions.

In NUREG/CR-6909, the cycles to failure are defined as the cycles at 25 percent maximum load drop, N_{25}. Following the same definition, for AREVA tests and for this report, cycles to failure refer to N_{25} cycles. For SS, constants of Equation 1 were evaluated in NUREG/CR-6909, as shown in Equation 2.

$$ln(N) = 6.891 - 1.920\ ln(\varepsilon_a - 0.112) \qquad \text{Equation 2}$$

NUREG/CR-6909 suggests no change on the factor of 2 on stress; this report also does not discuss that factor or the area of its applicability. In NUREG/CR-6909 (Table 12, pg. 76), comparison of the adjusting factors considered in the factors of 20 and 12, applied to the cycles of the mean fatigue curves, in order to obtain the cycles of the ASME B&PV Code and the NUREG/CR-6909 in-air design fatigue curves respectively are presented. This comparison is summarized below:

- The factor of 20 on life (cycles) applied to Langer's mean curve in the ASME Code is the product of the following sub-factors:
  - 2.0 for scatter of data.
  - 2.5 for size effect.
  - 4.0 for surface finish and atmosphere.

  Atmosphere refers to the difference between the industrial room conditions and the laboratory conditions, where experiments took place.

- The factor of 12 results, considered in the design in-air fatigue curve of NUREG/CR-6909, resulted from Monte Carlo simulations using sub-factors in the ranges shown in Table 2-1, and as described in Section 7.5 of NUREG/CR-6909.

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Table 2-1 Considered Factors in the Reduction of Fatigue Life in LWR Conditions

Factor	ASME B&PV Code	ANL NUREG/CR-6909 [3]	AREVA
Surface finish	4.0	**2.8** (2-3.5)	[ ]
Material variability and data scatter	2.0	**2.5** (2.1-2.8)	[ ]
Loading history	1.0	**1.6** (1.2-2.0)	[ ]
Size effect	2.5	**1.3** (1.2-1.4) [2]	[ ]
Total Adjustment	20	14.6 (12)	n/a[4]

1) [

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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.

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

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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. [

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Figure 2-2 Fatigue Curves and AREVA PWR Test Data

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2.2 *Effective Environmental Correction Factor F_{en}*

Although other methodologies exist to incorporate environmental effects on the fatigue life of components (e.g., in-LWR fatigue curves), the NRC has accepted the "*Fen* methodology" (References 3 and 4). Correction factors specific to different types of materials (e.g., stainless, carbon, low-alloy steel materials) are used to adjust the cumulative usage factor obtained from the in-air fatigue evaluations and incorporate the impact of the LWR environment on the fatigue life of components. In this report, only austenitic SS and PWR environment are examined.

Equation 3 evaluates the F_{en} factor, which is defined as the ratio of cycles in air and at room temperature (N_{RTair}) to the cycles in a LWR environment and at service temperature (N_{water}).

$$F_{en} = e^{0.734 - O^{*}T^{*}\varepsilon'_{k}{}^{*}} \qquad \text{Equation 3}$$

where,

ε'^{*}_{k} is the transformed strain rate based on the actual strain rate ε'_k and defined as:

$\varepsilon'^{*}_{k} = 0$ ($\varepsilon'_k > 0.4\%/s$)

$\varepsilon'^{*}_{k} = \ln(\varepsilon'_k/0.4)$ ($0.0004 \leq \varepsilon'_k \leq 0.4\%/s$)

$\varepsilon'^{*}_{k} = \ln(0.0004/0.4)$ ($\varepsilon'_k < 0.0004\%/s$)

T^* is the transformed temperature, which in this report is based on the water temperature, T, and is defined as:

$T^* = 0$ ($T < 150°C$)

$T^* = (T-150)/175$ ($150°C \leq T < 325°C$)

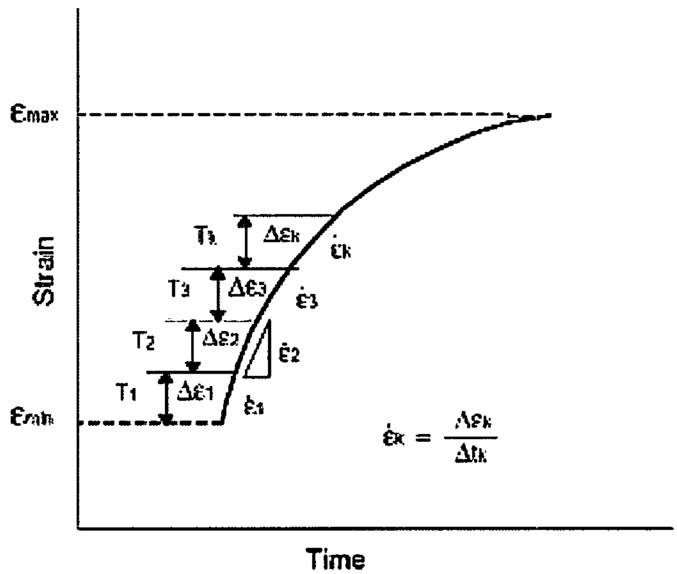
$T^* = 1$ ($T \geq 325°C$)

and O^* is the transformed dissolved oxygen based on the dissolved oxygen (DO) in the water and defined as:

$O^* = 0.281$ for all DO levels

In the case of complex loading signals, a modified rate approach (Reference 2) can be used to evaluate the F_{en} factor, according to Equation 4, and as shown in Figure 2-3.

Figure 2-3 Modified Rate Approach for the Evaluation of F_{en} Factor[2]



$$F_{enk} = \sum_{i=i\,\min}^{i\max} \frac{f_{en}(t_i)\left[\varepsilon(t_i + 1) - \varepsilon(t_i)\right]}{\varepsilon_{\max} - \varepsilon_{\min}} \qquad \text{Equation 4}$$

where, F_{en} (t_i) is the instantaneous correction factor for each increment k and evaluated, using Equation 3. The values ε_{max} and ε_{min} are the maximum and minimum strain amplitude, respectively, and $\varepsilon(t_i)$ is the strain at time point t_i.

2.3 *Definition of Experimental Margin*

Figure 2-4 Available Margin for Environmental Effects in the NUREG/CR-6909 In-Air Design Curve

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2.4 *Modified Effective Correction Factor F^*_{en}*

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3.0 AREVA EXPERIMENTAL TESTS

AREVA conducted fatigue tests in air and in a controlled PWR-simulated environment during the years 2005 to 2011. Table 3-1 shows the number of tests performed per calendar year. Experiments are conducted under a standard test protocol that permits consistency for the preparation of the specimens, their assembly on the loading device, the closure and control of the autoclave, the chemistry preparation, the temperature increase for the tests at 572°F (300°C), and the test launching. The water chemistry is analyzed before and after each test, and parameters are continuously recorded during the test (hydrogen content, pressure and temperature). The strain, number of cycles, and temperature were recorded during the tests. The cycles to failure, N_{25}, correspond to cycles at which the tensile strain decreases from its peak or steady-state value to 25 percent. This number of cycles typically produces an approximately 3 mm-deep crack in the test specimen.

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	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**	

3.1 *Material*

Austenitic SS Type 304L was used for all tests. Material was supplied by three sources, with main representative the rolled plate of about four inches in thickness:

a. A rolled plate of ≈4 inches in thickness.

b. A forged slab of ≈16.5 inches in thickness.

c. A cold forged branch.

The chemical composition and mechanical properties of Type 304L SS for the AREVA testing program are summarized in Table 3-2.

Table 3-2 Chemical Composition and Mechanical Properties of Tested Type 304L SS

Chemical Composition									Mechanical Properties(1)		
C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Y.S. (ksi)	U.S. (ksi)	El. (A% 5d)
Rolled plate of 4 in. thickness											
0.025	1.687	0.41	0.0001	0.032	9.12	18.3	0.38	0.217	37	83	64
Forged slab of 16.5 in. thickness											
0.026	1.71	0.62	0.001	0.018	9.60	19.29	0.04	0.12	33	76	73.5
Cold forged branch											
0.026	1.77	0.60	<0.001	0.020	9.55	19.48	0.35	0.07	>30	>70	>40

1) Y.S. = yield strength, U.S. = ultimate strength, El. = elongation at failure

3.2 *Factors Examined*

AREVA performed strain controlled fatigue tests on Type 304L SS specimens and parametric examination of the following factors:

a. Roughness.

b. Medium.

c. Strain Amplitude.

d. Strain Rate.

e. Loading Signal.

Temperature for all the in-PWR tests was the same, 572°F (300°C); therefore, the effects of temperature variation on the measured quantities was not taken into consideration. Each of the above factors is described briefly below:

a. Roughness: Polished specimens were used for testing ($R_t \leq$ 2.7μm) as well as ground specimens (39μm < $R_t \leq$ 85μm).

b. Medium: Experiments were performed both in air and in a controlled PWR-simulated environment.

c. Strain Amplitude: A range of strain amplitude was applied to specimens ranging from 0.206 to 0.59 percent for testing in PWR conditions and 0.19 to 0.6 percent for specimens tested in air.

d. Strain Rate: Different values of strain rate were used for triangular signals ranging from 0.01 to 0.4 percent/s. The strain rate for complex signals was variable.

e. Loading Pattern (Signal): Fully reversed triangular signal was used to simulate the loading conditions. In addition, complex signals A, B, C, and D, representative of cold and hot shocks, were used. Signals B, C, and D were obtained by rearranging parts of signal A.

Table 3-3 provides the parameters of the tests and number of specimens examined in a controlled PWR-simulated environment under different categories.

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

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3.2.1 Roughness

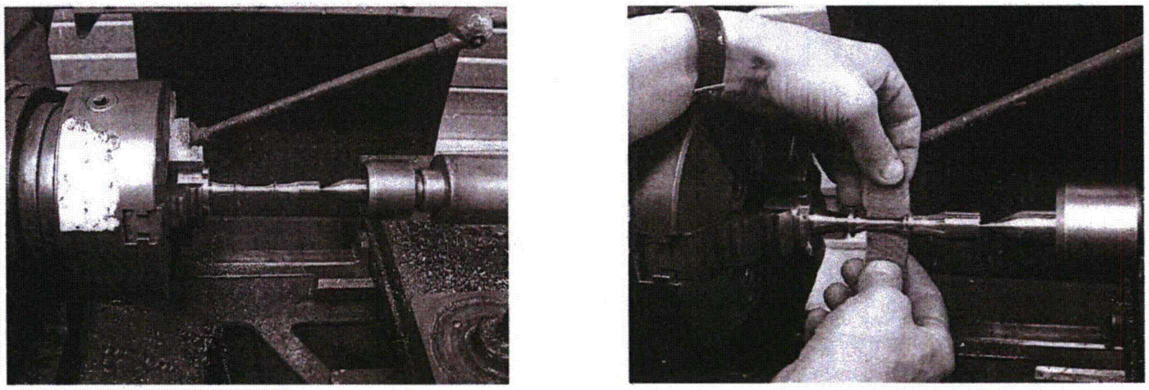
The cylindrical test specimens were cut off at the lower and upper parts of the 304L plate at a quarter thickness distance from surfaces, in the rolling direction. Then, they were machined and mechanically polished or ground. Details of the grinding operations performed on LCF test specimens are as follows:

- 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.

- Grinding pressure and speed are kept equal from one sample to another.
- Speed of rotation of the grinding wheel is 10000 revolutions per minute in the clockwise direction and is the opposite to the specimen's direction of rotation.
- Speed of rotation of the specimen is 800 revolutions per minute and the lathe carriage displacement is equal to 0.05 mm/turn.
- The total traveling speed of the lathe carriage is 40 mm/minute; the grinding wheel travels along a model or a template machined in the same dimensions of the specimen to be ground.
- Roughness profile of ground specimens is irregular, and pronounced grooves are locally observed

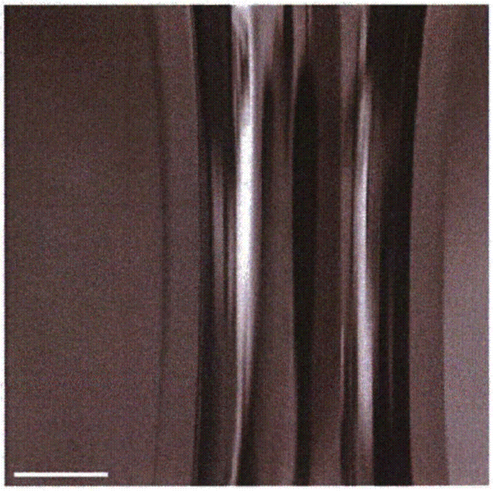
For the AREVA tests, both in air and in a controlled PWR-simulated environment polished and ground specimens were used. Polished specimens have roughness, R_t, in the range of 0.75 μm ≤ R_t ≤ 2.7 μm; ground specimens have roughness R_t in the range of 39 μm ≤ R_t ≤ 85 μm. Figure 3-1 shows the specimen polishing procedure (a) the specimen is fixed and in rotation and (b) abrasive paper and alumina powder are used for the polishing. Figure 3-2 shows (a) a polished and (b) a ground surface of specimens. Figure 3-3 illustrates the devices used for the grinding.

Figure 3-1 Specimen polishing procedure

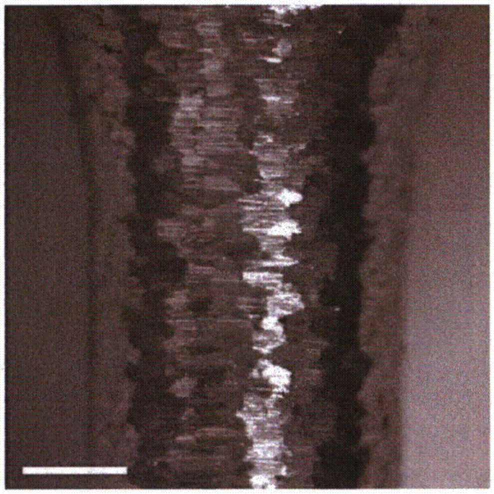


(a) (b)

Figure 3-2 Polished and ground specimen surface

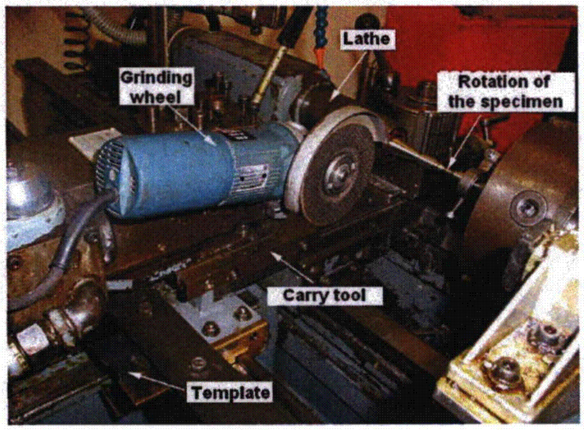


(a)



(b)

Figure 3-3 Devices for grinding and LCF specimens being ground



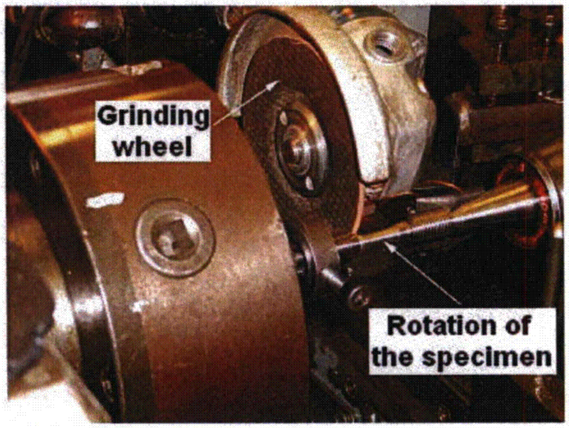


Table 3-4 provides definitions for available measures for roughness. For the AREVA specimens, roughness is expressed by R_t, R_a, or R_q values.

Figure 3-4 gives an approximate roughness profile, where symbols of Table 3-4 are explained. The roughness measures are specified over a specified length, as shown in Figure 3-4, which for the AREVA tests is 4 mm (0.157 in.).

Table 3-4 Measures for Roughness

Parameter	Description	Relation
R_a	Arithmetic average of absolute values	$R_a = \frac{1}{n}\sum_{i=1}^{n} \lvert y_i \rvert$
R_q	Root mean squared (rms)	$R_q = \sqrt{\frac{1}{n}\sum_{i=1}^{n} y_i^2}$
R_v	Minimum valley depth	min y_i
R_p	Maximum peak depth	max y_i
R_t	Maximum height of the profile	$R_t = R_p - R_v$

Figure 3-4 Roughness Profile

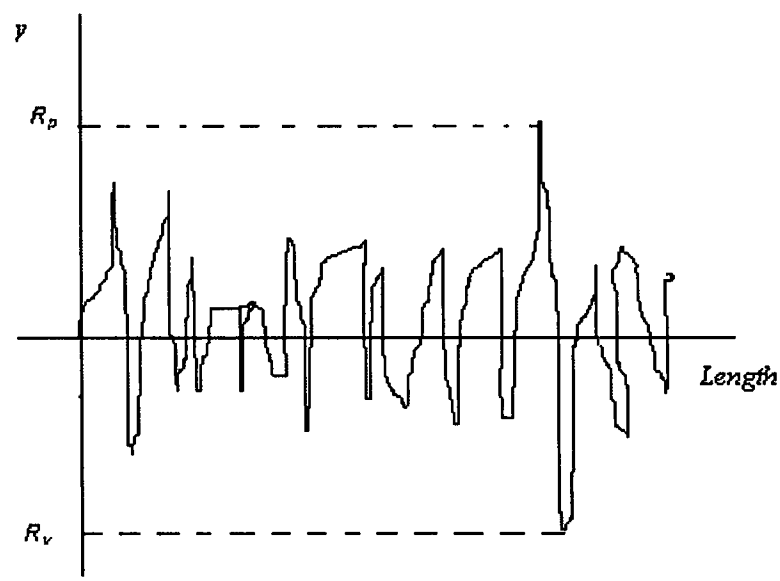


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Table 3-5 Relation of R_a and R_q with R_t for Examined Specimens

[ ]

The machining operation, as described previously, induces a superficial hardened layer, which is not totally removed by the polishing process. The material removal because of polishing does not generally exceed 30 µm in depth. A hardened layer of approximately 100 to 150 µm depth is kept at the surface of the polished specimens. The same thickness of hardened layer can be observed at the surface of ground specimens.

Table 3-6 presents the upper limit of permissible roughness (surface finish) in micrometers for representative components and piping. It also provides the roughness of specimens listed in NUREG/CR-6909, which is expressed in R_a. Equation 11 was used to obtain the listed R_t value in Table 3-6.

Table 3-6 Roughness for Representative Components and Piping

Component	R_t (micro-meters)
NUREG/CR-6909 tested specimens	9.7
Pressurizer	[ ]
Piping internal surfaces	[ ]
RPV internal	[ ]
SG internal	[ ]

Figure 3-5 presents a graph of roughness versus the cycles to failure, N_{25}, for all the AREVA tests in a controlled PWR-simulated environment. Analytical values of roughness for each specimen are shown in Table 3-11.

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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.

Figure 3-6 Specimen and Equipment for AREVA In-Air Fatigue Testing

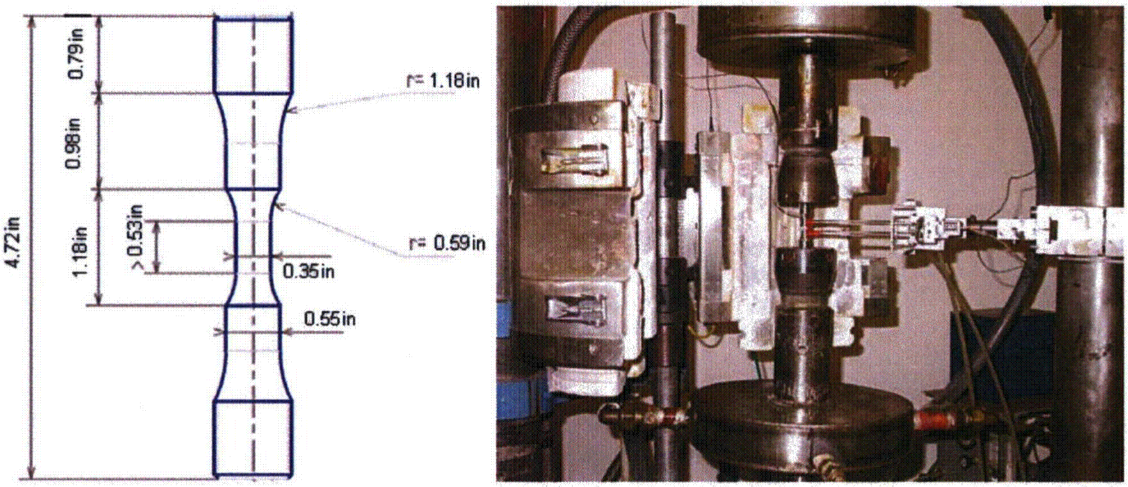


Table 3-7 gives information about the in-air tests performed at room temperature and Table 3-8 those performed at 572°F (300°C). Twelve tests were performed totally in in-air conditions. From them, five were polished and tested at room temperature; three were polished and tested at 572°F (300°C); and four were ground and tested at 572°F (300°C). Figure 3-7 plots the in-air tests listed in Table 3-7 and Table 3-8 along with the in-air design and mean curves given in NUREG/CR-6909. The test data is around and close to the mean curve for the material 304L SS.

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

Table 3-8 In-Air AREVA Tests at 572°F

Figure 3-7 AREVA In-Air Tests

3.2.2.2 In-PWR Tests

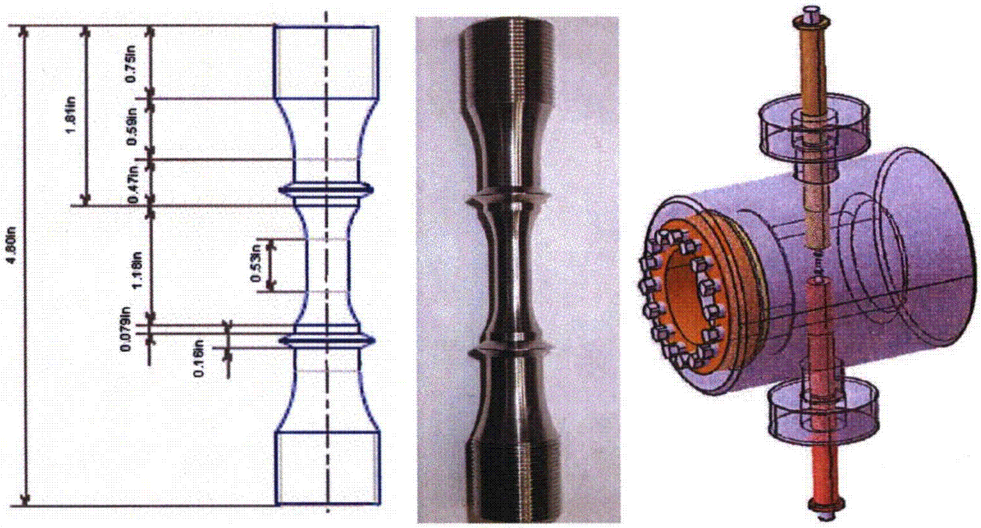
Section 3.3 provides a sample of available information for a test performed in a controlled PWR-simulated environment. Similar information is available for all the performed tests including those performed in air. Figure 3-8 and Figure 3-9 present the specimen geometry, the autoclave, and the experimental configuration for the tests in a controlled PWR-simulated environment.

The following loading and chemical parameters were controlled during the LCF tests performed under strain control in PWR conditions:

- Loading conditions: triangular or complex signals.
- Temperature: 572°F (300°C).
- Pressure: 140 bars.

- Dissolved oxygen content: lower than 0.01 ppm.
- Cl and F concentration: lower than 0.05 ppm.
- Hydrogen concentration: 25 - 35 cc (STP)/kg of PWR water.
- B concentration: nearly 1000 ppm (adjusted by boric acid additions).
- Li concentration: quantity needed for adjustment of pH (nearly 2 ppm).
- Conductivity: between 2 and 40 μS/cm.

Figure 3-8 AREVA Specimen and Autoclave for In-PWR Environment Fatigue Testing



Attention is given to the preparation of the autoclave. Before testing, the autoclave is closed and rinsed for one hour; the conductivity of the rinse water is controlled to verify the non-pollution of the autoclave. A hydrostatic test is performed with water at 145 bars for 2 hours to verify that there was no loss of pressure. The water is drained after tightness of the autoclave is confirmed.

The applied strain amplitude is controlled on the shoulders of the specimen, using a linear variable differential transformer/RDP Electronics Ltd (LVDT/RDP) extensometer sensor and is evaluated on the basis of an equivalent length of 23.5 mm (0.925 in.) at room temperature. The shoulders' displacement during the test is equal to 140 μm = 23.5 mm x 0.6 percent for signals of strain amplitude 0.6 percent, applied on the useful calibrated zone of LCF test specimens. On the calibrated zone of the specimen, a MTS extensometer is fixed.

Table 3-9 presents the tests performed in-PWR conditions, providing information about the applied strain amplitude, strain rate, roughness R_t, and cycles N_{25}.

Figure 3-9 General Configuration of In-PWR Conditions for AREVA Tests

Table 3-9 AREVA In-PWR Environment Tests

[ ]

3.2.3 Strain Amplitude

[ ]

Figure 3-10 AREVA In-PWR Tests

Figure 3-11 Strain Amplitude Versus Cycles to Failure for AREVA In-PWR Tests

[ ]

3.2.4 Strain Rate

AREVA tests for the triangular loading and polished specimens included values of strain rate of 0.01, 0.1, and 0.4 percent; for ground specimens, only the value of 0.01 percent/s was used. For complex loading A, B, C, and D, the strain rate is variable and evaluated in Section 4.4.

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

Strain rate for 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.

Figure 3-13 Strain Rate Versus Cycles to Failure for AREVA Ground Specimens

[ ]

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 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 3-14 Strain Amplitude Variation on the Inner Surface of the SIS Nozzle

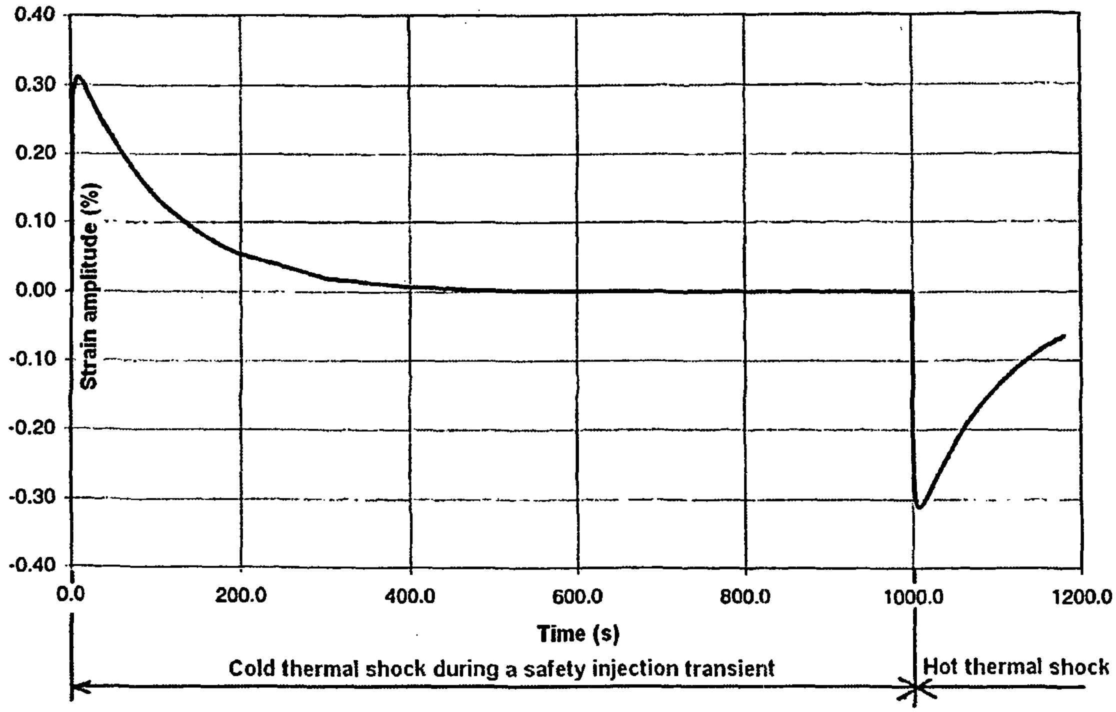


Figure 3-15 Loading Signal A with Strain Amplitude 0.3 percent

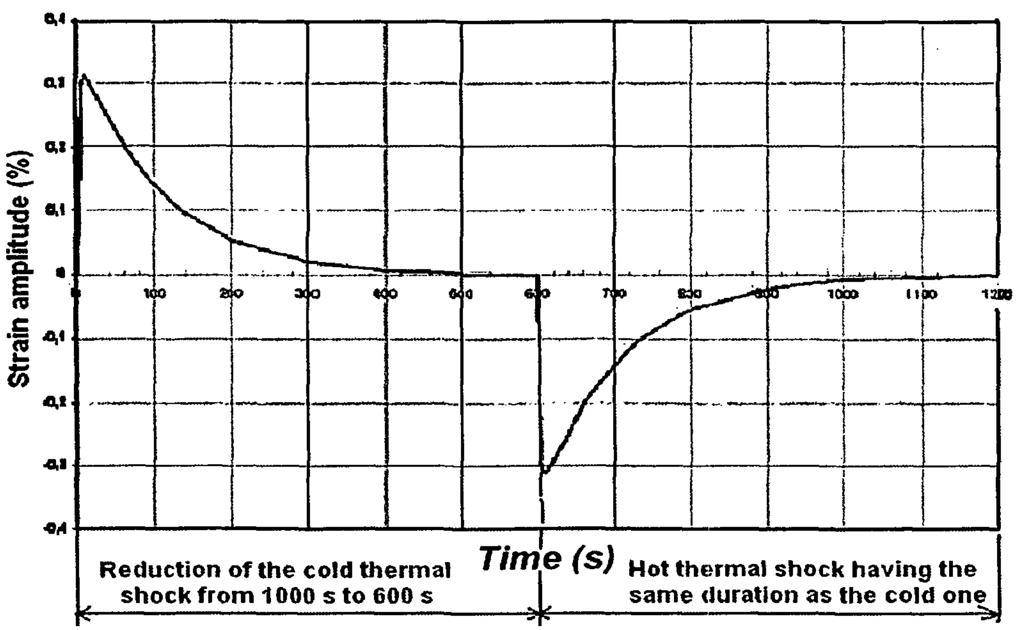


Figure 3-16 Short Loading Signal A for AREVA Tests

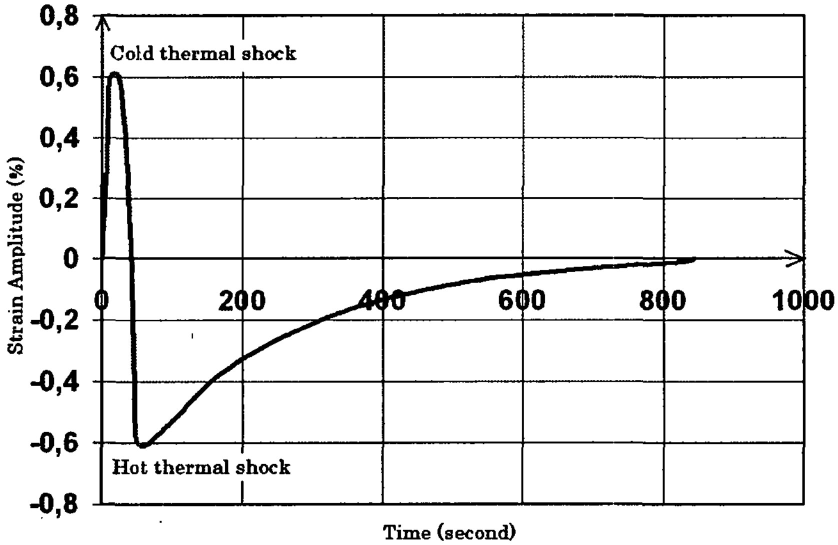
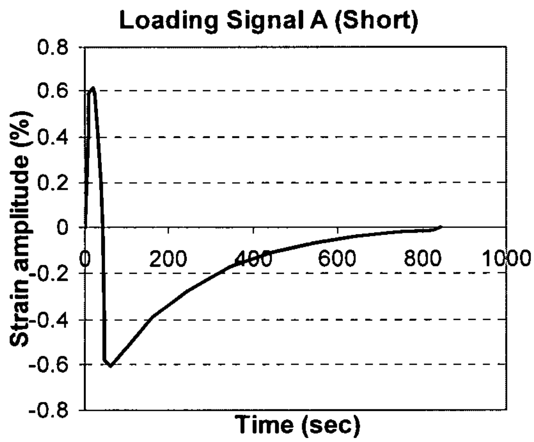
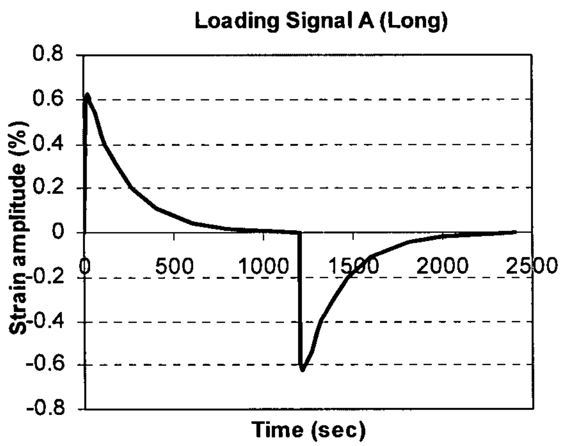
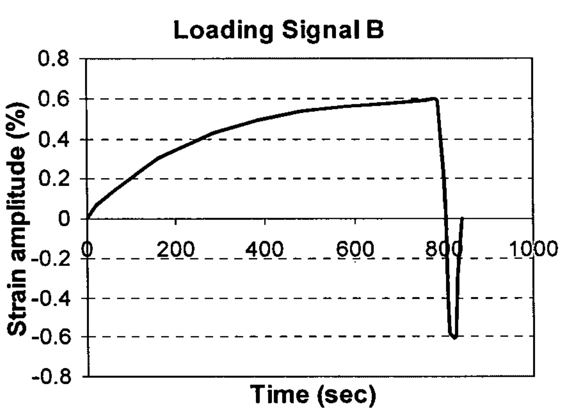
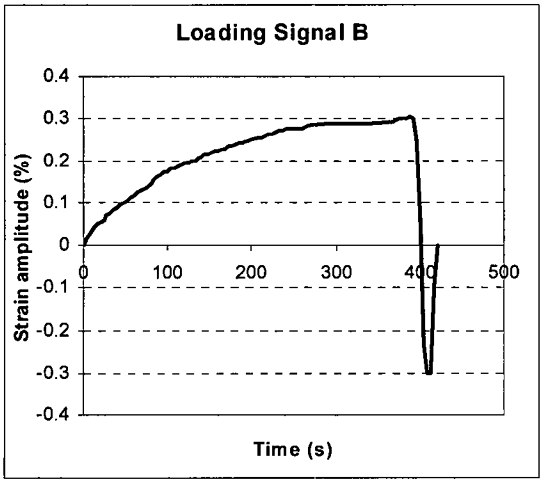
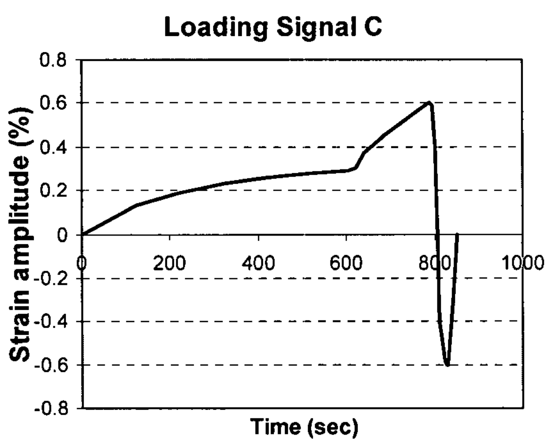
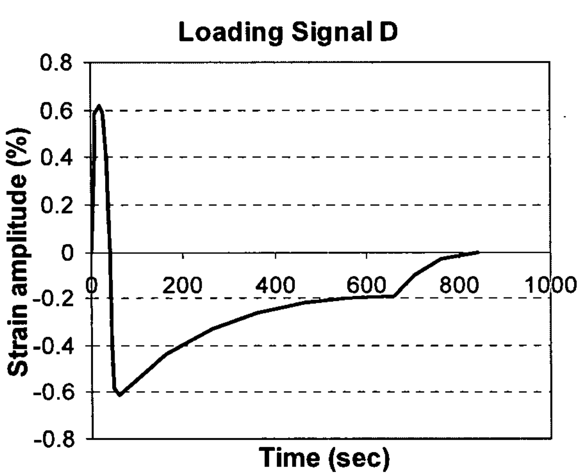
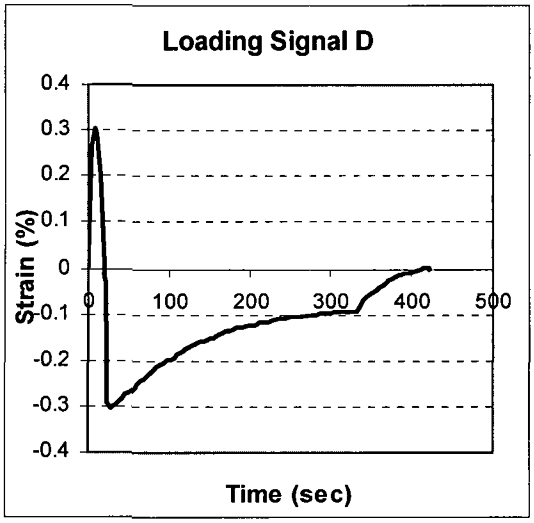


Table 3-10 Loading Signals Used for AREVA Tests

Complex Signal		Tested Specimens	
		Polished	Ground
	A Short (840s)	5	7
	A Long (2400s)	1	0
	B Short (840s)	2	2

Complex Signal		Tested Specimens	
		Polished	Ground
	B Short (420s)	1	0
	C Short (840s)	2	0
	D Short (840s)	2	2

Complex Signal		Tested Specimens	
		Polished	Ground
	D Short (420s)	1	0

3.3 *Test Sheets*

An example of test output recordings is shown in Figure 3-17 and Figure 3-18 for specimen 471QS1B. Figure 3-17 shows the stress deformation loops recorded during the test after 1 and 507 cycles, which is close to the mid-life of the LCF test specimen. Figure 3-18 presents the evolution of the maximum and minimum stress versus cycles during the test, and the determination of number of cycles N_{25}. Table 3-11 provides additional information about the measured quantities during the test. Words in parentheses correspond to the French words used in the figures.

Table 3-11 Provided Information for Tests in a Controlled PWR-Simulated Environment

Sample name (repère)
Diameter (diamètre) (mm)
Frequency (fréquence) (Hz)
Test temperature (température) (°C)
Strain amplitude control (pilotage) (percent)
Roughness (rugosité)(µm)
Name of machine used to perform the experiment (machine)
Total strain amplitude, $\Delta\varepsilon_t/2$ (percent)
Plastic strain amplitude, $\Delta\varepsilon_p/2$ (percent)
Elastic strain amplitude, $\Delta\varepsilon_e/2$ (percent)
Minimum stress, σ_{min} (MPa)
Maximum stress, σ_{max} (MPa)
Stress amplitude, $\Delta\sigma/2$ (MPa)
Fatigue life, cycles at 25% maximum load drop, N_{25}
Total fatigue life, cycles at rupture, N_r
A graph of stress versus deformation for the first cycle
A graph of stress versus deformation at half life
A graph of resistance versus cycles with N in a normal scale
A graph of resistance versus cycles with N in a lognormal scale
Stress amplitude for the first quarter of cycle, σ_{ao} (MPa)
Strain amplitude for the first quarter of cycle, ε_{pao} (percent)
Stress - Deformation graphs (Contrainte – Déformation)
Variation of minimum and maximum stresses, as a function of number of cycles (variation de la constrainte maximale et minimale en fonction du nombre de cycles)

Figure 3-17 Measurement of Elastic and Plastic Strain and Stresses

Figure 3-18 Definition of Cycles to Failure N_{25}

4.0 ANL FATIGUE TESTS AND COMPARISON WITH AREVA TESTS

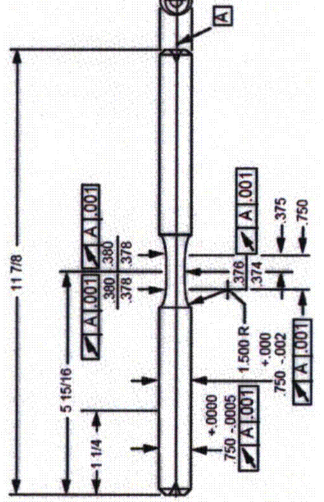
4.1 *Material and Devices Used for Testing*

ANL fatigue tests were conducted on austenitic steel Types 316NG, 316, and 304SS and two heats of CF-8M cast SS having the chemical composition (wt %) shown in Table 4-1 for in-air and in-LWR testing. Composition of the AREVA used material is presented in Table 3-2. Figure 4-1 shows a specimen's dimensions and testing device. Figure 4-2 presents a schematic diagram of the used autoclave for the tests in a LWR environment. ANL specimens are longer in comparison to those used for AREVA's testing. According to NUREG/CR-6909, geometry of the specimens does not play a significant role for temperatures up to 400°C.

Table 4-1 ANL Steel Chemical Composition

Material	Heat	Source	C	P	S	Si	Cr	Ni	Mn	Mo	Cu	N
TP316NG	D432804	Vendor	0.011	0.020	0.001	0.52	17.55	13.00	1.76	2.49	0.10	0.108
		ANL	0.013	0.020	0.002	0.49	17.54	13.69	1.69	2.45	0.10	0.105
TP304	30956	Vendor	0.060	0.019	0.007	0.48	18.99	8.00	1.54	0.44	-	0.100
CF-8M	74	ANL	0.064	-	-	0.73	19.11	9.03	0.54	2.51	-	0.048
CF-8M	75	ANL	0.065	-	-	0.67	20.86	9.12	0.53	2.58	-	0.052

Figure 4-1 ANL Specimen and Testing Device[8]



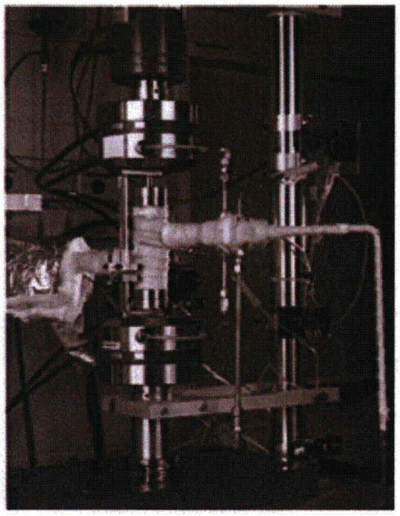
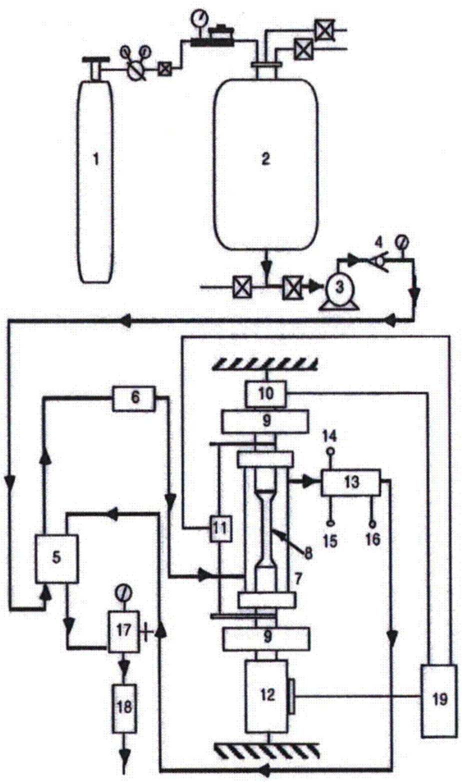


Figure 4-2 Schematic Diagram of Autoclave System for ANL Fatigue Tests[8]



1. Cover-gas supply tank
2. Water supply tank
3. Pulsafeeder high-pressure pump
4. Check valve
5. Heat exchanger
6. Preheat exchanger
7. Pipe autoclave
8. Fatigue test specimen
9. MTS hydraulic collet grips
10. MTS load cell
11. Displacement LVDT
12. MTS hydraulic actuator
13. ECP cell
14. Platinum electrode
15. Specimen electrode
16. Reference electrode
17. Mity Mite™ back-pressure regulator
18. Orbisphere dissolved-oxygen meter
19. MTS electrohydraulic controls

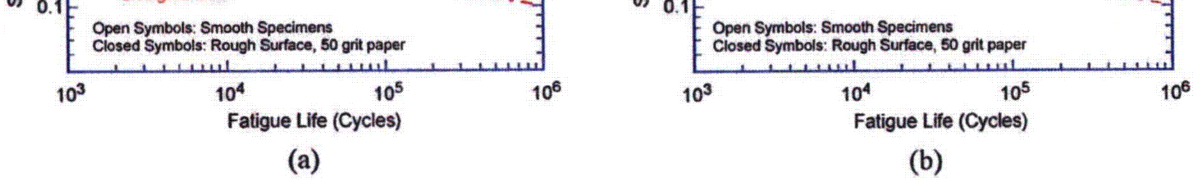
4.2 *Roughness*

AREVA performed several tests with ground specimens primarily in the range of strain amplitude, 0.4 percent to 0.59 percent.

In NUREG/CR-6909, steel Types 304 and 316NG SS were tested and the specimens were ground in a lathe under controlled conditions with 50-grit sandpaper to produce circumferential cracks with an average roughness of 1.2 μm. Results are shown in Figure 4-3a and Figure 4-3b for steel 316NG SS and Type 304, respectively.

The vast majority of data in Figure 4-3 refer only to polished specimens (open symbols). The significant reduction on fatigue life because of roughness is not justified through experimental work.

Figure 4-3 Effect of Surface Finish on Fatigue Life[2]



According to Maiya, et. al. (References 6 and 7), the effect of surface finish primarily impacts the cycles for the initiation of the crack, N_o and not the cycles for its propagation, N_p. The fatigue life, N_f, can be expressed as:

$$N_f = N_o + N_p \qquad \text{Equation 13}$$

where,

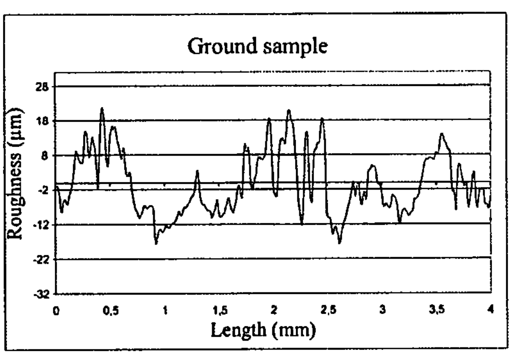
$$N_o = 1012\,(R_q)^{-0.21} \qquad \text{Equation 14}$$

In Equation 14, R_q is the root mean squared roughness as specified in Section 3.2.1.

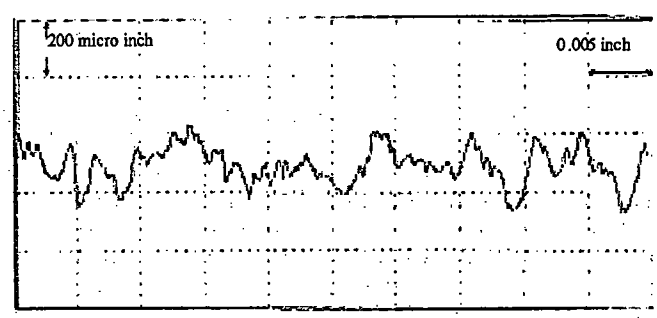
The conclusion of the Maiya, et. al study suggests that at larger strains the effect of roughness is more significant than at lower strains. Nevertheless, this conclusion is not verified by the AREVA tests.

Figure 4-4a shows a representative roughness profile for the AREVA tests and Figure 4-4b for the ANL tests. The units in the figures are different, but the following conversion may be used to compare them: 10μm (micro-meter) ≈ 393.7μin (micro-inch).

Figure 4-4 Representative Specimen's Roughness Profiles (a) AREVA (b) ANL[8]



(a)



(b)

Figure 4-5 shows an in-air testing data comparison between AREVA experimental data and ANL data as these are reported in References 7 and 8.

Figure 4-5 In-Air Testing Data for Ground Specimens

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Figure 4-6 In-PWR Testing Data for Ground Specimens

NUREG/CR-6815 (Reference 8) correlates the surface finish with the level of DO. More specifically, for Types 316NG and 304 SS, the fatigue life of ground specimens is lower than that of the smooth specimens in air and low–DO water environments. In high–DO water, the fatigue life is the same for rough and smooth specimens. In AREVA PWR testing configuration, the level of DO was relatively low, typically $\approx$ 0.005 ppm; therefore, a severe case was examined for the influence of roughness on the fatigue life of specimens in LWR environment.

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4.3 *Medium*

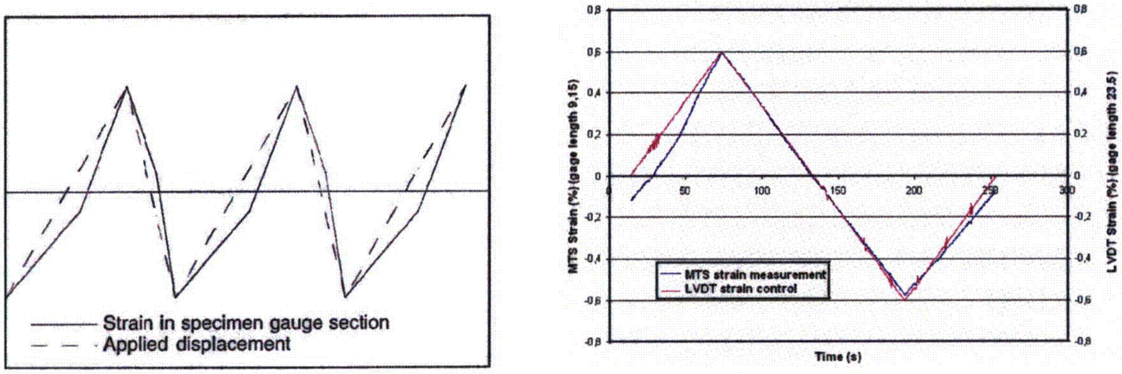
Figure 4-7 compares available test data in a simulated PWR environment from other studies (Reference 9). Most of the performed AREVA tests are in the range of strain amplitude from 0.45 percent to 0.59 percent.

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.

Figure 4-8 Triangular signals used a) ANL and b) AREVA



(a) (b)

Table 4-2 gives evaluated values of the F_{en} factor. More specifically, the modified strain approach of Section 3.2 was used for the evaluation of F_{en} for complex loading signals A, B, C, and D. Equation 3 was used for the evaluation of the F_{en} factor for the triangular fully reversed signals. Maximum and minimum values for the complex loading signals shown in Table 4-2 are values of the strain rate evaluated at a specific time interval.

As Table 4-2 shows, the evaluated NUREG/CR-6909 F_{en} factor is ≈6 for all complex loading signals A, B, C, and D. AREVA's experimental work, nevertheless, showed that an experimental F_{en} factor, $F^{exp}{}_{en}$, can be evaluated using Equation 15. [

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$$F^{\exp}{}_{en} = \frac{N}{N_{25}}$$ Equation 15

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.

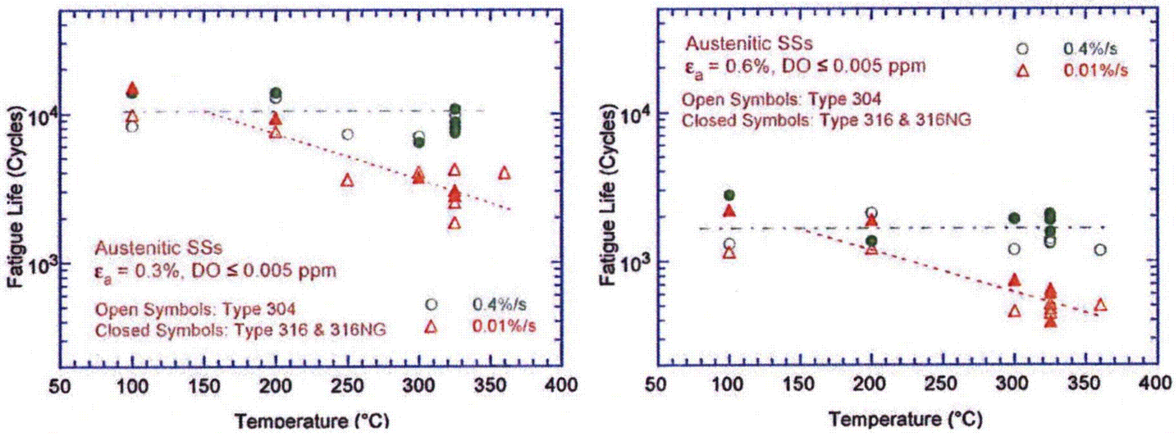
2) The modified rate approach in NUREG/CR-6909 was used for this evaluation.

Table 4-3 Experimental F_{en} Factor for A, B, C, and D Loading Signals

4.5 *Temperature*

All of the AREVA tests were performed in constant water temperature, 572°F (300°C). This temperature is in the upper range of operation temperatures for the U.S. components operating in PWR plants. Figure 4-9 presents the effects of temperature for different types of SS and values of strain rate and strain amplitude, as given in NUREG/CR-6909. The selection of 300°C as a testing temperature for the AREVA tests is reasonable and does not limit the conclusions about the possibility of reduction of the F_{en} factor. The temperature of 300°C typically exceeds the average temperature in a transient or a combination of them for representative PWR components.

Figure 4-9 Effect of Temperature in LWR Conditions [2]



4.6 *Strain Amplitude*

A summary of data on polished specimens considered in NUREG/CR- 6909 is shown in Table 4-4, demonstrating the used strain amplitude. Tests were applied in a wide range of strain amplitude. The majority of the AREVA tests are performed in strain amplitude ranges higher than 0.4 percent. [

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Table 4-4 Literature Data for Stainless Steel in PWR Conditions and Polished Specimens

Steel	Specimen	Strain rate tension (%/s)	Strain range (%)	Strain amplitude (%)	N_{25}
ANL TP 316	1796	0.5	0.8	0.4	12500
	1812	0.05	0.8	0.4	6375
	1791	0.005	0.77	0.385	3040
	1793	0.005	0.8	0.4	3020
	1794	0.005	0.5	0.25	7370
	1814	0.05	0.29	0.145	33200
ANL TP 304	1806	0.4	0.73	0.365	11500
	1810	0.04	0.77	0.385	5800
	1808	0.004	0.77	0.385	2850
	1821	0.004	0.76	0.38	2420
	1829	0.0004	0.73	0.365	1560
	1834	0.00009	0.69	0.345	1415
	1807	0.4	0.51	0.255	25900
	1823	0.004	0.51	0.255	6900
	1826	0.01	0.29	0.145	89860
	1847	0.01	0.32	0.16	165300
CF-8M	1850	0.004	0.76	0.38	10700
	1854	0.04	0.75	0.375	4720
	1851	0.4	0.75	0.375	6420
	1844	0.004	0.72	0.36	2180
	1843	0.004	0.8	0.4	1464
ANL High DO TP 304	1852	0.4	0.74	0.37	10800
	1827	0.004	0.75	0.375	3650
	1845	0.0004	0.71	0.355	7310
CF-8M High DO	1842	0.004	0.75	0.375	1375
	1838	0.004	0.78	0.39	1320
ANL High DO TP316	1426	0.8	0.8	0.4	12069
	1427	0.082	0.82	0.41	6679
	1428	0.0074	0.74	0.37	5897
	1797	0.005	0.78	0.39	4520
	1414	0.5	0.5	0.25	26230
	1418	0.5	0.5	0.25	25714

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.

5.0 CALCULATIONS

Table 5-1 summarizes information for the performed experimental LCF tests (e.g., the strain amplitude, ε_a, the strain rate, the roughness R_t, the cycles N_{25}, and the in-air design fatigue cycles, N_{RTair}). Evaluated parameters (e.g., d and RF factors) evaluated using Equation 5c and Equation 10, respectively, are presented. Table 5-2 classifies the results for the RF with respect to the strain amplitude. Figure 5-1 additionally provides a graph of the RF factor versus the strain amplitude for the different statuses of specimens listed in Table 5-1.

Table 5-1 AREVA Tests in PWR Environment

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

Figure 5-1 Reduction Factor for AREVA tests

6.0 APPLICATION

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Table 6-1 Suggested Values for the RF Factor

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Figure 6-1 Flow-chart of Fatigue Evaluation for Stainless Steel Type 304L

7.0 CONCLUSIONS

AREVA performed environmentally assisted fatigue testing on thirty 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.

8.0 REFERENCES

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