AREVA

Response to Second NRC Request for Additional Information

ANP-10326Q2NP
Revision 0

ANP-10326NP, Revision 1, Environmentally Assisted Fatigue: Modified Effective Correction Factor for Austenitic Stainless Steels

May 2015

AREVA Inc.

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Nomenclature

Acronym	Definition
TR	Topical Report
SS	Stainless Steel
RF	Reduction Factor
SEM	Scanning Electron Microscopy
Rt	Measure of roughness
ε_a	Strain Amplitude
LCF	Low Cycle Fatigue
AFNOR	French National Organization for Standardization
ASTM	American Society for Testing and Materials
LVDT	Linear Variable Differential Transformer
MTS	Materials Testing System
NDE	Non Destructive Examination
PWR	Pressurized Water Reactor

QUESTION 1

Section 3.0 of ANP-10326P, Revision 1 briefly describes AREVA's experimental testing. Provide the following additional information:

a. Summarize the air and water test procedures used and identify if any standardized test procedures (i.e., ASTM) were utilized.

b. Page 3-17 describes the procedures used to control the applied strain amplitude. Describe the types, location, and orientation of the strain gages used and how the strain amplitude was recorded and verified.

RESPONSE 1

a. A standardized test procedure was followed for both the in-air and in-PWR environment fatigue tests. The French standard AFNOR A03-403 (Reference 1) was used. AFNOR A03-403 is derived from ASTM E606-80 (Reference 2), which is also included in the references.

By comparing the French standard AFNOR A03-403 with the latest ASTM standard, E606/E606M-12 (Reference 3), the following can be deduced:

- The testing methodology and apparatus description sections of the French and U.S. standards, which provide details of the testing machine, strain control, fixtures, extensometers, force transducers, X-Y recording, cycle counter, calibration, and strain computer are very similar.

- The sections that provide details concerning the specimen design, manufacturing, and test procedure are very similar.

- For the sections that describe the analysis of data and, more specifically, the determination of the cyclic stress strain curve, the strain - life relationship, and the report, the French standard gives more details on how the results should be presented.

Reference to the French standard AFNOR A03-403 was added in the TR. See the enclosed mark-up.

b. The AREVA Low Cycle Fatigue (LCF) tests in the PWR environment were performed under axial displacement control by using a Linear Variable Differential Transformer (LVDT) extensometer attached to flanges machined on specimen shoulders. The LVDT extensometer is located inside the autoclave, as Figure 1-1 shows. As an example, for the application of +/-0.6% strain amplitude a displacement of +/- 140µm between the flanges is imposed. A standardized MTS automated system (software and program) is used to control the LVDT and thus to impose and record the displacement.

Calibrations of the displacement to be applied on the AREVA specimen shoulders in the PWR environment were performed in air at 20°C or at 300°C under strain control, using two axial extensometers. The first extensometer was located on the specimen gage, while the second was attached on the specimen shoulders. Figure 1-2 shows the AREVA devices used for the calibration tests.

At the end of the tests, the evolution of strain/displacement versus time is plotted and hysteresis loops are plotted to ensure the correct run of the test.

References for Response 1:

1. French Standard AFNOR A03-403, 1990, "Produits métalliques des essais de fatigue oligocyclique" (LCF testing for metallic products), www.afnor.org.

2. ASTM Designation: E606-80, 1980, "Standard Recommended Practice for Constant-Amplitude Low Cycle Fatigue Testing."

3. ASTM Designation: E06/E606M-12, 2012 "Standard Test Method for Strain-Controlled Fatigue Testing."

Figure 1-1 AREVA autoclave system for fatigue tests in water

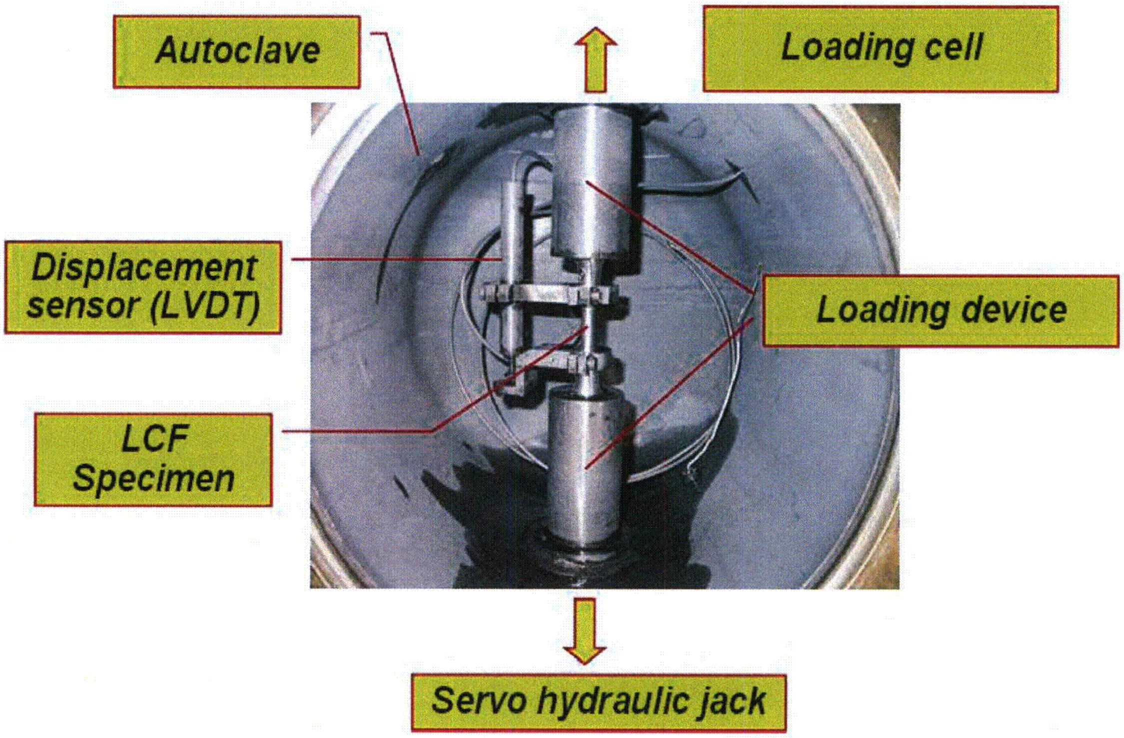
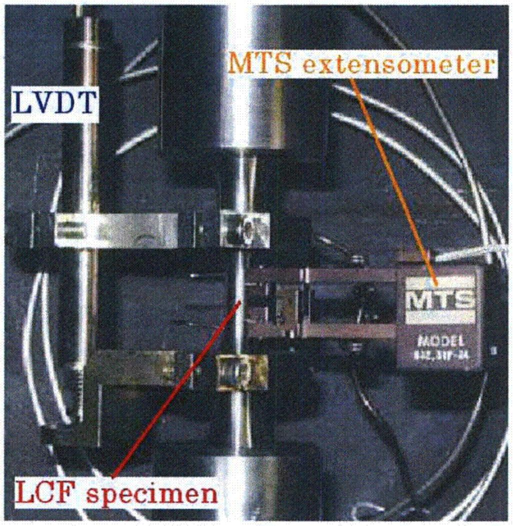
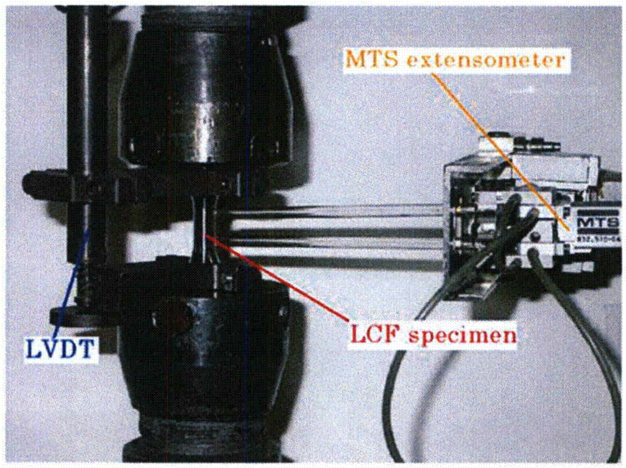


Figure 1-2 Devices for strain-displacement correlations at 20°C and 300°C





AREVA device for calibration tests at 20°C	**AREVA device for calibration tests at 300°C**

QUESTION 2

The last sentence on page 3-1 of ANP-10326P, Revision 1, states "This number of cycles typically produces an approximately 3mm-deep crack in the test specimen." The staff is concerned that strain data from these specimens may be inaccurate if cracks developed on the opposite side of the specimen from the strain gage. Describe how this potential situation was addressed, if applicable, and justify any use of data from such specimens, including pictures from representative cracks as appropriate.

RESPONSE 2

The reported in ANP-10326P, Revision 1 cycles to failure, N_{25}, correspond to cycles for the tensile stress, σ_{max}, to decrease to 25% from its peak or steady-state value, as a result of the propagation of the main fatigue crack. Usually, this number of cycles produces in the test specimen approximately a 3 mm deep crack. Figures 2-1 and 2-2 are an excerpt from Reference 1, where X = 25% and r = 25. The first figure addresses materials with a stable behavior or with a stabilized behavior after hardening. Figure 2-2 shows a material with a continuous softening behavior.

During the Low Cycle Fatigue (LCF) tests, numerous secondary cracks initiate and grow in the whole specimen gage surface until the creation of the main fatigue crack that finally leads the specimen to failure. The initiation and growth of multiple secondary cracks is expected and does not affect the strain amplitude control. At the end of the specimen's fatigue life the damage created by the main fatigue crack is visible and detectable on the Cyclic Stress Response (CSR) curve (Stress (σ) versus Cycles (N)).

Before the launch of the main testing campaign, AREVA studied in detail the crack initiation and propagation with experiments in air and in PWR environments, performing quantitative or qualitative Scanning Electron Microscopy (SEM) examinations. The homogeneity of damage in the specimen gage surface has been verified thanks to numerous SEM examinations. [

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Examples of a main crack and secondary cracks, observed by Scanning Electron Microscopy (SEM), are shown in Figures 2-6 and 2-7, respectively (References 2 and 3).

In agreement with the AFNOR A03-403 Standard, the AREVA LCF tests were only considered valid after post-mortem examinations, which included, as a minimum, a very careful visual examination of the main fatigue crack. In several cases, an optical or electronic microscopy was used to examine the main crack validity. For all cases it was assured that the main fatigue crack was contained in the specimen gage and was "natural", meaning that it was not affected by any specimen or testing device defects or malfunctions (e.g., surface scratches, porosities, inclusions or notches let by the extensometer knives, specimen deformation caused by a misalignment of the loading device, etc.).

References for Response 2:

1. French Standard AFNOR A03-403, 1990, "Produits métalliques des essais de fatigue oligocyclique" (LCF testing for metallic products), www.afnor.org

2. De Baglion, L., Mandez, J., Le Duff, J.A., Lefrancois, A., ASME PVP2012-78767 2012, “Influence of PWR primary water on LCF behavior of type 304L austenitic stainless steel at 300°C-Comparison with results obtained in vacuum or in air,” Toronto, Ontario Canada.

3. L. De Baglion, Ph.D. Thesis, 2011, "Low cycle fatigue behavior and damage of a type 304L austenitic stainless steel in various environments (Vacuum, Air or PWR water) at 300 degrees Celsius, http://tel.archives-ouvertes.fr/tel-00623190/fr/, Institut P.

Figure 2-1 Fatigue life for materials with a stable behavior or with a stabilized behavior after hardening

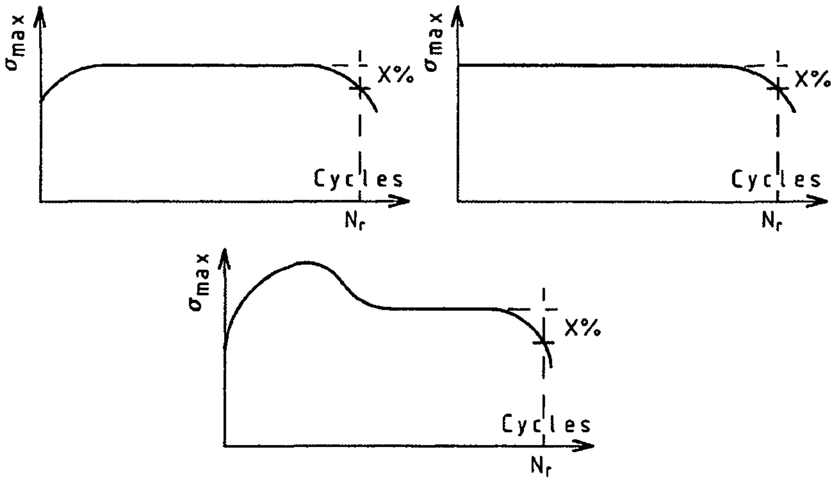

Figure 2-2 Fatigue life for materials having a continuous softening behavior

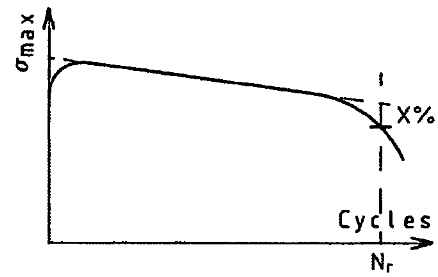

Figure 2-3 Specimen gage surface

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Figure 2-4 Specimen developed surface

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Figure 2-5 Crack number distribution for one part, depending on the angular sectors and the cracks lengths populations

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Figure 2-6 Main crack observed in the specimen gage surface after an in-PWR test (temperature = 300°C, strain amplitude = ±0.6%, strain rate = 0.01%/s)

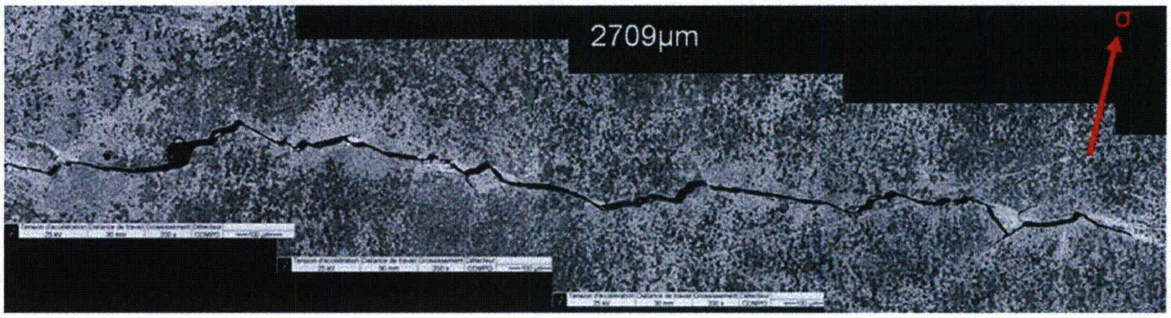

Figure 2-7 Secondary cracks observed on a failed specimen tested in PWR water (temperature = 300°C, strain amplitude = ±0.6%, strain rate = 0.01%/s)

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QUESTION 3

Table 3-3 of ANP-10326P, Revision 1 identifies [ ] specimens were tested under PWR environmental conditions. AREVA divided [ ] into four categories for [ ] e.g., refer to Figure 3-11 in ANP-10326P, Revision 1), [ ]

RESPONSE 3

AREVA's intention [

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The type of 304L austenitic stainless steel used for the AREVA experiments is a mean modern material in terms of chemical composition and mechanical properties. It is representative of grades used to build nuclear power plant components. The material demonstrates low scattering around the mean value of the fatigue life. [

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QUESTION 4

Page 3-6 of ANP-10326P, Revision 1 identifies that polished specimens used for testing had maximum surface roughness height, R_t, values in the range 0.75 micrometer (μm)≤ R_t ≤ 2.7 μm and that ground specimens had Rt values in the range 39 μm ≤ R_t ≤ 85 μm.

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RESPONSE 4

The reported upper fabrication value for the internal surface roughness of different nuclear components, in Table 3-6 of ANP-10326P, Revision 1, is appropriate. [

] This value is considered as a reasonably achievable surface condition for most manufacturing activities. Additionally, this roughness is acceptable for performance of the required Non Destructive Examination (NDE), as referenced in ASME B&PV Code, Paragraph NB-4424.2(a) (Reference 1) for welds.

However, the AREVA experiments used specimen surface roughness with Rt values in the range of 39 μm and 85 μm. [

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References for Response 4:

1. ASME B&PV Code 2013, Section III, Rules for Construction of Nuclear Facility Components, Division 1, Subsection NB, Class 1 Components.

QUESTION 5

Table 3-10 of ANP-10326P, Revision 1 shows the complex loading signals used in the AREVA tests. Page 4-9 indicates that the modified rate approach of Section 3.2 was used to evaluate the F_{en} values for the complex signals. To enable the staff to perform a confirmatory calculation using these loading signals, provide the tabular stress and temperature time histories for each of the complex loading signals.

RESPONSE 5

For complex loading signals the modified strain rate approach was used in order to evaluate the Fen values. As stated in Sections 3.2 and 4.5 of ANP-10326P, Revision 1, the PWR tests were performed at a constant temperature of 572°F (300°C). The strain time histories for the AREVA complex signals are provided in Table 5-1. Table 3-10 of ANP-10326P, Revision 1 was updated to separate the cases of short loading signal A having strain amplitude +/-0.6% and +/-0.3%. See revised Table 3-10 in the enclosed mark-up.

Table 5-1 Strain time histories for complex loading signals

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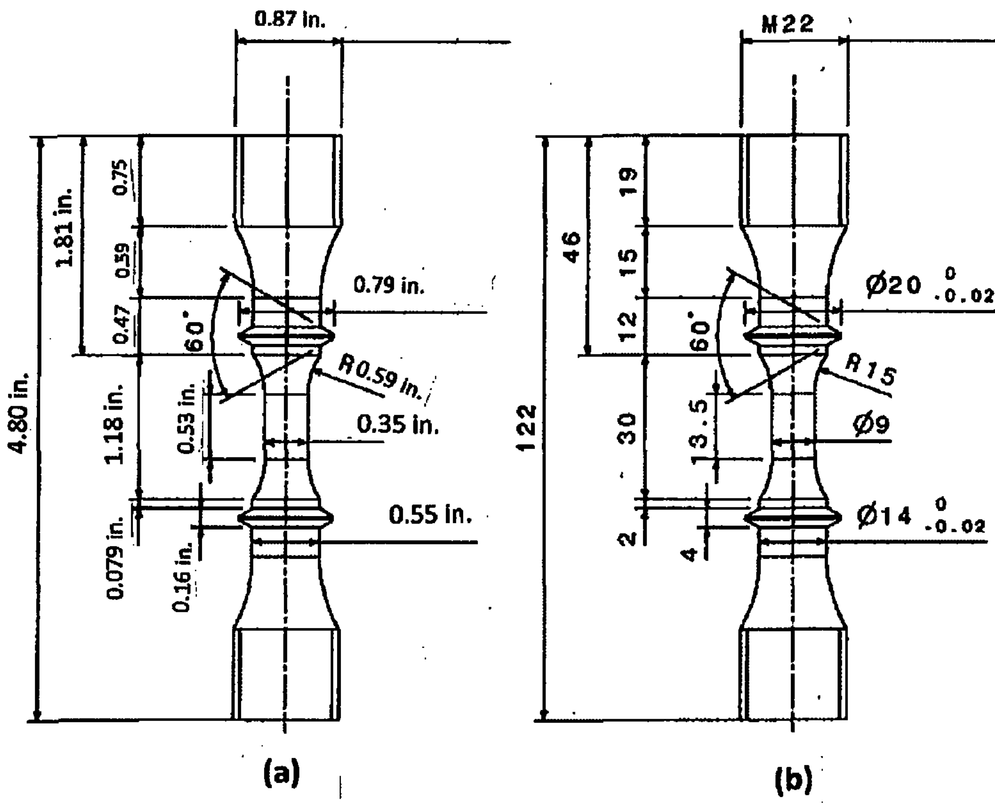
QUESTION 6

Figure 3-8 of ANP-10326P, Revision 1 shows the specimen geometry used by AREVA for the in-PWR environment fatigue tests, but does not include diameter (or wall thickness, if the specimens are hollow) as was provided in Figure 3-6 for the in-air environment. Provide a revised figure with this information.

RESPONSE 6

All of the in-PWR and in-air tested specimens are solid. The specimen gages for both the in-air and in-PWR specimens are exactly the same (13.5 mm length and 9 mm diameter) to allow for a direct comparison of the fatigue test results. Figure 6-1 provides the dimensions for the specimens tested in a PWR environment. For the revised Figure 3-8 of ANP-10326P, Revision 1, see the enclosed mark-up.

Figure 6-1 Specimen dimensions for the in-PWR environment LCF testing, (a) in inches and (b) in mm



QUESTION 7

The results of AREVA's tests for specimens in a pressurized water reactor (PWR) environment are summarized in Table 5-1 of ANP-10326P, Revision 1. [

] Verify if the staff's findings are correct [ ] and, if so, explain the impact of this error on the final report conclusions.

RESPONSE 7

The suggested Reduction Factor (RF) values in Table 6-1 of ANP-10326P Revision 1 are derived [

] do not affect the reported results and conclusions [ ] which remain correct and valid. [

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Table 7-1 AREVA Test Data

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QUESTION 8

Table 6-1 of ANP-10326P, Revision 1 identifies AREVA's suggested values [

] as shown by Equation 16 of ANP-10326P, Revision 1. [

] This range aligns well with NRC's research findings, as summarized from NUREG/CR-6909, Revision 0 in Table 2-1 of ANP-10326P, Revision 1, where it is shown that surface finish effects range from to 3.5.

[

] fall within the range of all NRC test results for 304L materials, thus indicating no apparent differences in specimen fatigue lives from AREVA's tests.

In view of the fact that AREVA's test results confirm the NRC's findings [

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RESPONSE 8

AREVA understands how the design fatigue curve for stainless steels in NUREG/CR-6909 was derived by considering independently, and within the ranges shown in Table 2-1 of ANP-10326P, Revision 1, the effects of surface finish, material variability along with data scatter, loading history, and size effect. Nevertheless, AREVA was essentially interested [

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a. [

] . Therefore, the surface finish effect was not eliminated, but instead was most properly accounted for

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b. [

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Topical Report Proposed Revision 1 Markups

Figure 3-7 AREVA In-Air Tests

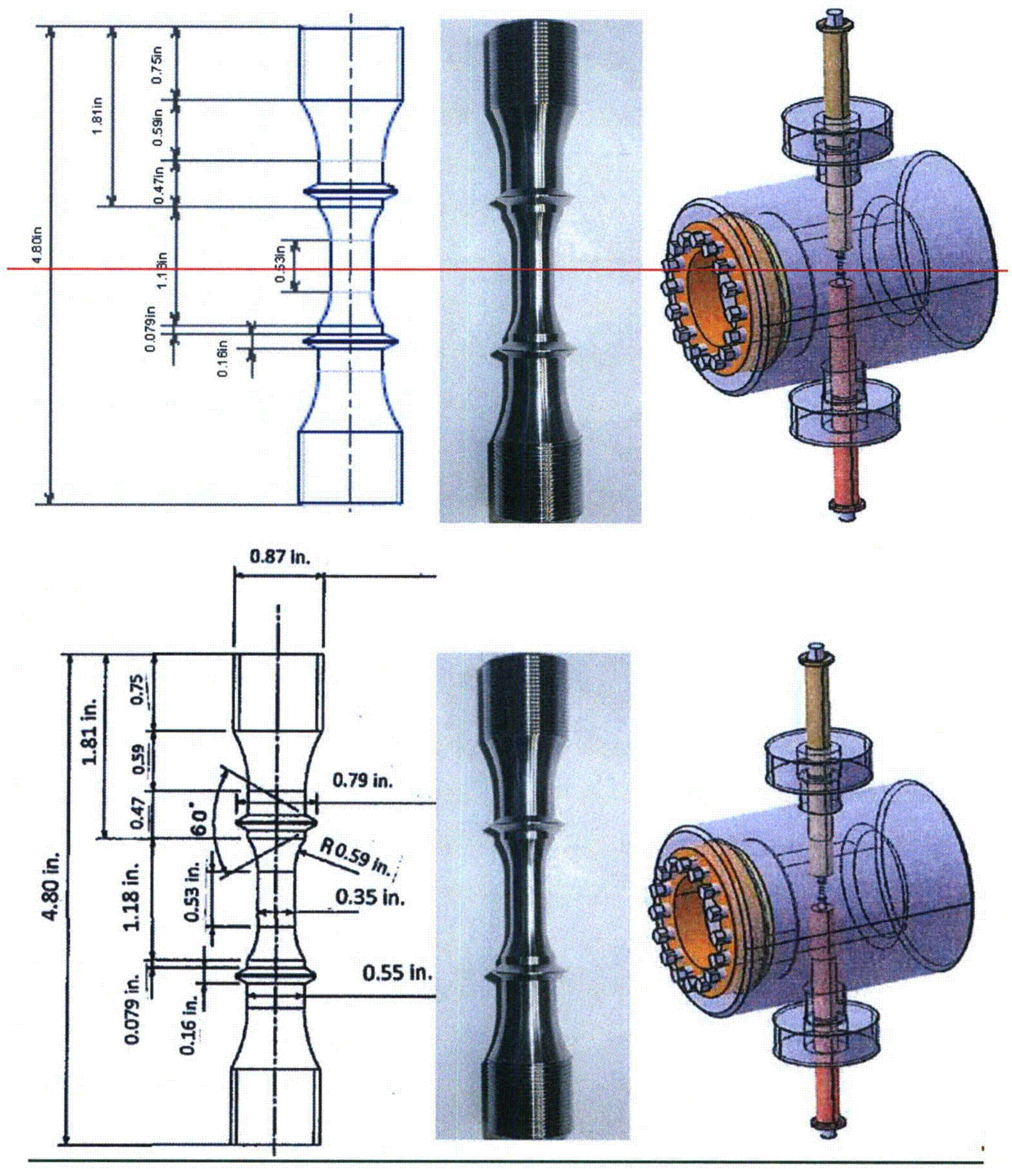
3.2.2.2 In-PWR Tests

The in-PWR tests were performed according to the French Standard AFNOR A03-403 [10]. 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:

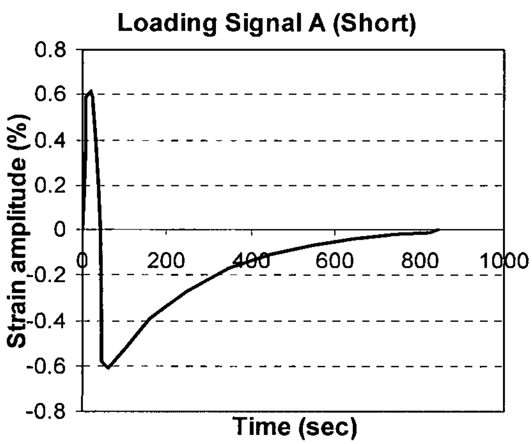
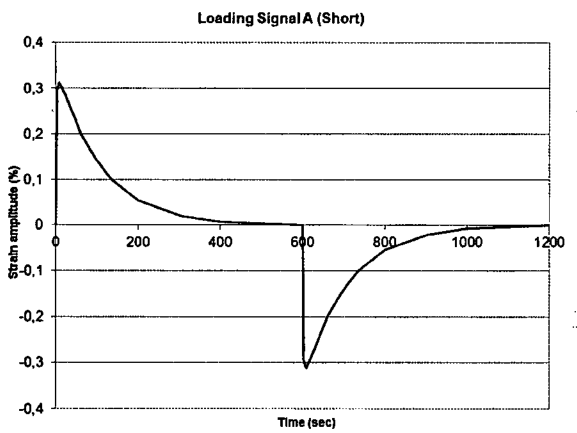
- Loading conditions: triangular or complex signals.
- Temperature: 572°F (300°C).

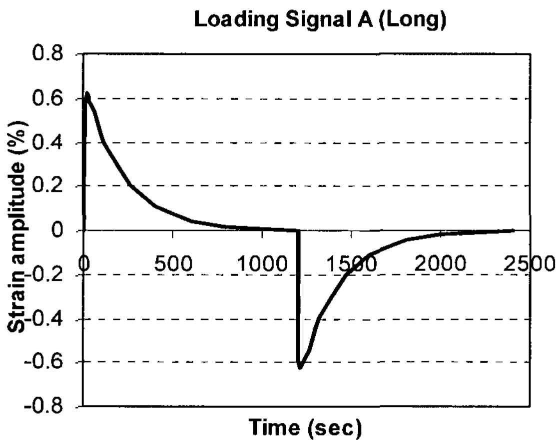
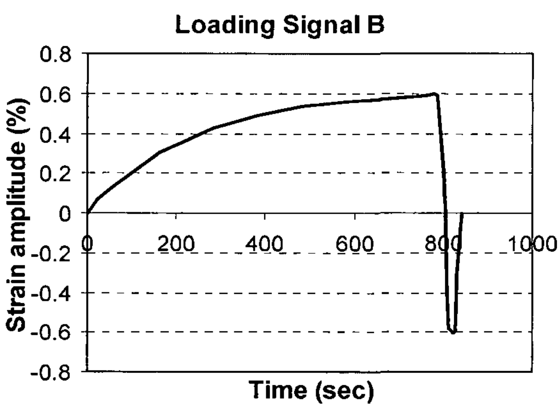
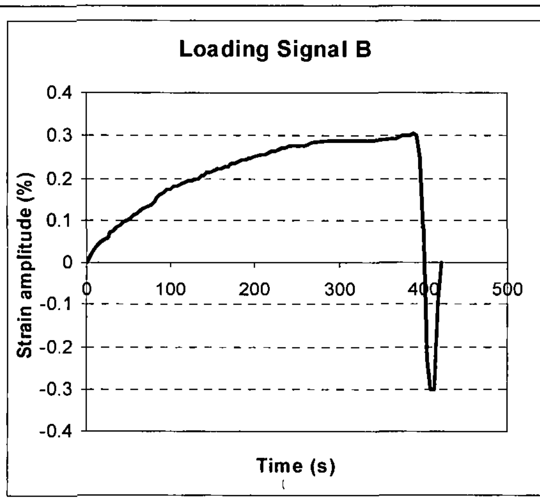
Figure 3-8 AREVA Specimen and Autoclave for In-PWR Environment Fatigue Testing

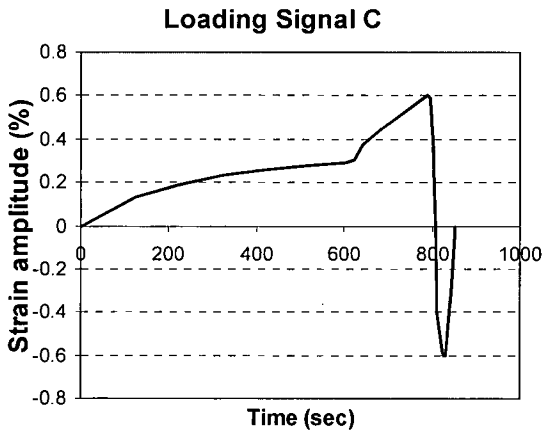
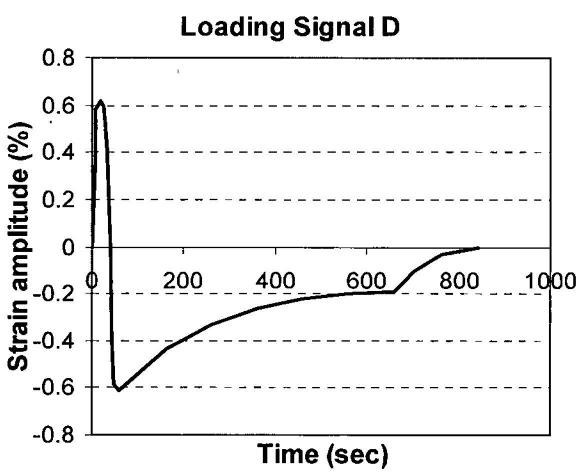


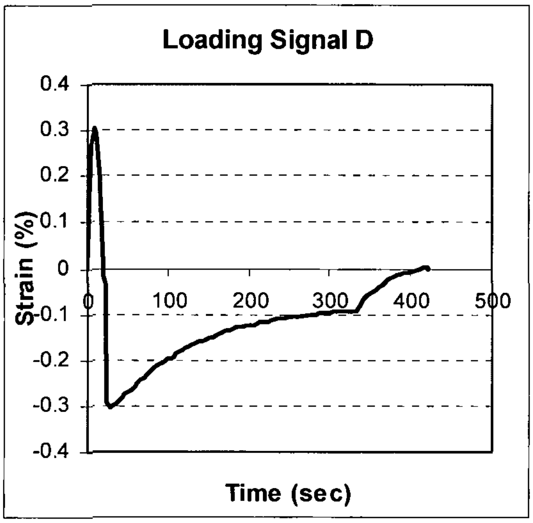
Attention is given to the preparation of the autoclave. Before testing, the autoclave is closed and rinsed for one hour; the conductivity of the rinse water is controlled to verify the non-pollution of the autoclave. A hydrostatic test is performed with water at 145 bars for 2 hours to verify that there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

Table 3-10 Loading Signals Used for AREVA Tests

Complex Signal		Tested Specimens	
		Polished	Ground
	A Short (840s)	~~5~~3	~~7~~4
	A Short (1200s)	2	3

<table>
<tr><th rowspan="2">Complex Signal</th><th></th><th colspan="2">Tested Specimens</th></tr>
<tr><th></th><th>Polished</th><th>Ground</th></tr>
<tr><td>
</td><td>A
Long
(2400s)</td><td>1</td><td>0</td></tr>
<tr><td>
</td><td>B
Short
(840s)</td><td>2</td><td>2</td></tr>
<tr><td>
</td><td>B
Short
(420s)</td><td>1</td><td>0</td></tr>
</table>

Complex Signal		Tested Specimens	
		Polished	Ground
	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 5-1 AREVA Tests in PWR Environment

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

10. French Standard AFNOR A03-403, 1990, "Produits métalliques des essais de fatigue oligocyclique" (LCF testing for metallic products), www.afnor.org