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STATUS OF FRENCH FATIGUE ANALYSIS PROCEDURE

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Abstract

During the past 15 years many works has been done on stainless steel fatigue curves :

- in many cases over 10^5 cycles the RCC-M mean curve has been found un-conservative, in a similar situation than ASME Section III curve [12],
- the fatigue data other 10^6 cycles can now be done under strain control in a reliable way (improvements in fatigue test machine)
- a large test program has been done in Japan and partially in USA.
- a limited program has been done in France.

This paper presents a new proposal for fatigue stainless steel mean curve in air (the existing ASME curve C seems to cover environmental effect on real structures) and a comparison with the NRC Regulatory Guide 1.207 [14] proposal for new curves.

In order to transfer these mean curve data to structures, different complementary tests have been developed, some under air conditions, some under environmental effects.

The paper ends with proposed code improvements in fatigue analysis rules in the RCC-M French Code.

INTRODUCTION

Thermal fatigue is widely recognized as important potential damage mechanism in cooling piping systems of electrical power plants, and in particular the Nuclear Power plants [1, 2, 3]. The significance increases as plants get older, requiring safety justifications of the initial design life or over if necessary.

The field experience confirms different types of fatigue damage: mechanical fatigue under pressure cycling, thermal fatigue damage at low (thermal shocks) and high cycle (mixing areas), crack like defects, stress concentration locations, vibration fatigue…

The consequences are a set of rules derived for Fatigue Design of components more based on crack initiation and for plant operation more based on a limited crack growth.

The practical consequences are: surveillance and monitoring, in particular the frequencies and the performance of ISI that can be clearly a very costly tasks.

Discussion in different Code Development Groups shows difficulties to transfer laboratory tests to structures; mainly due to the fact in structural fatigue analysis many more hypotheses have to be considered "conservatively" in simple rules for fatigue life prediction.

FIELD EXPERIENCE

EDF operates 58 similar PWR plants since 1977, and different degradations or leaks have been encountered along the years.

The first event appeared in 1978 when a thermal sleeve attached to a nozzle was discovered with a large break in the attached welds. The root cause has been attributed to vibration fatigue connected to crack like situation in the attached weld. In the same time, the question of thermal shock cycling of thermal sleeve attached weld has been largely studied.

All the other crack like situations have been re-evaluated, like socket weld or tube penetration in vessels.

Different leaks and deep cracks have been encountered on different plants: Reactor Heat Removal System dead-leg (1981), RHR small bore connected piping under vibration (1983), stratification in Safety Injection System (1983), leak at a pressurized valve and dead leg vortex in Safety Injection pipe (1984, 1992, 1996), thermal stripping around the Reactor Coolant Pump (1989), RCP thermal barrier cracking (1990) by high cycle and low frequency thermal fatigue loads, bolt mechanical fatigue in Control Rod Mechanism (1995) and some other cases of vibration fatigue of small bore piping.

In 1998, a major fatigue event was encountered in all the 58 plants with local degradation, few deep cracks and one through wall crack in RHR systems. The root cause was attributed to high cycle thermal fatigue in mixing tee under large temperature differences.

This quick review of field experience confirms different difficulties:

- at the design level: local thermal or vibration loads are not known, and many degradations are connected to this fact,
- some Code design rules don't clearly request detailed fatigue analysis, like some class 2 and 3 piping systems,
- monitoring of some locations are needed, but are not sufficiently reliable for high cycle thermal fatigue,
- reasonably conservative methods have to be included in the design codes, and periodic review of all the hypotheses of these design analysis have to be up-dated, in accordance with field experience and in-service inspection results,
- due to excessive conservatism, the design rules requirements have to be slightly reduced in order to make reliable residual life evaluation and ISI performance and frequencies optimisation.

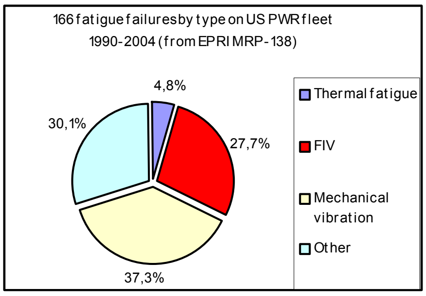

Figure 1 : **Fatigue failures on USA fleet**

This figure 1, from an EPRI study, confirms that fatigue is a safety issue only if the load is unknown or known with large uncertainties; like Flow Induced Vibrations and mechanical vibrations. Thermal fatigue seems to be well considered at the design and surveillance level and number of failures seems to be very limited.

EXPERIMENTAL AND ANALYSIS PROJECTS

The EDF fatigue program has started in the beginning of the 1980s, in collaboration with AREVA and CEA and is detailed in reference [4].

During the past 10 years we have developed a set of fatigue curves done with standard specimens and some detrimental effects are analyzed in these standard tests. In particular, for piping fatigue analysis, tests on structures are needed to derive design curves and stress indices or fatigue strength reduction factors.

Fatigue tests on standard specimens

A very large program has been developed in Japan in the past 10 years [5]. In parallel, a large number of fatigue tests have been done in EDF with different laboratories on a limited number of heats that are representative of French materials.

We performed a set of standard tests at 150°C and 300°C, with different mean stress level, with different surface finished, in air and in PWR environments (at 0.4% per second strain rate). All data collections are done with very high Quality

Assurance in the test performance and give very reliable data.

The major results are :

- the Langer mean curve used in ASME-Section III [12] and RCCM [13] is not conservative for stainless steel in air over 10^5 cycles,
- there is no difference on the fatigue curve between 304L and 316L, up to 300°C
- the PWR environment is negligible at 150°C for stainless steels; but not negligible at 300°C (for strain rate less than 0.4% /s)
- a new air mean curve is proposed by EDF using its large data bank recently developed :

$$\Delta\varepsilon/2\ \% = 32{,}093 / (N^{**}0.5) + 0.112$$

Fatigue tests on weldments

A specific program on that aspect has been finished recently. The objective is to compare fatigue resistance of non-welded, welded and grinded, and un-flushed welds under bending loads through the pipe wall. The following figures illustrate tests and results obtained.

Figure 2 : Test facility

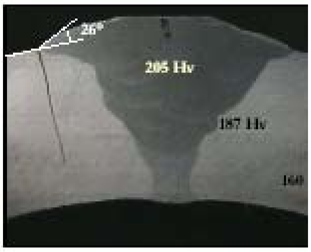

Figure 3 : Cracked specimen

Configuration d'éprouvette	*Brute*	*Référence*	B6	B1	B4	B2
		P_a *(mm)*	±0,47	±0,7	±0,8	±0,9
		ε_a *(%)*	±0,052	±0,092	±0,093	±0,095
		ε_m *(%)*	0,099	0,41	0,55	0,64
		N (cycles)	$10^6\rightarrow$	$10^6\rightarrow$	$10^6\rightarrow$	$10^6\rightarrow$
	Soudée	*Référence*	S3	S1	S4	S2
		P_a *(mm)*	±0,6	±0,8	±0,9	±1,07
		ε_a *(%)*	±0,07	±0,085	±0,094	±0,121
		ε_m *(%)*	0,081	0,099	0,128	0,38
		N (cycles)	375 000	150 000	95 000	53 000
	Soudée arasée	*Référence*	SA6	SA3	SA2	SA5
		P_a *(mm)*	±0,63	±0,9	±0,96	±1,08
		ε_a *(%)*	±0,07	±0,094	±0,108	±0,11
		ε_m *(%)*	0,08	0,137	0,142	0,15
		N (cycles)	$10^6\rightarrow$	$10^6\rightarrow$	512 000	291 000

Table 1 : Test matrix

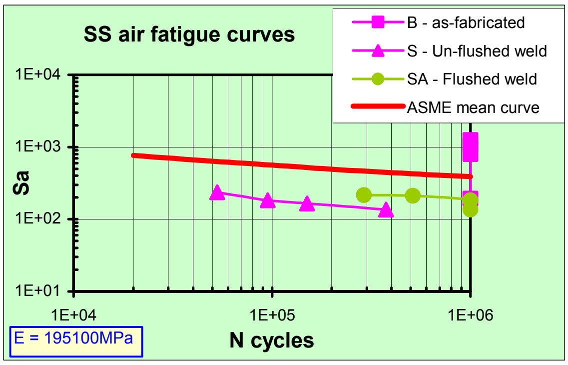

Figure 4 : Comparison of test results with ASME-RCCM Code mean curve

From this experimental work, one of the first conclusions is that the Fatigue Strength Reduction Factor for grinded pipe is equal to 1.1, and for un-flushed weld between 2 and 2.6 (1.7 in ASME-RCCM Code [12,13]). These results have to be confirmed with complementary tests that are planed.

Thermal fatigue tests on structures

Different thermal fatigue tests on water loops have been done in EDF laboratories in the 80's and are presented in different papers [4,5]. These tests concerned thermal sleeves tests, thickness variation tests, socket welds test, valve crotch region tests and stratification tests.

Different laboratories have done some thermal shock tests, in particular in CEA and AREVA, in EC-JRC in Petten and in some other countries (Finland, Switzerland and Japan….).

Three major tests are selected to check the Code results versus the experimental results : INTHERPOL (EDF), Thermal Shocks (JRC), FAT3D (CEA). All these tests are cyclic thermal loads on stainless steel cylinders or pipes under PWR environment with representative plant strain rates.

INTHERPOL EDF [7,8,9]

- test on 406mm outer diameter pipe with thickness of 10mm
- stainless steel 304 L
- thermal shocks on a sector of 20° of the pipe, all along the pipe
- ΔT of 120 or 140°C in 4 or 5 seconds
- with circumferential welds and different inner surface finished

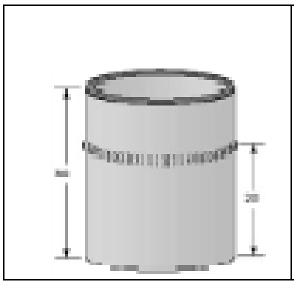

Figure 5 : INTHERPOL specimen

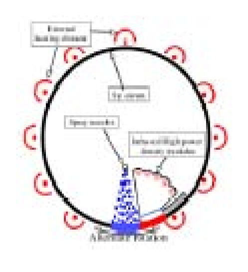

Figure 6 : INTHERPOL test principles

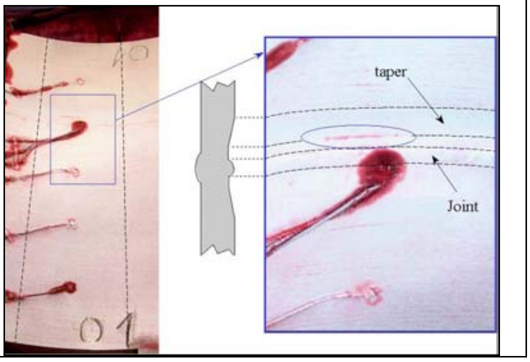

Figure 7 : Test INTH01 cracks

	location	N cycles	Salt	Δε/2 %	
INTH 01	counterbore	124000	304	0,156	
	Base metal	155000	225	0,115	
	base metal	265000	207	0,106	
INTH 02	weld	>488000	245	0,126	no crack
	Base metal	>488000	306	0,157	no crack
INTH 03	weld	>552000	294	0,151	no crack
	Base metal	>552000	312	0,160	no crack
INTH 04	counterbore	>552000	366	0,188	
	brossé	552000	308	0,158	
	point	370000	320	0,164	
	grinded	292000	311	0,159	

Table 2 : INTHERPOL results

Thermal Shocks JRC [7,8,10]

- test on 48mm outer diameter pipe with thickness of 14mm
- stainless steel 316 L
- thermal shocks
- Tmax 400°C, ΔT of 275 or 375°C in 40 or 50 seconds

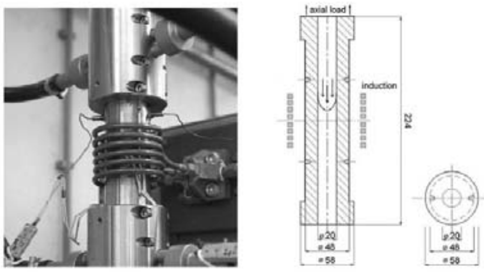

Figure 8 : JRC test facility and test specimen

#	t_{heat} (s)	T_{max} (°C)	T_{water} (°C)	First damage (cycles)	Cycles done	Crack propagation
T1	14	300	25		5000	(1)
	44	300	25		20000	
	49	400	25	20000-27500	27500	
T2	44	300	25	0-55660	70000	(2)
T3	49	400	25	14700-20000	20000	(3)
T4	44	350	25	15000-20000	25000	(4)

Table 3 : JRC test conditions

(1) Failure after application of 50KN tension load 52500 cycles

(2) Maximum crack depth : 3mm

(3) Maximum crack depth : 6.1mm

(4) Maximum crack depth : 1.5mm

#	T_{max} (°C)	T_{water} (°C)	Δε/2 %	Cycles done	Crack propagation
T2	300	25	0,33	70000	(2)
T3	400	25	0,47	20000	(3)
T4	350	25	0,39	25000	(4)

Table 4 : JRC Test results

FAT3D CEA [11]

- test on 166mm outer diameter pipe with thickness of 7mm
- stainless steel 316 L
- thermal shock, cooling time 11 or 15 seconds
- Tmax 360°C, ΔT up to 220°C in 90 or 190 seconds

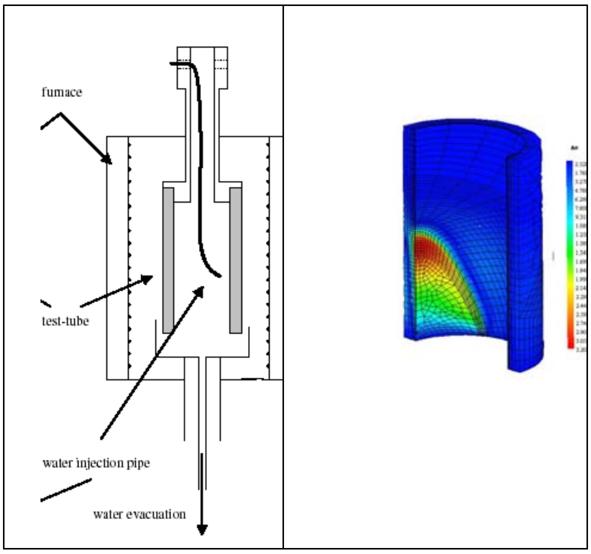

Figure 9 : FAT3D principles

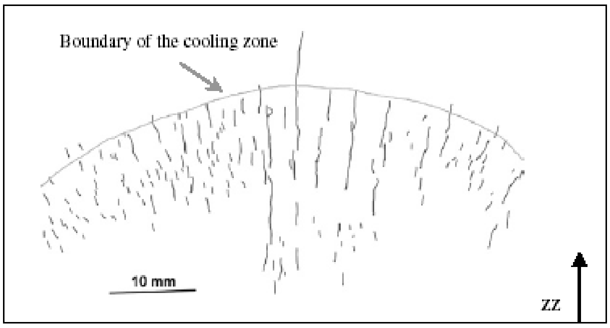

Figure 10 : FAT3D degradation after test

#	Cycle (s)	cooling (s)	ΔT outer surface (°C)	$T_{cooling}$ (°C)	Cycle for crack initiation
FAT3D 1	190	15	360	25	3800-11845
FAT3D 2	130	15	290	25	21417-30093
FAT3D 3	91	4911	220	25	14186-22923

Table 5-a : FAT3D Test conditions

#	σ_{el}	Δε/2 %	Cycles done	Max crack depth
FAT3D 1	1171	0,75	17532	6.7 mm
FAT3D 2	830	0,40	30093	> 4 mm
FAT3D 3	705	0,31	48147	> 3.2 mm

Table 5-b : FAT3D – Stress evaluation

RESULTS AND COMPLEMENTARY NEEDS

Results

All these tests have been analyzed by different ways:

- elastic strain evaluation and (S, N) curves
- cyclic plastic strain evaluation and (S, N) curves
- crack initiation + crack growth analysis
- crack like defect specific method and material resistance curves.

All the results are consistent with the Design objectives: for a usage factor less than 1, no crack through the wall with margins, case by case margins.

Few cases have to be analyzed with a maximum of precautions: small wall thickness or small ligament cases (crack depth greater than 60% of the wall thickness…)

Complementary needs

Different open questions are extracted from all these studies in order to better understand and improved the existing methodologies:

- reference fatigue (S, N) curves and fatigue strength reduction factors (welds, surface finish, mean stress, environmental effects...)
- endurance limit value, constant amplitude versus spectrum loads and correlation with maximum strength resistance of the material
- plasticity effects and K_e or K_v
- bi-axiality effects
- transferability of small specimen test to large structures : crack initiation / crack growth
- short crack and crack closure effects
- mechanical versus thermal loads crack growth
- multi crack initiation and propagation
- damage evaluation : counting method and linear cumulating of fatigue design, like rain flow method with plasticity effects.

New fatigue curves proposed by USNRC and Argon National Laboratory

A new Regulatory Guide [14] has been issued recently by USNRC, on the basis of Argon National Laboratory NUREG [15] synthesis developed on USA and Japanese programs [6]. It proposes a new stainless steel curve in air, a set of fatigue curves for all materials (carbon and low alloy steels, Ni-based alloys and stainless steels), and a Fen coefficient to consider environmental effects. Figure 16 compares past and new fatigue curves for stainless steel in air, the comparison of EDF data and the stainless steel mean Langer air curve confirm that over 10^4 cycles a new mean curve has to be derived. EDF has done a proposal (fig.15) that will be discussed in the RCC-M Code organization.

CONCLUSIONS

In front of all these important data, different conclusions can be drawn :

- a conservative design method [4,5] is available for low and high cycle fatigue of components, the safety margins are greater than 1, but are case by case dependent,
- no realistic quantified method is available and validated for residual life evaluation, taking into account all the major contributors to fatigue resistance of components, only very conservative approaches are available
- effect of weld areas on thermal fatigue of un-flushed welds has to be confirmed
- the mean stainless steel fatigue curve in air has to be revised, but the change in design curve is not completely justified to-day; more data on structures have to be collected and analyzed before fixing the transfer coefficients to derive a fatigue design curve
- environmental effects on structures under thermal fatigue loads are generally covered by existing Code rules, some cases have to be analyzed more in detail to confirm the influences of the different parameters: water chemistry, strain rate, material composition, flow rate… The structure fatigue results analyzed in this paper seems to show that the existing ASME curve C can be used for practical application to structures, with an optimized Ke, without any Fen factor added.

Consequently, R&D efforts have to be pursued actively to better understand and reduce uncertainties, mainly on loads definition, but also in damage evaluation for crack initiation, and in particular for crack growth through the pipe wall. A complete revised Code proposal has to follow these R&D programs.

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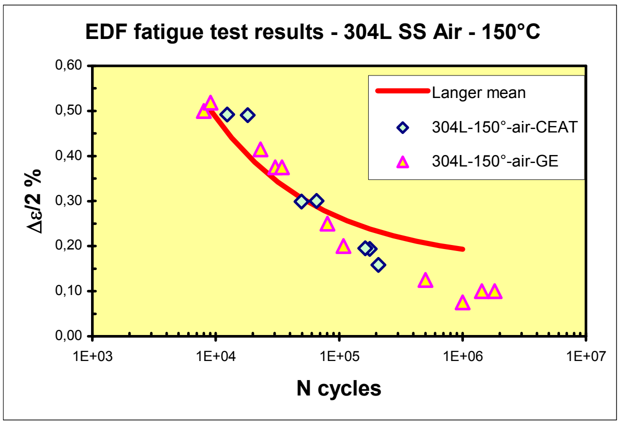


Figure 11 : SS air curve compare with EDF results

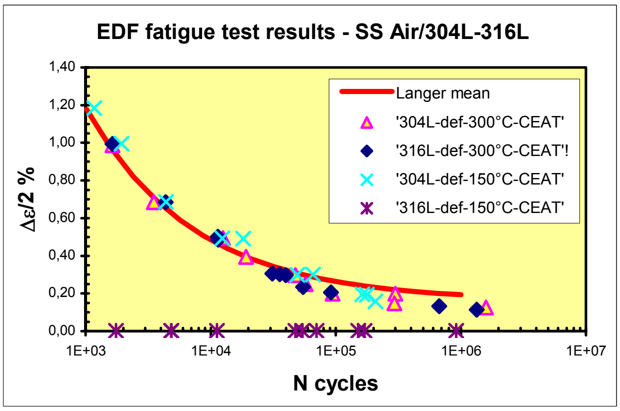


Figure 12 : Comparison of 304L and 316L

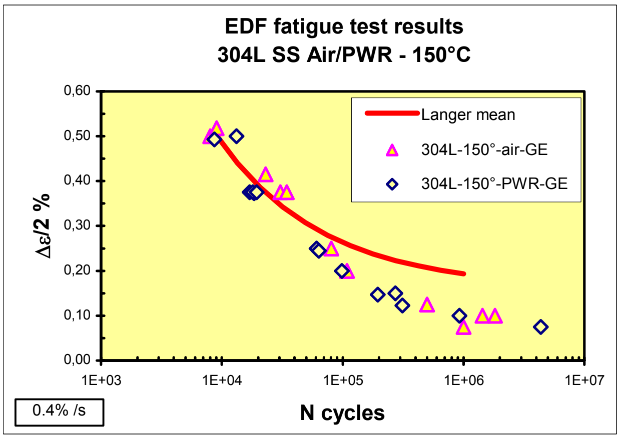


Figure 13 : SS test comparison – PWR environment effects at 150°C

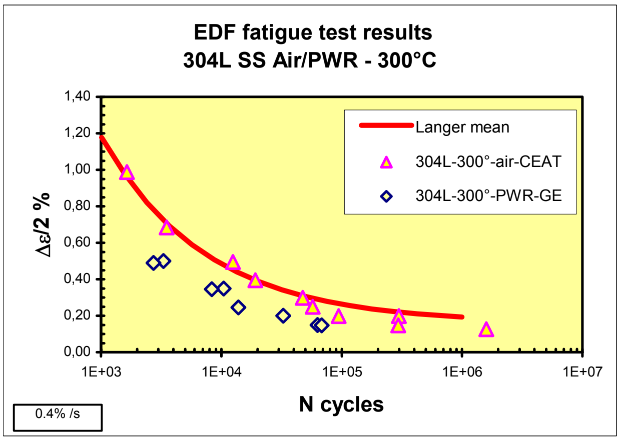
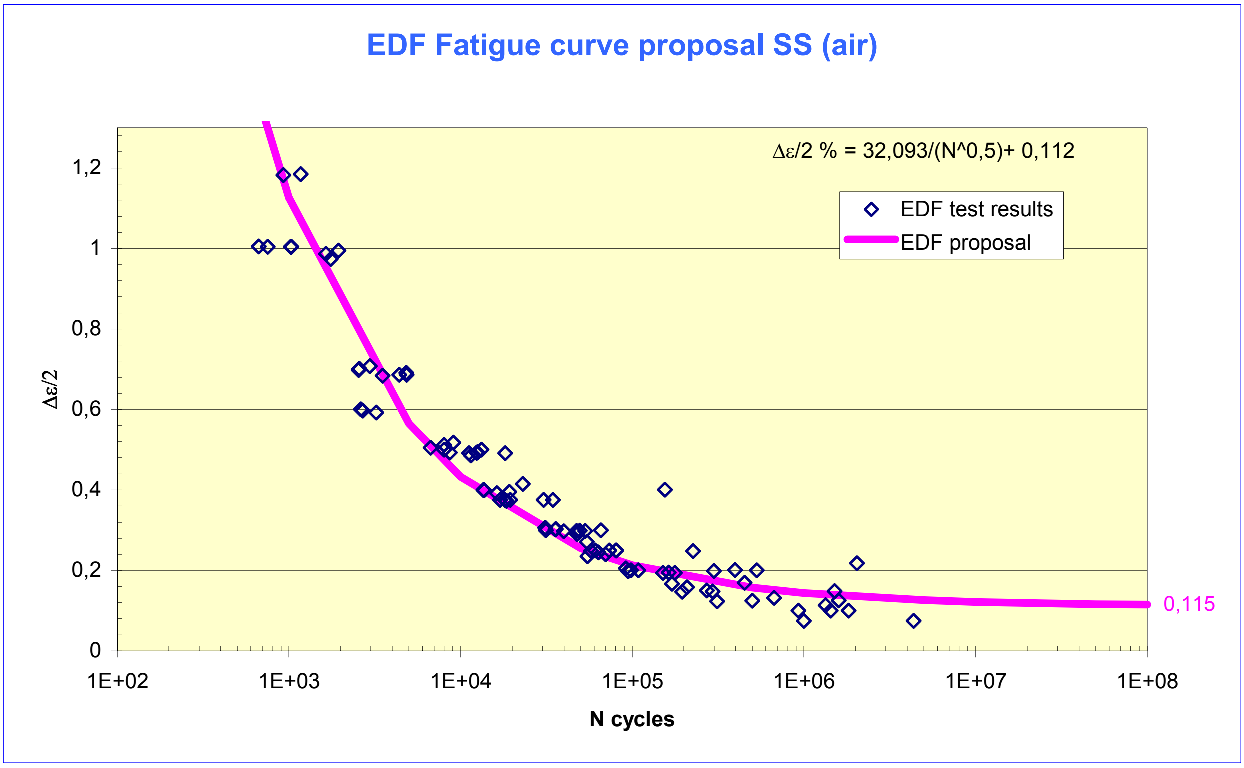
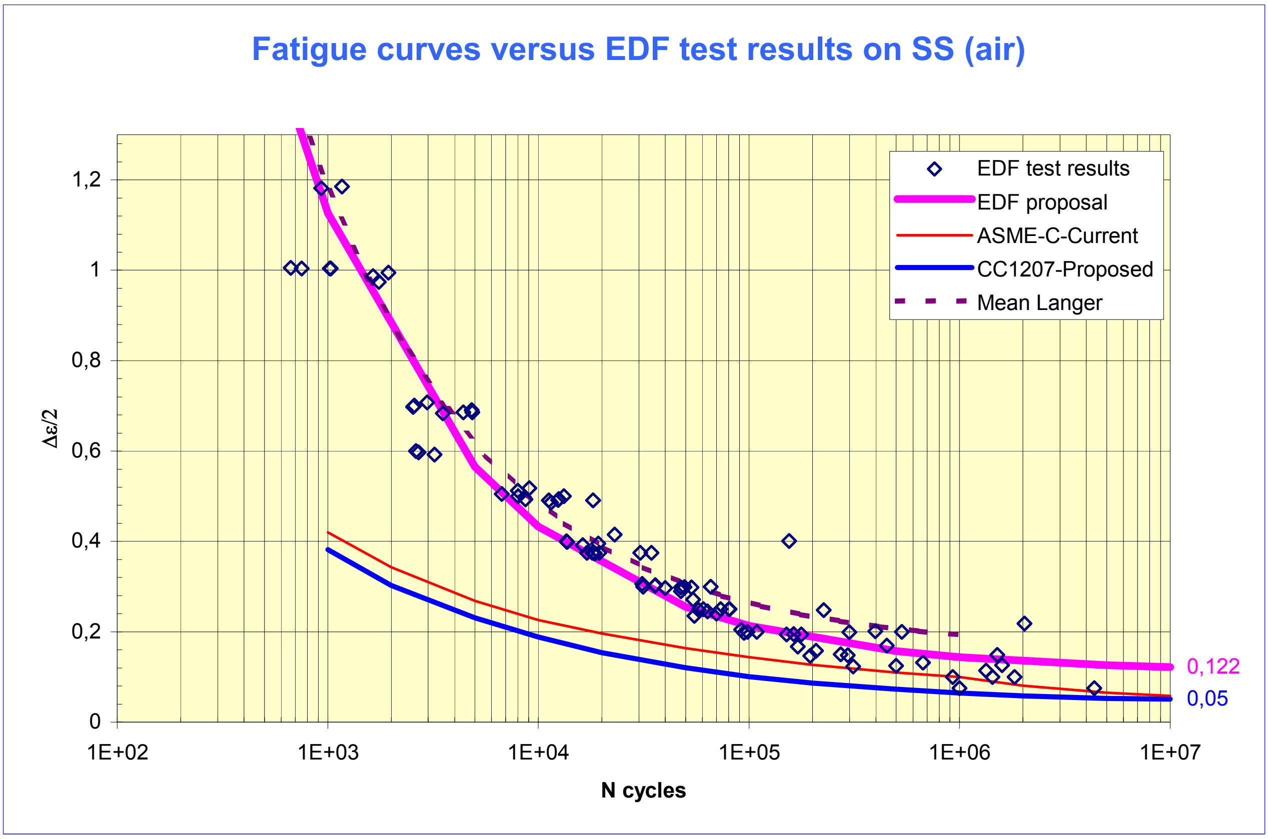


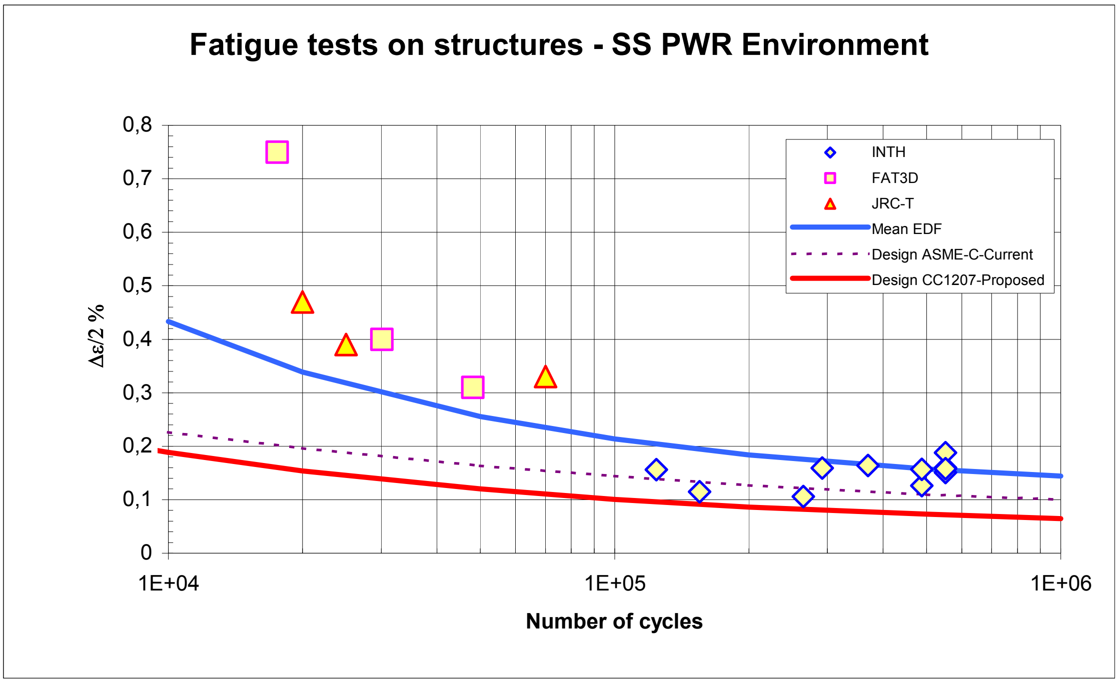
Figure 14 : SS test comparison – PWR environment effects at 300°C



re 15 : EDF mean SS curve in air proposal



re 16 : All the EDF test specimen results plotted on different SS Fatigue Curves in air



re 17 : All structure test results plotted on the EDF mean curve, the ASME C curve [12] or the RG 1.207 curve [14]