NUGENIA position on Fatigue including environmental effects

Environmentally-Assisted Fatigue Assessment – The European view of the State of the Art for stainless steels in LWR environments

NUGENIA is an international non-profit association under Belgian law established in 2011. Dedicated to the research and development of nuclear fission technologies, with a focus on Generation II & III nuclear plants, it provides scientific and technical basis to the community by initiating and supporting international R&D projects and programmes. The Association gathers member organisations from industry, research, safety organisations and academia.

The activities of NUGENIA cover plant safety & risk assessment, severe accidents, reactor operation, integrity assessment and ageing of systems, structures & components, development of fuel, waste & spent fuel management & reactor decommissioning, innovative light water reactor design & technologies, harmonisation and in-service inspection & their qualification.

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POSITION PAPER

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FOREWORD

The NUGENIA position paper on fatigue including environmental effects is a living document issued by NUGENIA Technical Area 4 “System and Component Integrity”.

This NUGENIA position paper provides a state-of-the-art summary and describes open gaps of the specific technical field of fatigue including environmental effects that is in the scope of NUGENIA. The position paper is meant for an audience with a good knowledge on Gen II & III reactors, but without an in-depth knowledge of the specific technical field. Thus it provides a comprehensive state-of-the-art summary related to the regarded topic/position and comprehensive description of the open gaps of the dedicated technical field without being excessively detailed.

NUGENIA position papers clearly reference most recent projects on the dedicated technical field and are comprehensible without the referred documents. NUGENIA position papers are consensus documents, i.e. reflecting a common position of the “community” behind the document. The “community” does not only include the authors and contributors of the document, but in fact the whole technical area(s) from which the scope of the position paper originates. Individual organisational contributions to this paper are listed in the acknowledgements section.

30 April 2015

1 Introduction

There has been a significant research effort in recent years addressing the influence of high temperature light water reactor (LWR) coolant environments on fatigue of pressure vessel and circuit materials. The response of these materials to cyclic loading resulting from plant transients is predicted on the basis of materials properties and design codes similar to the ASME III and XI design codes [1,2] for fatigue endurance (commonly referred to as fatigue initiation) and fatigue crack growth respectively. These materials research activities have addressed both the effects on fatigue life, using conventional fatigue endurance testing methods, and fatigue crack growth using fracture mechanics specimens. For both ferritic and austenitic steels, significant effects of high temperature water on fatigue endurance have been observed under specific conditions. For both classes of steel, the largest reduction in fatigue life due to the environment occurs under high strain range, low strain rate conditions and temperatures above ~200-250ºC. However, whereas for carbon and low alloy steels, oxygenated environments relevant to BWRs are most detrimental, the greatest effect on fatigue life for austenitic stainless steels is observed in low oxygen (PWR) environments.

The United States Nuclear Regulatory Commission (USNRC) has issued Regulatory Guide 1.207 concerning the influence of light water reactor environments on fatigue life of reactor materials [3], together with a supporting Argonne National Laboratory (ANL) report, NUREG/CR-6909 [4][a] in which formulae are presented for the prediction of fatigue endurance of ferritic and austenitic steels, as well as nickel-based alloys, in air and in high temperature water. It is clear that the effect of light water reactor coolant environments can be to significantly reduce fatigue endurance life compared to what would be expected based on data obtained in air. It is also clear that the adoption of the formulae presented in NUREG/CR-6909 requires a significant change in approach for plant safety assessments, especially with regard to taking into account the strain rates of plant transients. Application of the revised procedures can result in predictions of very high cumulative fatigue usage factors for some plant components and transients which appear inconsistent with the relatively good performance of stainless steel components in operating reactors over several decades. However, despite the extensive nature of the data that have been used to derive the relationships provided in the NUREG/CR-6909 document, there are a significant number of knowledge gaps. These gaps have been reviewed in a recent study that was sponsored by EPRI [5].

This review was updated within a European context during 2013 through a NUGENIA endorsed in-kind project (INCEFA[b]). The contributors to this project were:

- AMEC (UK)
- AREVA (France and Germany)
- CEA (France)
- CIEMAT (Spain)
- EDF (France)
- EKK (Germany)
- INESCO (Spain)
- JRC (Netherlands)
- PSI (Switzerland)
- SCK-CEN (Belgium)
- UJV-Rez (Czech Republic)
- University of Cantabria (Spain)
- VTT (Finland)

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[a] *A significant March 2014 update to NUREG/CR-6909 [Rev. 1] is available now in draft form.*
[b] *INcreasing Safety in NPPs by Covering gaps in Environmental Fatigue Assessment*

The result of this collaborative project was a European view on the state of the art for EAF assessment capability covering three broad areas:

1. International variations in EAF assessment procedures and goals
2. Current understanding of gaps in understanding affecting assessment capability
3. Ideas for improving understanding to the benefit of assessment capability.

This position paper reports these findings and their implications, with particular emphasis on the performance of austenitic stainless steels in PWR environments. It is clear that the reliability of this paper as a reference is very dependent on the quality and range of individual contributions; in this respect readers are advised to review these in the acknowledgements section of the paper.

2 International variations in EAF assessment procedures and goals

Experiences of environmental fatigue assessment has been gathered for the following countries:

- USA
- UK
- France
- Germany
- Spain
- Belgium
- Japan
- Czech Republic

There are two categories of assessment methodology:

1. Use of fatigue life correction factors (F_{en}) to adjust fatigue usage factors calculated using inert (air) code design curves for the effects of high temperature light water reactor environments. F_{en} is calculated as the ratio of the fatigue life in environment at the appropriate temperature to the fatigue life in ambient temperature air[c].
2. Application of environmentally adjusted fatigue curves, which are derived by applying appropriate transference factors to a mean fit to S-N data in air.

In fact, most of the above countries are currently developing approaches based on the assessment approach developed by USNRC, but in some cases with modifications intended to reduce excessive conservatism. The NRC methodology is becoming accepted as US practice for environmental fatigue life assessment for new plant and plant life extension and it is therefore sensible to begin by summarising this approach and more recent developments within ASME before then describing different strategies which diverge from this. The Japanese approach is quite similar to the USNRC approach and, in fact, was developed earlier. There are some differences which provide an interesting comparison with that being promoted in the USA and so the Japanese methodology is next described. The approach currently used in the Czech Republic originates from Russian practice and currently does not explicitly include the effects of the reactor environment. Although proposals have been made to include environmental effects using an approach somewhat similar to USNRC, they have not yet been adopted into the Czech code. The position in many European countries is currently in flux. Some countries such as the UK tend to follow ASME but have not made a final decision as to how to include environmental effects in new plant assessments. Others such as France and Germany have their own codes, RCC-M and KTA, respectively and, again, work is underway to develop these approaches to include environmental effects. A brief summary of the French approach is also provided.

2.1 USA guidance

2.1.1 USNRC position

For new nuclear plant in the USA the overriding rules that must be complied with are those set out in USNRC Regulatory Guide 1.207[3]. For austenitic stainless steels these rules draw their advice from the 2007 first issue of NUREG/CR-6909 which was produced by ANL on behalf of USNRC [4].; a revised version of this report was recently issued in draft form for comment. For existing plant, environmental fatigue assessment may be performed to the rules set out in the earlier NUREG/CR-5704[6] guidance within which F_{en} factors are lower but safety factors inherent in the design curves are higher; the logic of assessment is similar to that now enshrined in the NUREG/CR-6909 guidance but the equations for calculation of F_{en} are quantitatively different. The CR-6909 requirements are summarised as follows:

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[c] *However, the current ASME Section III air curve does not recognise an effect of temperature.*

1. Calculate the fatigue usage in air using ASME code analysis procedures and the new stainless steel fatigue air curve provided in NUREG/CR-6909, reproduced below as Figure 1 (adopted in the ASME code from 2009 onwards). ASME Code Section III fatigue analysis procedures consider all fatigue cycles based on the anticipated number of thermal and pressure transients, and for each load-cycle or load set pair, an individual fatigue usage factor is determined by the ratio of the number of cycles anticipated during the design lifetime of the component to the number of allowable cycles. The fatigue usage in air is simply the summation of the derived individual fatigue usage factors.
2. For all types of austenitic stainless steels (e.g. Types 304, 310, 316, 347 and 348), calculate F_{en} for each set of cycles using Equations 1-4, with the Equation 5 strain threshold qualification applied.
3. Calculate the environmental fatigue usage using Equation 6.

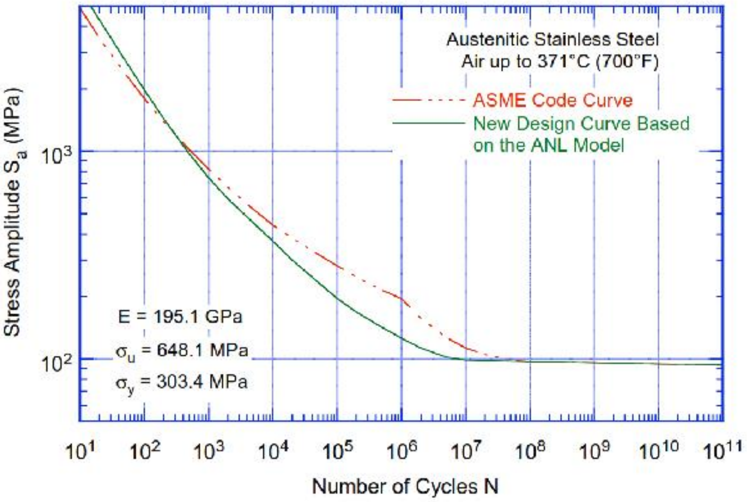

Figure 1: Fatigue design curve for austenitic stainless steels in air[4]
Note that 'ASME Code Curve' (red) refers to the 2007 ASME III design code and earlier. The 2010 ASME Code curve is identical to the ANL design curve. This curve (green) is based on best fit to available laboratory data, corrected for mean stress effects, then adjusted by factors of 12 on life or 2 on stress (whichever is more conservative) to allow for effects such as mean stress, surface finish, size and geometry.

$$F_{en} = \exp\left(0.734 - T' O' \dot{\varepsilon}'\right)$$ Equation 1

Where $T', \dot{\varepsilon}', O'$ are transformed temperature, strain rate and dissolved oxygen level defined as:

$$T' = 0 \qquad (T < 150^oC)$$

$$T' = (T - 150)/175 \qquad (150 \le T < 325^oC)$$ Equation 2

$$T' = 1 \qquad (T \ge 325^oC)$$

$$\dot{\varepsilon}' = 0 \qquad \left(\dot{\varepsilon} > 0.4\%/s\right)$$

$$\dot{\varepsilon}' = \ln\left(\dot{\varepsilon}/0.4\right) \qquad \left(0.0004 \le \dot{\varepsilon} \le 0.4\%/s\right) \qquad \text{Equation 3}$$

$$\dot{\varepsilon}' = \ln\left(0.0004/0.4\right) \qquad \left(\dot{\varepsilon} < 0.0004\%/s\right)$$

$$O' = 0.281 \qquad \text{(all DO levels)}^{d} \qquad \text{Equation 4}$$

And the strain threshold is defined by:

$$F_{en} = 1 \qquad \left(\varepsilon_a \le 0.10\%\right) \qquad \text{Equation 5}$$

$$U_{en} = U_1 F_{en,1} + U_2 F_{en,2} + U_i F_{en,i} \ldots\ldots + U_n F_{en,n} \qquad \text{Equation 6}$$

Where U_n is the fatigue usage calculated for the nth load cycles, and $F_{en,n}$ is the environmental factor applicable for these cycles.

There are a number of key aspects to the US guidance that have influenced strategies to relax conservatism perceived to be inherent in the rules:

1. The equations apply equally to all types of austenitic stainless steel.
2. The only sensitivities able to influence fatigue life are:
    a. Temperature
    b. Strain rate
    c. Strain amplitude, through recommendation of a threshold below which there is no environmental effect
3. Except for the strain amplitude threshold, the F_{en} factor is not sensitive to strain amplitude.
4. Even when the factors of 12 on life and 2 on stress are removed the rules generally predict failure based on laboratory data that is not seen in mature plant.

2.1.2 ASME approach

Environmental effects are not currently included in the ASME code and the current ASME Section III air line for austenitic stainless steels is identical to the NUREG/6909 design line. ASME has proposed two alternative approaches to assessment of environmental effects on fatigue for adoption as Code Cases. Code Case N-792 uses a F_{en} approach and, for austenitic steels, is very similar to the NUREG/CR-6909 methodology, apart from the fact that no strain threshold is included [7]. Code Case N-761 provides an alternative approach using a set of fatigue design curves derived directly from environmental S-N fatigue data [8]. Harrison and Gurdal have compared the two approaches with component type environmental fatigue testing [9]. They conclude that the F_{en} approaches produces significantly shorter fatigue lives (by a factor of ~2-3) than the N-761 approach, although both predict shorter fatigue lives than experimental

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[d] *Note that the draft revision to NUREG/CR-6909 now includes an effect of oxygen concentration*

fatigue data obtained by Jones et al[49] and EPRI[50] testing specimens designed to replicate plant components.

2.2 Divergence approaches

2.2.1 Mechanistic understanding

One approach relies upon developing mechanistic understanding through which current empirical rules may be extrapolated more reliably. The end result of this could be a methodology by which the effects of a plant transient can be modelled deterministically rather than through application of design curves [11]. In this context, mechanistic understanding is defined as a multi-scale description of physical and chemical effects determining fatigue behaviour through the stages of crack nucleation, small crack (Stage I) growth and the transitions from Stage I to long crack (Stage II) growth. Although the environment is likely to affect each of these stages, the extent of environmental contribution may differ between the stages. Thus, the application of a single F_{en} factor to the whole of the S-N curve may not be appropriate, since, for example, the nucleation phase will occupy a greater portion of fatigue life at low strain amplitude (high cycles) than in the high strain range, low cycle regime where crack growth is more significant. The ultimate aim of developed understanding would be to develop a more mechanistically focussed, less empirical assessment approach for environmental fatigue which may allow reductions in the current level of conservatism.

2.2.2 Reducing data uncertainty

This strategy leads to use of a methodology based on the USNRC F_{en} approach but with reduced conservatism. The aim is to develop an air fatigue curve in line with the NUREG/CR-6909 fatigue air curve but with reduced conservatism through justified reduction in data scatter. Two factors may contribute to scatter:

1. The database underpinning the ANL model includes data for a range of different grades of austenitic stainless steel which may result in excessive scatter when applied to plant containing only specific grades of steel, i.e. a targeted choice of data relevant to the European context, e.g. stabilised steels as used in Germany.
2. Some of the data were generated many years ago with less refined experimental methods than are now available which may also contribute to data scatter. Some organisations are therefore focusing on generating improved data for use to generate a revised environmental S-N curve which is anticipated to contain reduced, but nevertheless sufficient, conservatism.

2.2.3 Transference factors

Currently, the design curves in ASME III (air) and NUREG/CR-6909 (air and water) are obtained by application of a transference factor, currently 12 on cycles or 2 on stress, whichever results in a shorter life. The overall transference factor is obtained by multiplication of several contributing factors, including data scatter, specimen/component size effect, surface finish and “atmosphere”. The latter was intended to relate to the difference between laboratory and industrial conditions, but not to specific environments such as LWR coolant. However, it is unclear whether multiplication of these separate contributors is appropriate or whether the contributions of some of these parameters may differ in air and LWR environments. For example, there is evidence that surface finish effects may be smaller in water than in air [10]. Through accumulation of targeted data the goal is therefore to develop improved transference factors to assist in application of laboratory F_{en} factors to real plant situations. These factors may also enable a range of factors to be allowed for which are not explicitly taken into consideration explicitly, for example hold time and mean strain/stress. Work is also underway to define methodologies for combining different effects without simply multiplying them together.

2.2.4 Modelling of stress transients

In several countries effort is concentrated on the most reliable approximation of real plant transients, recognising that the strain rates inferred from such approximations can significantly affect derived NUREG/CR-6909 F_{en} factors. Real plant transients are almost never regular and so must be approximated into load pairs. Reference 12 advises how to group transients into pairs and also how to deal with time and stress discontinuities between the valleys and the peaks of load pairs (see Figure 2 for illustration). There are three currently accepted methods for determining the strain rate for load pairs[12]:

1. Average Strain Rate

$$\dot{\varepsilon} = 100 \times \Delta\sigma / (\Delta t \cdot E)$$

$\dot{\varepsilon}$ = average strain rate for the load pair (%/sec)

Δσ= stress difference between the highest stress point of the maximum tensile stress event and the lowest stress point of the maximum compressive stress event (psi)

Δt= time between peak and valley, ignoring time discontinuity (sec)

E= Young's Modulus

2. Detailed Strain Rate

The Detailed Strain Rate approach is similar to the average approach, except that a weighted strain rate is obtained based on strain-based integration over the increasing (tensile) portion of the paired stress range.

The issues associated with the proper linking of transients to create load pairs are less pronounced because of the integration process.

$$\dot{\varepsilon} = \frac{\sum \Delta\varepsilon_i \frac{\Delta\varepsilon_i}{\Delta t}}{\sum \Delta\varepsilon_i}$$

$\dot{\varepsilon}$ = detailed strain rate for the load pair (%/sec)

$\Delta\varepsilon_i$= change in strain at Point i, in/in (given by $(\sigma_i - \sigma_{i-1})/E$)

σ_i= stress intensity at Point i, psi

σ_{i-1}= stress intensity at Point i-1, psi

Δt= change in time at Point i, sec (given by t_i-$_{ti-1}$)

E= Young's Modulus

3. Integrated Strain Rate (more specifically "integrated F_{en} approach")

In this case a F_{en} factor is computed at multiple points over the increasing (tensile) portion of the paired strain range, and an overall F_{en} is integrated over the entire tensile portion of the strain range.

As for the Detailed Strain Rate approach, this method seeks to reduce the issues associated with the proper linking of transients to create load pairs.

$$F_{en} = \frac{\sum F_{en,i} \Delta \text{£}_i}{\sum \Delta \text{£}_i}$$

$F_{en,i}$=F_{en} computed at Point i, based on $\dot{\text{£}}_i = 100 \Delta \text{£}_i / \Delta t$

Remaining parameters as defined for the Detailed Strain Rate approach

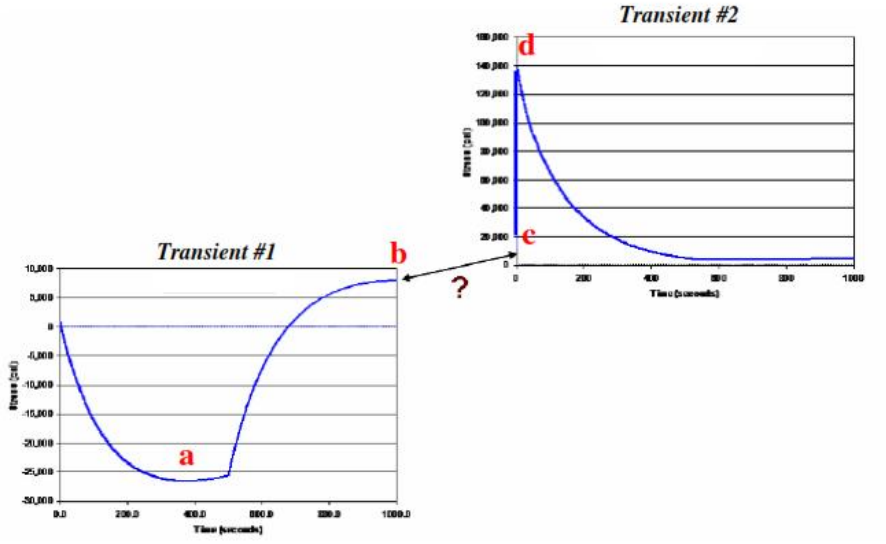


Figure 2: Illustration of load pairing[12]

It will be clear that the current three recommended approaches will each produce different results for a given set of plant transients. Since each method is designed to be conservative, work is underway in Spain and Belgium evaluating other methods with perhaps reduced conservatism. These include:

- Continuous methodology
- Transient to transient methodology
- EPRI load pairs methodology
- Rainflow Load Pairs methodology
- Methods to distinguish between transients with different load forms during negative strain rate phases

2.2.5 Modelling of thermal and environmental transients

The NUREG/CR-6909 and Japanese procedures recommend conservatism through use of the highest temperatures and lowest dissolved oxygen contents in fatigue assessments for austenitic stainless steels. Thus, some activity is focussed on being able to allow for benefits from certain phasings of stress, thermal and environmental cycling. In particular, work is underway to determine the most suitable temperature to use in evaluation of non-isothermal transients.

2.2.6 Modelling of non-uniform stressing

Many real plant transients do not create uniform stressing in components (e.g. thermal transients). Presently available procedures, which are based on test data from specimens with through-wall (membrane) stresses, are unable to take any benefit from this. This is an issue that is warranting further attention in the UK[13,14] because it potentially provides a means of producing more realistic, less conservative, assessment approaches. An example of the benefits possible through examination of this issue comes from a test in which thermal shock was imposed on the inside surface of a thick cylinder[14]. Depending on the level of detail in the assessment, a calculation of design life using the ASME 2010 air fatigue curve predicted between 900 and 7835 cycles to failure for this test. The test actually ran for 59,378 cycles without failure.

2.3 Japanese approach

Japan's approach was reported by CIEMAT within the INCEFA project. Japan has created an independent assessment approach, the logic of which is very similar to the ANL approach. Differences that do arise do so because of, a) different material test databases used to derive recommended air fatigue curves, and b) different methods for incorporating temperature dependence. Also, the Japanese model has different equations for stainless steel in PWR and BWR environments while the existing ANL model uses identical equations, although dissolved oxygen effects are taken into account in the recent draft revision to NUREG/CR-6909. Reference 15 compares the results of the US (Argonne National Labs) and Japanese (JSME) assessment rules, these comparisons are reproduced in Figure 3 and Table 1.

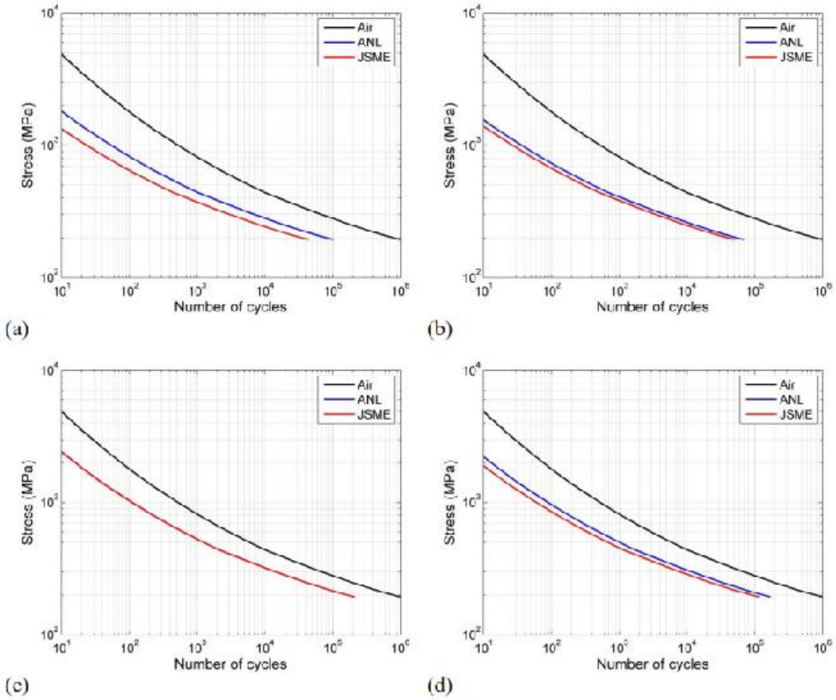
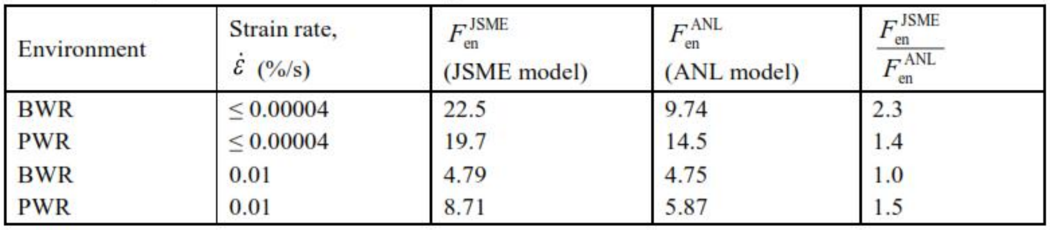


Figure 3: Comparison between estimated fatigue curves from the ANL model and JSME model for austenitic stainless steel in (a) BWR environment for 0.0001 %/s strain rate, (b) PWR environment with 0.0001 %/s strain rate, (c) BWR environment with 0.01%/s strain rate, (d) PWR environment with = 0.01 %/s strain rate. Note that the ANL curve and the JSME curve are almost identical in (c) which explains why it is hard to see the blue ANL curve[15].



Environment	Strain rate, $\dot{\varepsilon}$ (%/s)	F_{en}^{JSME} (JSME model)	F_{en}^{ANL} (ANL model)	$\frac{F_{en}^{JSME}}{F_{en}^{ANL}}$
BWR	≤ 0.00004	22.5	9.74	2.3
PWR	≤ 0.00004	19.7	14.5	1.4
BWR	0.01	4.79	4.75	1.0
PWR	0.01	8.71	5.87	1.5

Table 1: Comparison between calculated F_{en} values for austenitic stainless steel[15]

From the reproduced information from Reference 15 it is clear that, even though F_{en} factors do differ between the two approaches, there is only slight difference between Japanese and US fatigue curves in PWR conditions (with greatest conservatism for the Japanese model). For BWR conditions there is greater difference at low strain rate and no significant difference at high strain rate.

2.4 Czech Republic approach

The Czech approach was summarised for the INCEFA project by UJV-Rez. The basis of evaluation and prediction of fatigue life in the Czech STD A.M.E. standard [16] can be found in the original Russian approach defined in PNAE documents [17]. Comparison between ASME and STD A.M.E. shows significant differences between the two approaches [18]. The main differences relate to applied stresses, safety factors and different positions of fatigue curves on a plot of stress amplitude vs. number of cycles to crack initiation (S-N). Also the operating temperature is taken into account in a different manner. Consequently the direct application of the NUREG approach is not judged to be possible in the case of WWER power plants. Therefore other methods to allow for environmental effects are being considered for the Czech standard.

The present guidance [16] is based on air fatigue design curves and formulae which incorporate factors of safety of 2 for stress and 10 for cycles. These curves are considered to be bounding for many situations. However, the standard also places responsibility on the assessor to introduce additional fatigue strength reduction factors when required for environment, weld deposits and weld joints, and radiation. It is currently the assessor’s responsibility to decide when these factors are required and what values to attribute to them.

Recently, consideration is being given in the Czech Republic to adopting assessment practices closer in style to the USNRC guidance (e.g. Reference 19). Figure 4 shows how the current and proposed new Czech standards compare with current US guidance. It should be noted that the revised curves have not yet been approved for incorporation in the Czech code.

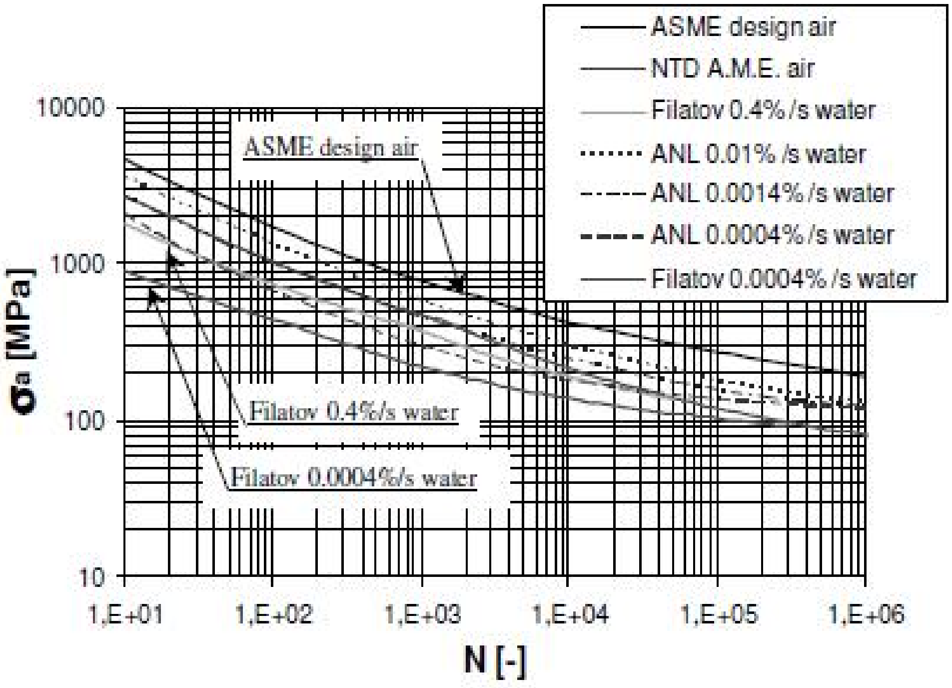


Figure 4: Comparison of US design curves with current and possible new Czech design curves (note current Czech curve is shown in basic form without any additional safety factors which must be determined by the assessor)

2.5 French approach

The French approach, being adopted through developments of the RCC-M code supported by EDF and AREVA, is described based on contributions by EDF to the INCEFA project, supported by ASME PVP conference publications [20,21,22]. As already noted, the French approach follows the ANL methodology. Key departures in various stages of implementation are as follows:

- The factor on strain, used as a transference factor on the best fit S-N curve in air to produce a design curve, is reduced from 2 to 1.4. This is justified through reduced material variability for the limited selection of materials in use in France, especially in the high cycle domain. Statistical analyses are underway to underwrite this position. To begin with the statistical variability evident in French focussed tests have been compared with the variability evident in the data on which NUREG/CR-6909[4] is based. The French data variability is also compared with that in Japanese data [37]. The results are illustrated in Figure 5 and Figure 6 where predicted cycles to failure are plotted against actual cycles to failure. It is clear that there is less variability for the French data, albeit that these data do not extend to very high numbers of cycles where the variability is highest for the US and Japanese data. The statistical analyses continue and have recently been extended to consider better treatment of ‘run-out’ data (i.e. data for specimens that did not fail in test due to long endurance properties).

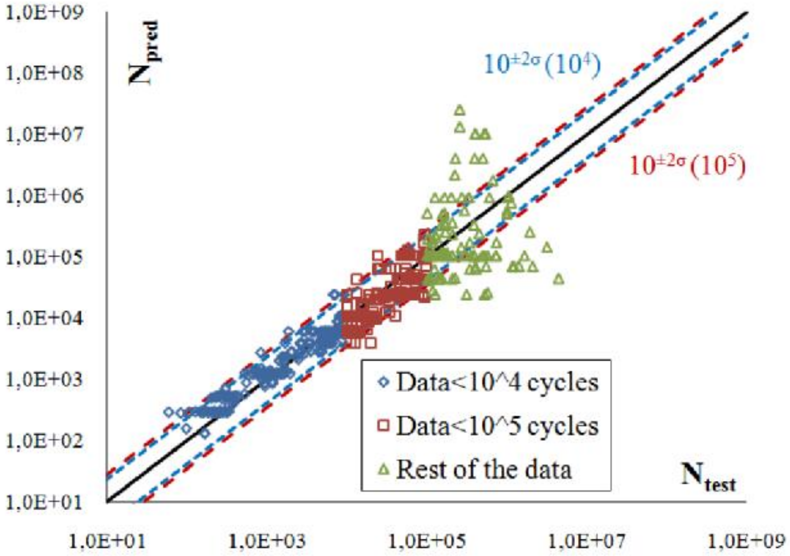


Figure 5: Plot of the predicted number of cycles versus the measured number of cycles for French experimental air data

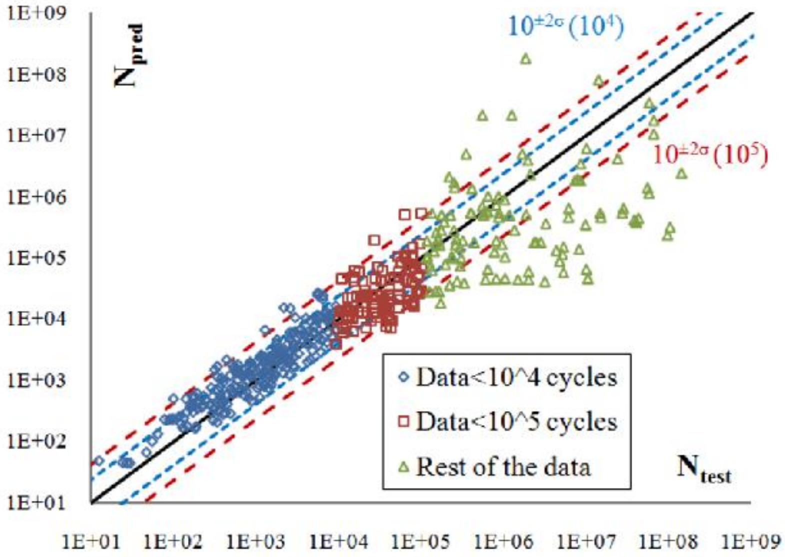


Figure 6: Plot of the predicted number of cycles versus the measured number of cycles for US and Japanese data from NUREG/CR-6909

- Although it is accepted in France that the ANL F_{en} factor methodology is appropriate for smooth surfaced laboratory triangular waveform loaded test specimens, it is claimed that this is not the case for more plant relevant transient loads and specimens with plant relevant surface finishes. This assertion is not unique to France and the evidence for it appears throughout this paper. However, the approach currently being developed in France to deal with this is novel. The methodology[20] relies upon test evidence being available for the combination of surface finish and environment relevant to the assessment being made. A comparison is made between the fatigue endurance defined by the accepted design curve, derived by applying transference factors to mean air data, and the fatigue endurance derived by adding transference factors for material variability and size effects (as recommended by the design code) to the endurance result obtained for the relevant surface finish in water. If the current recommended design curve bounds the result derived by adding specific transference factors to the experimental result, the F_{en} factor is set to unity and the established design curve is used. If not then the F_{en} factor is adjusted to that necessary to produce a result equal to the experimental result with the transference factors for material variability and size added. In either case the resulting fatigue endurance prediction is significantly more advantageous than that predicted otherwise using established NUREG/CR-6909 recommendations. Because this process is somewhat onerous, it is only applied to the most sensitive parts of the plant, e.g. for which calculated usage factors determined through application of recommended F_{en} factors to design curves exceed 0.1. In summary, the methodology highlights plant items for which current recommended design curves already contain all or some significant percentage of margin necessary to allow for environmental effects, and then takes advantage of these already existing margins by reducing additional margins to be added (Figure 7 demonstrates using French data the ability of the ASME design curve to bound endurance data which already allows for the effects of environment and surface finish, with margin to spare).

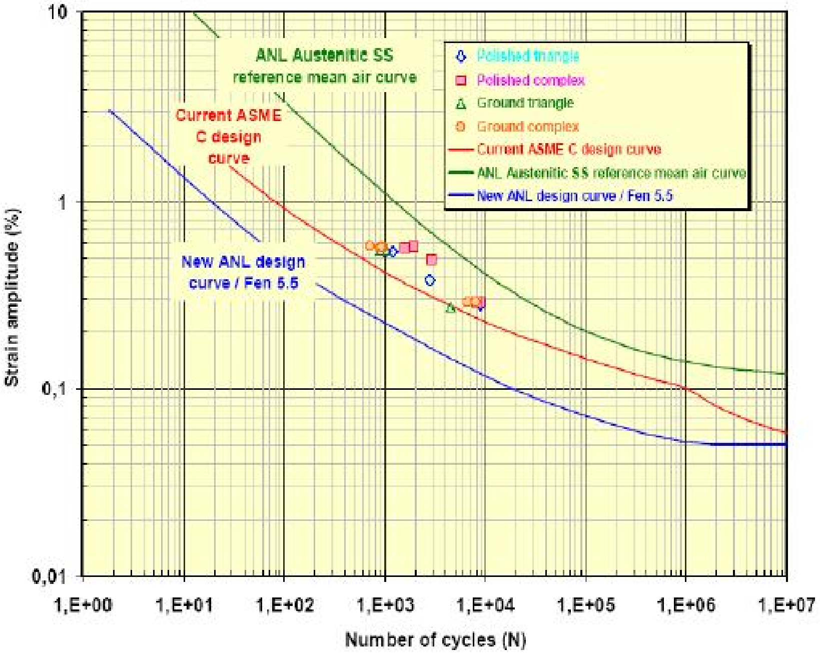


Figure 7: Example of the effect of surface state combined with loading and environmental effect[20]

2.6 Summary of national variations and their implications

Although many of the reviewed methodologies contain common features, there are nonetheless some significant variations in detail:

- Different transference factors used to derive air design curves from mean data curves.
- Different approaches to calculation of environmental factor (F_{en}) result in different values of F_{en} being calculated.
- Different methods for calculating strain rate result in different fatigue lives for the same transients.
- It has been argued by some that existing assessment procedures contain sufficient conservatism to avoid the need to allow explicitly for environment. Although this is generally consistent with plant experience, the degree of conservatism is not well quantified relative to the known effect of environmental enhancement.

Current approaches to improving assessment practices include:

- Increased mechanistic understanding
- Reduction in data scatter due to improved data quality and focus on plant specific materials.
- Introduction of better quantified transference factors and improved methods of combining their effects.
- Quantification of interactions between transference factors in air (e.g. surface finish) and environmental enhancement factor.
- Addition of parameters influencing transference factors which are not currently considered, e.g. plant relevant loading, including hold times which are not presently considered explicitly.
- Improving the reliability of transient modelling in assessments.
- Allowing for phasing of thermal and environmental transients.
- Allowing for non-uniform (e.g. through-wall) stressing.
- Consideration of the contribution to fatigue damage when the applied stress is negative, although increasing (R<0).
- Evaluation of the influence of decreasing through-wall stress gradients.

Through collaboration, some of these initiatives are being combined to greater effect; the INCEFA project is a good example of this [23].

3 Current understanding of gaps in understanding which affect assessment capability

Reference 5, prepared for EPRI, remains the definitive accepted description of gaps in environmental fatigue understanding. Reference 24, which develops a research roadmap to address the identified knowledge gaps recommends that the highest priority research should be focussed on testing three distinct hypotheses. For each of these three hypotheses, the gaps in understanding, that if tackled completely would fully address the hypothesis, are prioritised such that the gaps allocated high priority would deliver maximum understanding to test the hypothesis. The three high priority hypotheses and the associated high priority gaps in understanding are summarised as follows (using the hypothesis and gap numbering from References 5 and 24):

- Hypothesis 1: Cyclically variable parameters in a thermally induced stress cycle reduce or negate the environmental influence on fatigue
    - Gap 15 which states that [only] limited data are available on the influence of variable temperature and variable strain rate within test cycles and on the influence of out-of-phase variations of temperature and strain rate.
    - Gap 28 which states that very few data are available under plant representative loading conditions and the influence of complex loading conditions (including hold times and spectrum loading) waveforms and combined loading are not well quantified. Crack growth data are obtained under isothermal conditions whereas many plant transients involve simultaneous temperature and load cycling (either in- or out-of-phase).
    - Gap 33 which states that more data using component like features with plant representative loading conditions are required to develop and validate methods for considering corrosion fatigue in LWR environments.
- Hypothesis 3: Conservatism due to the use of bounding transients for design purposes is sufficient to accommodate environmental enhancement of fatigue damage
    - Gap 4 which states that the reasons for the apparent discrepancy between laboratory data and plant experience regarding the effects of environment on fatigue are not fully understood. Excessive conservatism in the current rules for design and/or the influence of complex loading may, at least in part, provide an explanation.

  - Gap 35 which states that for many PWR and BWR plants, there is a lack of knowledge of actual plant transients which is important because of the sensitivity of EAF to temperature and strain rate variations.
- Hypothesis 6: Conservatism is introduced by the calculation methods recommended for the determination of F_{en} factor which are largely unsubstantiated and do not adequately consider the relevant parameters and their time dependent influences
  - Gap 1 which states that there is a disparity between the lower bound values of F_{en} derived by NUREG/CR-6909 and the Japanese Environmental Fatigue Evaluation Method for Nuclear Power Plants (JSME S NF1-2009)[e].
  - Gap 7 which states that mechanistic understanding leads to the expectation that the degree of environmental enhancement of fatigue damage should depend on strain range. This is not consistent with the F_{en} factor approach.
  - Gap 16 which states that test data supporting averaging procedures for complex non-isothermal transients are very sparse and this represents a significant uncertainty. Therefore, the averaging procedures are based largely on assumptions. Mechanistic understanding is required as a basis for identifying those parts of the cycle for which water environment is damaging. This understanding can then be used as the basis for developing averaging procedures, which should then be validated with test data involving cyclically variable parameters.
  - Gap 17 which states that NUREG/CR-6909 recommends a 'modified rate approach' for which a unique F_{en} factor is determined for each cycle. Only very limited test data are available to substantiate the modified rate approach or the use of partial FUFs.
  - Gap 36 which states that the basis for the selection of effective stress parameters for biaxial stress conditions is not established. Test data are required under conditions of biaxial loading for the treatment of plant thermal transients and non-proportional loading for combined thermal and mechanical transients. The most appropriate parameter may be different for the crack nucleation and subsequent propagation of microstructurally small cracks.
  - Gap 39 which states that, while methods for the determination of cycle effective strain rate can be proposed for conformance to ASME Code analysis, there are very few experimental data or plant data that can be used to validate the methods for use in corrosion fatigue assessments. Methods need to be consistent with mechanisms which operate under plant conditions.
  - Gap 41 which states that interpreting a plant transient with variable strain rate in terms of the single strain rate curves is problematic, and no relevant guidance is available.
  - Gap 47 which states that the need exists to provide guidance on circumstances where the approach of NUREG/CR-6909 is not appropriate because of DO levels.

It can be observed that, taken together, the various initiatives described above taking place in different countries address all of the high priority gaps relevant to fatigue endurance assessment. Although none of the research referred to is complete, there are nonetheless interim results worth summarising. These support the continued emphasis on these research areas. Recent and current work by the INCEFA participants is summarised in the remainder of this section.

3.1 Surface condition

For the INCEFA[23] project, AMEC and AREVA contributed the results of an experimental study of the effect of surface condition on the fatigue endurance of stainless steel in air and in high temperature PWR primary water.

The majority of fatigue endurance tests that are undertaken in air are based on the use of specimens with a highly polished surface. However, many locations on plant have a less smooth surface condition and it

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[e] This has been addressed in Rev 1 of NUREG/CR-6909

is well known that rough surface finishes may have a deleterious effect on the fatigue endurance performance of stainless steels tested in air. NUREG/CR-6909 and the latest version of ASME III use a transference factor of 12 on cycles (or 2 on stress if larger) which is intended to account for the effects of surface condition as well as material variability, data scatter, specimen size and loading history. This value includes a factor of between 2 and 3.5 for surface condition. The NUREG/CR-6909 F_{en} approach involves multiplying the measured effects of surface condition in air by the value of F_{en}. However, since only very limited data exist on the effect of surface condition on fatigue endurance in high temperature water, it is unclear whether or not the application of both the environmental penalty factor and the surface condition transferability factor based on air data is applicable. If the application of the transference factor for surface condition could be avoided, or its value reduced, when a F_{en} factor is applied, there would be a substantial benefit for plant safety assessments.

- AMEC tests (25).
    - Tensile fatigue endurance tests were undertaken in lithiated, hydrogenated, non-borated water at 300ºC using solid specimens fabricated from 304L stainless steel. The surface conditions studied were polished, fine ground and scratched. Ground specimens were also tested after a period of pre-oxidation in the high temperature water environment prior to loading. Control tests on all three surface finishes were also undertaken in ambient temperature air.
    - From the test results, it is clear that surface condition does have an important effect on fatigue endurance data. Measured fatigue lives in air may be shortened by a factor of approximately 5 for abraded compared to polished specimens, with surface scratches producing a reduction of about an order of magnitude. However, the effect of surface finish is substantially reduced, to a factor of about 2, when the tests are undertaken in high temperature water. This trend is consistently followed for both abraded surfaces and scratched surfaces. It is also evident that the test results for polished specimens are generally consistent with the predictions of NUREG/CR-6909. Based upon the test results, it is concluded that the NUREG/CR-6909 formulae appear to correctly account for the effect of lower strain rate on fatigue endurance, although further data are required to fully substantiate this. In addition, based on limited data, it appears that surface oxidation does not strongly influence fatigue endurance.
    - The main observation from this study is significant in that surface condition effects in high temperature water are substantially reduced compared to the effect in air. Whilst it is sound practice to utilise a transference factor to account for surface condition effects when undertaking a fatigue assessment for service in air, use of the factor derived from air data together with the environmental reduction factor, F_{en}, determined using smooth specimens may be excessively conservative. Based on these preliminary data, a reduction in the F_{en} factor by about a factor of two when applied to the air design line in NUREG/CR-6909 which includes a surface finish factor derived from air data may be appropriate. Clearly, more data are required to substantiate this proposition.

- AREVA tests [10].
    - Testing was performed in a lithiated, borated and hydrogenated PWR water environment at 300°C, using solid 304L stainless steel specimens. Results were obtained for polished and heavily ground surfaces (environment, load form, strain rate and strain amplitudes were also varied, see section 3.2).
    - The results showed that there is little or no effect of surface finish for high strain amplitude of ±0.6%. For lower strain amplitude of ±0.3%, a factor of 2 was obtained between the fatigue life of polished and ground samples.
    - With regard to the complexity of combinations between detrimental effects, according to the various experimental conditions, a competition occurs notably between PWR water

environment and surface roughness effects on damage mechanisms. From a design point of view, it is notable that the resultant fatigue life reduction is lower than the one deduced from the multiplication of each detrimental effect considered separately.

To conclude, although only limited data are presently available regarding effects of surface condition, it is already clear from the above studies that straightforward multiplication of environmental and surface condition penalties in EAF assessments can be very conservative. Nevertheless, significantly more data are required to allow benefit in EAF assessments. Due to the potential significance of these results, surface finish was identified as one of the three main issues to be addressed by the INCEFA project [23].

3.2 Load form

Load form variability can arise from different types of regular cycle (e.g. saw tooth, sine wave, complex), or periodic changes in cyclic frequency, amplitude or wave form.

An example of data relating to different types of regular cycle come from AREVA tests[10] performed in both air and PWR water (lithiated, hydrogenated and borated) environments at 300°C using solid 304L stainless steel test specimens. Tests involved strain control using a triangular waveform or a complex loading signal at various strain rates and strain amplitudes (surface finish was also a variable for some tests as described in section 3.1).

Four different complex waveforms were used as illustrated in Figure 8. Complex waveform Type A (top left in figure) was representative of a double thermal shock transient, i.e. a cold shock followed by a hot shock occurring in a PWR safety injection system. The remainder of the waveforms (B, C and D) were modified by rearranging portions of the original waveform labelled 1, 2, 3 and 4 to evaluate the effects of the position (in compression or in tension, and relative to the other portions of the transient) of the lowest strain rate parts on the fatigue lifetime. As already noted, strain amplitude was also a variable for these tests. At a strain amplitude of 0.6%, all four complex waveforms share the same 5.9 F_{en} factor using the strain integral method (or modified rate approach) for computing strain rate as defined by NUREG/CR-6900.

The test results revealed actual F_{en} factors for the complex waveforms in the range 1.5 to 3.8. The lowest F_{en} factors were for the tests where the low strain rates were in the compressive part of loading, whereas higher F_{en} factors arose when the low strain rates coincided with tensile loading. The variability in F_{en} factor for the different transients was attributed to whether the fatigue cracks would be open or closed during the slow strain rate phases. During triangular waveform cyclic loading with a similar strain rate the test programme results demonstrated a F_{en} factor of 5.1 for polished specimens which is reasonably in agreement with the NUREG/CR-6909 value of 5.9. This good agreement makes it more significant that for the plant representative waveform (Type A above) the F_{en} factor reduces to ~2.2-2.8. These results strongly support further work to increase data and understanding sufficiently to support relaxation of the NUREG/CR6909 guidance for realistic transients.

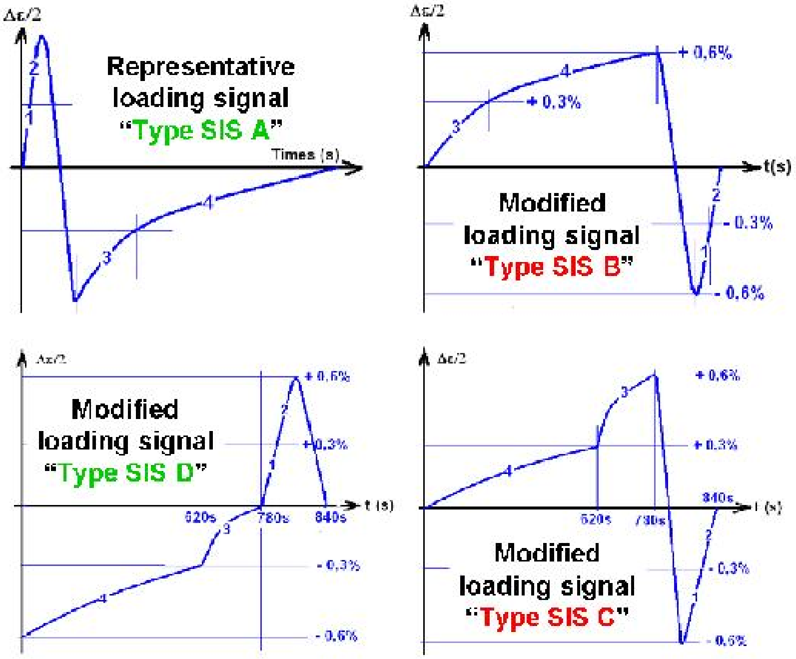


Figure 8: Illustration of load waveforms used in AREVA tests[10]

Another example of the effect of changes in the form of cycling on fatigue was demonstrated for fatigue tests in room temperature air on solution annealed niobium stabilized austenitic stainless steel (X6CrNiNb1810 mod) reported by E.On and VTT [26]. For these tests cycling was performed firstly at strain amplitudes above the fatigue threshold, and then finally at a strain amplitude below the threshold. Although cumulative fatigue usage exceeded unity before the strain amplitude was reduced below the fatigue threshold, it proved impossible to achieve failure before fatigue usage exceeded 2. In subsequent testing in the same programme, two interrupted tests continued at a higher strain amplitude after run-out at a strain amplitude below the endurance limit. These specimens lasted at the second level longer than virgin specimens. In particular, a specimen strained for 10^7 cycles at an initial 0.19 % amplitude exhibited superior behaviour in continued testing at 0.22 % strain amplitude. In terms of cumulative damage calculation, the cycles at the lower amplitude caused "negative" damage. The behaviour in both types of test was attributed to cyclic hardening and is indicative of relaxed fatigue assessment possibilities for situations when strain amplitudes vary over equipment lifetime.

3.3 Hold time

E.ON and VTT [38] have been studying the effects of hold times during fatigue testing in air. The test technique involved cyclic loading at room temperature in air, interrupted periodically for holding in air at elevated temperature under no load. A variety of stainless steels were tested. The data available to date are not adequate for definite quantitative assessment, but, qualitatively, it is clear that non-stressed holds at high temperature lead to an increase in fatigue life. It is suggested that the effect could be influenced by strain hardening and it is likely to be more pronounced with more frequent holds as would occur in real plant operating conditions. The results of this hold test campaign are summarised and presented in terms of the strain life curve model in Figure 9. The current understanding from this work is summarised as follows:

- The hardening effect is generic for stainless steels. It has been found in all grades studied so far, including 304L, 316L and titanium and niobium stabilised materials.
- Hardening occurs irrespective in which phase of the cycle the holds are introduced.

- Hardening occurs in all temperature combinations between room and normal operating temperatures, but it is more effective when cyclic strain occurs at low temperature and hold at high temperature.
- Hardening reduces cyclic plastic strain and thus extends the fatigue life. Life extension is largest at low strain amplitude, i.e. in the high cycle region.

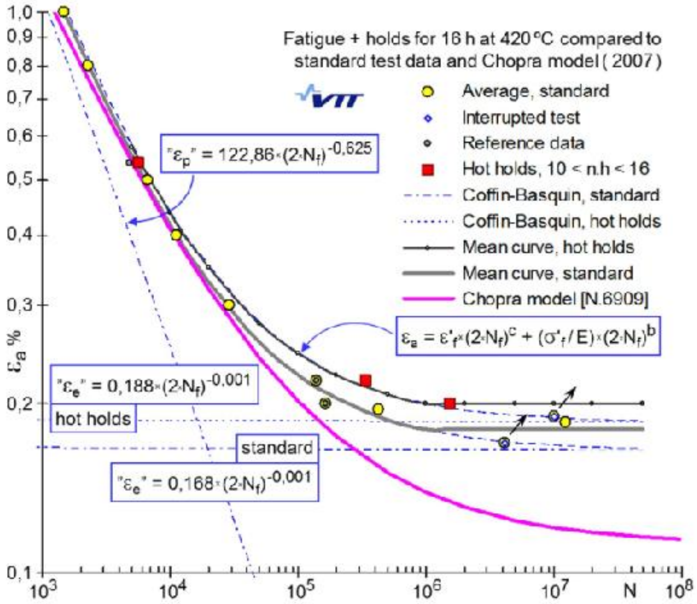


Figure 9: Effect of hot holds on SN curve model for niobium stabilised stainless steel [38]

A limited number of studies have explored hold time effects in LWR environments [40, 41].

Medway et al[51] tested the effects of hold time for blunt notch compact tension specimens in 300°C LWR environment, albeit for carbon steel not stainless. Longer fatigue life occurred when holds were at maximum load than when the holds were at minimum load. This was attributed to possible crack blunting at the maximum load.

Higuchi et al [40] tested 316 stainless steel specimens in BWR and PWR water, firstly with holds at peak strain and then with holds below peak strain (BWR water only). There was no effect of holds at peak strain in PWR water on fatigue life; whereas in BWR conditions there was an effect at high strain rates with fatigue life reducing as hold time increased. In BWR conditions the fatigue life reduction due to holds disappeared when the holds were below peak strain for a specimen in which strain was held at peak minus 0.06% and holding stress was about yield stress of the material. These tests were all in the Low Cycle Fatigue region.

Seifert et al[41] studied the effect of static load hold times of 6 to 744 h on corrosion fatigue life of low- and high-carbon and stabilised austenitic stainless steels with both sharply notched and pre-cracked fracture mechanics specimens in simulated boiling water reactor (BWR) hydrogen (HWC) and normal water chemistry (NWC) at 288°C. There was no significant effect of long static load hold times on short and long corrosion fatigue crack growth rates in BWR/HWC & NWC environment in solution annealed SS. Since there was little effect of hold times on corrosion fatigue initiation life it was judged that the current NUREG approach remained adequate, as was the assumption that saw tooth loading usually gives an upper bound for environmental effects on CF initiation (and crack growth) at low (BWR/HWC, PWR) and high ECPs (BWR/NWC). As with the Japanese work, these tests were all focussed on Low Cycle Fatigue.

3.4 Material composition

Section 2.2.2 described initiatives underway to reduce data uncertainties and thereby justify reductions in factors of safety used to translate fatigue curves into curves that are suitable for safety justifications. Section 2.5 also described the developments of fatigue assessment codes in France that are taking advantage of observed improved statistics for French data arising from the more limited selection of materials relevant to plant in France compared to the database underlying the NUREG/CR-6909 analysis.

E.ON and VTT [38] have generated data aimed at supporting a less conservative reference curve for the stabilised steels which are used on plant in Germany than is recommended by NUREG/CR-6909[4] based on data obtained on non-stabilised grades. Strain controlled constant amplitude tests demonstrated good long life performance at room temperature, Figure 10. Comparison to the NUREG/CR-6909 reference curve for non-stabilised steels revealed a notable difference at low strain amplitudes (i.e. in the high cycle region of the ε-N curve). Similar data for a titanium stabilised stainless steel, also sampled from real NPP piping, was added for comparison. The trend was the same for both these stabilised steels. On the basis of these results it has been suggested that the ASME Code Section III (2010) design curve[1] may not be appropriate for fatigue assessment of components fabricated from stabilised stainless steel grades in general, and especially for the X6CrNiNb1810 and O8X8H10T steels investigated.

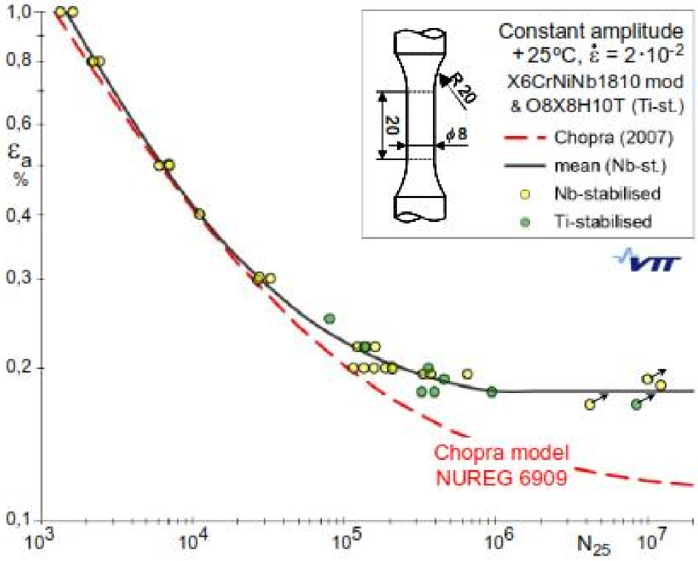


Figure 10: Fatigue data for two stabilized steels[38]

Recent data suggest that material composition effects may be significant even for non-stabilised stainless steels. Data obtained by Platts et al. on a heat of Type 304L stainless steel (39) also appear to show a substantially higher fatigue limit than the 0.12% value indicated by the NUREG/CR-6909 reference curve and the ASME III (2010) code design line.

3.5 Mean stress/strain

It is widely accepted that mean stress can be detrimental to fatigue life. For this reason the air curve for stainless steel recommended by ASME (Figure 1) contains an allowance for possible effects of mean stress. The adjustment has been made using the Modified Goodman approach which provides a means of determining the fatigue endurance limit for given values of alternating stress amplitude and mean stress. (Figure 11 shows a basic Goodman diagram). The adjustment determines the maximum permissible mean stress defined by Modified Goodman for a given stress amplitude, then the measured stress amplitude is reduced to that which would be expected given the assumed mean stress. The approach is acknowledged to be conservative in NUREG/CR-6909[4] for several reasons, including:

- Assumption of maximum possible mean stress, when actual mean stress may be lower.
- Data already available and referred to by NUREG/CR-6909 indicate that the actual effects of mean stress on fatigue life can vary significantly within the range defined by the Modified Goodman approach, being affected, for example, by temperature and whether or not loading is stress or strain controlled. Indeed, for load controlled tests at high temperatures or large levels of mean stress, the fatigue limit has been reported to increase [42]. This is attributed to secondary hardening, which may vary between different heats and grades of stainless steel.

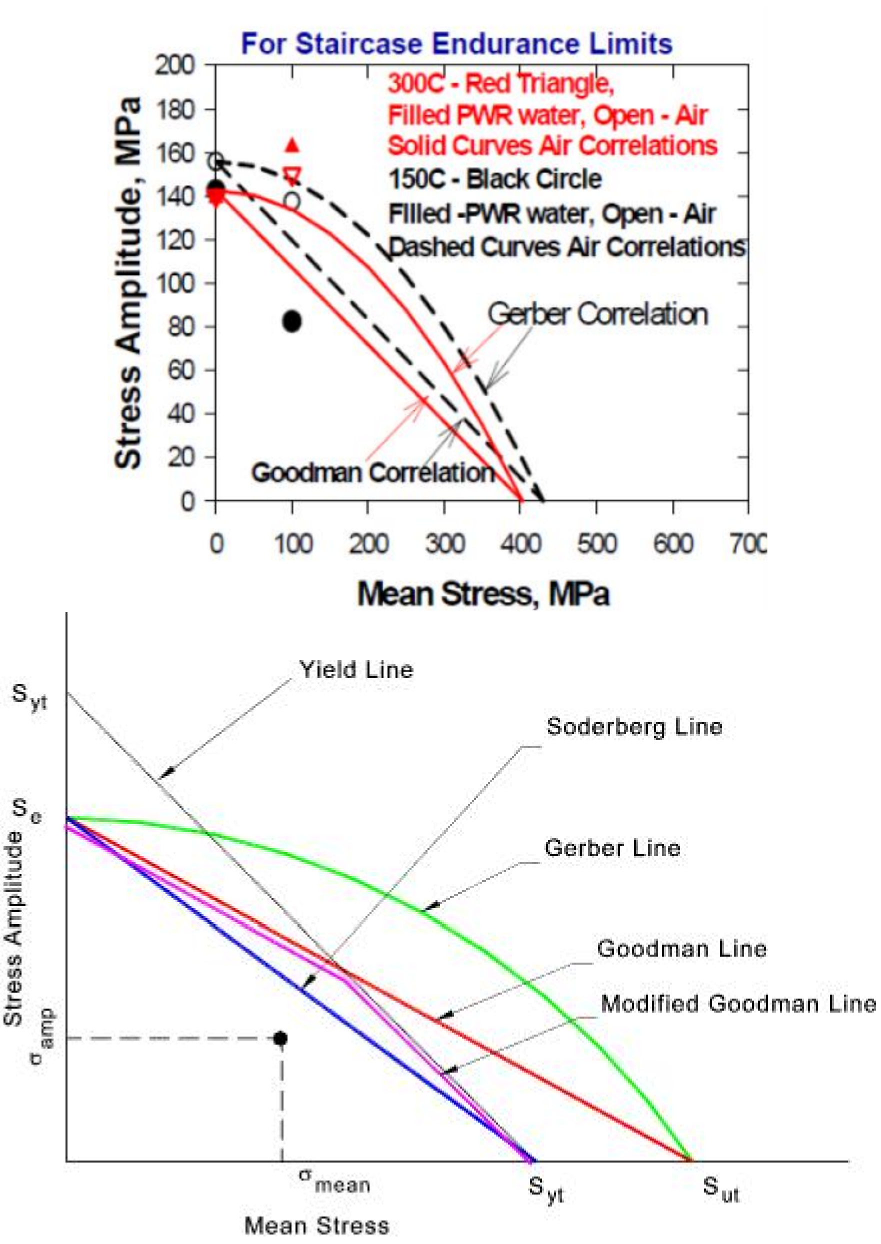


Figure 11: a) Goodman diagram for austenitic stainless steel, with fatigue endurance data in air and PWR water[42]
b) Generalised Modified Goodman diagram

Work is underway in France (EDF, AREVA and CEA), where tests are being conducted under a range of conditions:

- an imposed level of mean stress with stress controlled cyclic loading.
- an imposed level of mean stress with strain controlled cyclic loading.
- an imposed level of mean strain with strain controlled cyclic loading.

Findings so far[43] have shown that mean stress is more detrimental in strain control than in stress control for a 304 steel. However, presently the tests remain inconclusive and subject to interpretation and they therefore continue. Some early results are available and are presented in Section 3.9 as examples of the interdependence of sensitivities.

3.6 Temperature

E.ON and VTT[27] have for a few years been studying possible conservatism introduced into environmental fatigue assessments through use of factors intending to allow for temperature effects. Through a series of tests in air and PWR environments and various temperatures (25, 200 and 325°C), strain rates ($4x10^{-6}$ to $1x10^{-4}$/s) and strain amplitudes (endurance limit up to ~0.5%), the effects of temperature in air have been separated from the effects in water for solution annealed niobium stabilized austenitic stainless steel (X6CrNiNb1810 mod).

The concern being addressed is possible conservatism through double counting the effects of temperature, firstly in determining stress amplitude according to ASME III guidelines, and then in determining F_{en} factor as per NUREG/CR6909 guidance. The results indicate that conservatism is most pronounced at low strain amplitudes below 0.25%. The conservatism is illustrated in Figure 12 where, for all except one matching point, the NUREG predictions are much more conservative than the results from the tests.

Interim conclusions from the work state that conservatism could be reduced by separating temperature effects completely from environmental effects, so as to reduce the risk of double counting temperature effects. It is also acknowledged that some of the apparent conservatism could derive from the use of stabilised stainless steels in the tests compared with non-stabilised grades for the tests upon which ASME and NUREG guidelines are based (see section 3.4). Work is needed to separate any material effects if the conservatism associated with temperature is to be quantified sufficiently to be allowed for in fatigue assessments, particularly for non-stabilised grades of material.

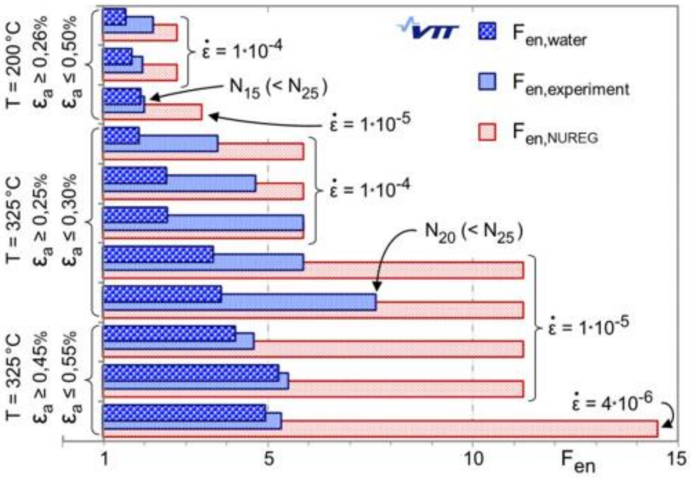


Figure 12: Comparison of predicted and measured effects of environment[27]
($F_{en,water}$ = F_{en} due only to water environment

$F_{en,experimental}$ = Overall F_{en} apparent from experiments
$F_{en,NUREG}$ = NUREG/CR6909 calculated F_{en})

3.7 Thermal and mechanical load phasing

In Japanese tests [34-36], the fatigue life of austenitic stainless steel in low-DO environments in TMF tests with in- and out-of-phase thermal cycling was comparable to that in isothermal tests at the average test temperature of the TMF tests (beyond the temperature and strain thresholds for environmental effects). As expected, the fatigue lives of the in-phase tests are shorter than those for the out-of-phase tests. For the thermal cycling tests, fatigue life is longer for out-of-phase tests than for in-phase tests, because applied strains above the threshold strain occur at high temperatures for in-phase tests, whereas they occur at low temperatures for out-of-phase tests. The methodology proposed from this work to allow for these effects is referred to as the ‘Modified Rate Approach’.

Work at PSI[44] addressing thermo-mechanical fatigue reported through the INCEFA project[23], shows similar behaviour to that seen in the Japanese work. Figure 13 clearly shows a difference in environmental fatigue behaviour depending on phasing of thermal and mechanical loading. The Thermo Mechanical Fatigue (TMF) life is between that of the isothermal LCF tests at minimum and maximum temperature. The in-phase TMF life is shorter than that of out-of-phase TMF and close to the LCF life at maximum temperature. The out-of-phase TMF life is close to that of LCF at minimum temperature. The shorter in-phase TMF life is not unexpected based on the temperature effects, because the applied strains above the threshold strain for environmental effects (~ 0.125 %) occur at the high temperatures in in-phase TMF tests, whereas they occur at low temperatures for out-of-phase TMF experiments.

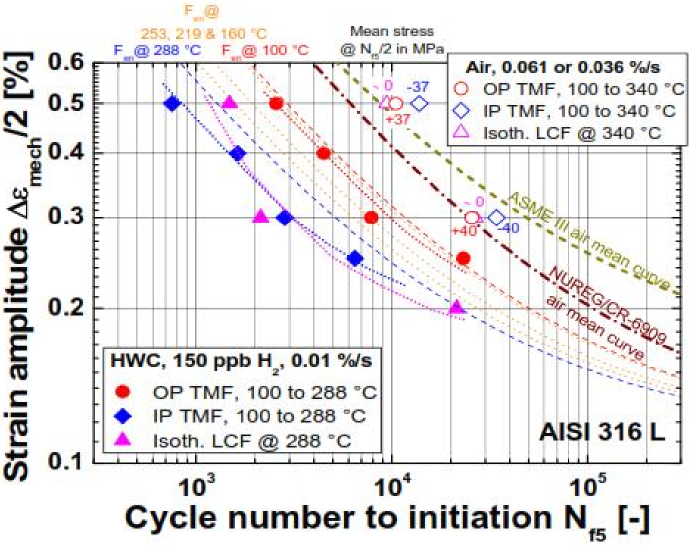


Figure 13: Comparison of fatigue life times of In-Phase (IP) and Out of Phase (OP) Thermo Mechanical Fatigue and Low Cycle Fatigue at 288 °C in BWR/HWC to IP and OP TMF and LCF at 340 °C in air and to ASME III and NUREG/CR-6909 air mean curves[44]

3.8 Non-unidirectional loading

Multiaxial loading is known to result in diminished fatigue lives for a number of steels [28-33]. Unfortunately data do not exist for austenitic stainless steels of the types used in PWR plant. Work is underway at the CEA in France to address this. The test configuration is shown in Figure 14. In the latest unreleased draft of NUREG/CR-6909 it is explicitly stated that present conservatisms in current fatigue assessment guidelines do not allow for multiaxiality, which is instead addressed through design procedures. Nevertheless, if conservatism in these procedures is to be reduced then effects of multiaxiality do need to be better understood.

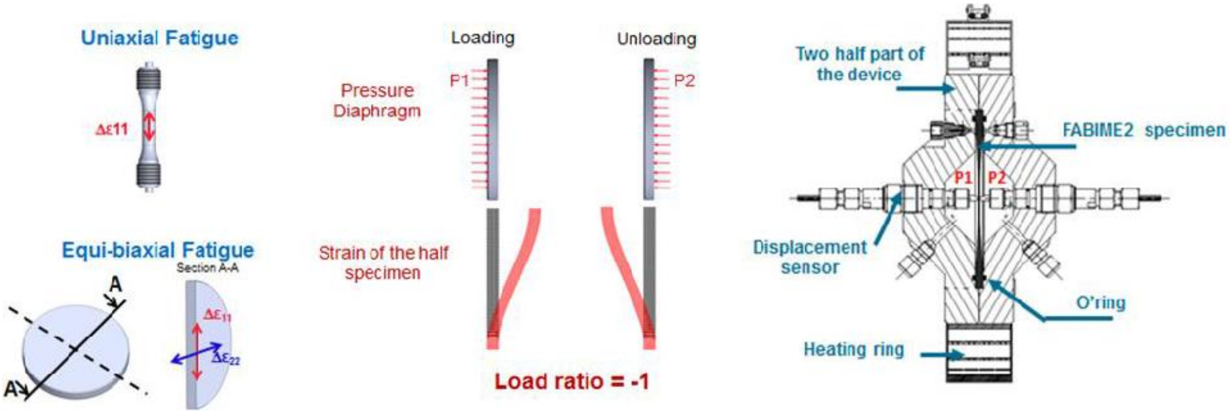


Figure 14: Proposed multiaxial test configuration in CEA tests

3.9 Inter-dependence of sensitivities

If environmental fatigue susceptibility varies differently with respect to a primary parameter according to the value of a secondary parameter, then the two sensitivities may be defined as inter-dependent. Examples demonstrating inter-dependence of sensitivities arise from many programmes addressing environmental fatigue. Examples of inter-dependence revealed by recent test programmes are:

- In the AMEC tests summarised in Section 3.1, the effects of surface condition were lower in water than was apparent in air.
- In the AREVA tests summarised in Sections 3.1 and 3.2 the effects of water on environmental fatigue susceptibility varied with both surface condition and waveform.
- French (EDF and AREVA) work (presently unpublished) shows greater effects of surface finish when there is mean stress, with the effects increasing as mean stress rises from zero to 200MPa.
- Taheri et al [45] found that shot blasting had no benefit when there was mean stress (Figure 15).
- Although not as recent, it is also worth recalling that the tests already referred to in the context of mean stress [42], revealed different effects of mean stress on fatigue life in air compared to in water, as well as differences depending on whether tests are strain or stress controlled.

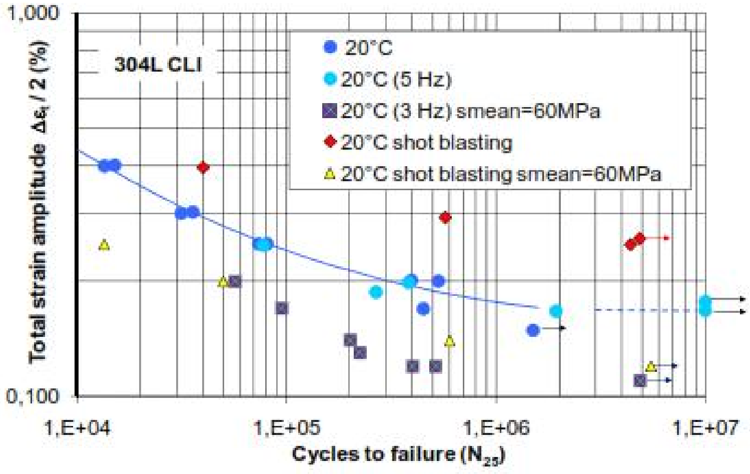


Figure 15: Combined effects of shot blasting and mean stress for 304 stainless steel tested in air[45]

4 Ideas for improving understanding to the benefit of assessment capability

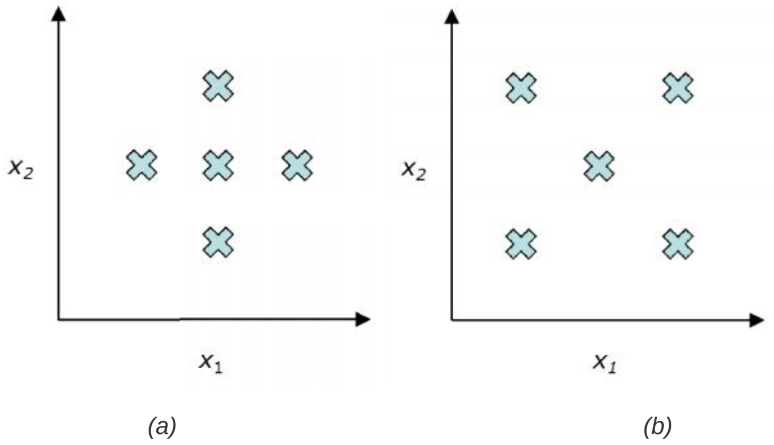
It is evident from the contents of this paper that there are a number of significant activities within and outside of Europe in pursuit of improved environmental fatigue assessment capability. It is of course important for these activities to remain focussed on maximum benefit to the overall objectives. In this respect a number of ideas generated during the in-kind phase of the European collaborative project INCEFA warrant discussion [23]. These ideas can be grouped as follows:

- Strategies to maximise experimental benefit.
- Possible benefits to be gained from increased mechanistic understanding.

4.1 Maximising experimental benefit

Collaborative projects increase the volume of data available for guiding development of assessment rules, whilst managing costs associated with testing for each contributor to the collaboration. JRC will guide the testing for INCEFA based on a statistically-based Design of Experiments (DoE) methodology [46].

Traditionally, many test matrices are planned according to the principle that only a single parameter is varied at a time so that the impact of the single parameter on the test outcome can be studied. A resulting test plan for two independent variables and five test runs is shown in Figure 16(a). The test plan in Figure 16(b) is less intuitive since the values of the independent variables x_1 and x_2 are changed simultaneously. However, in contrast to the one in Figure 16(a) it allows capturing interactions between x_1 and x_2: the impact of a change of the value of x_1 on the outcome of the test may depend on the value of x_2. For example, increasing the applied force in a creep test may reduce the lifetime at elevated temperature but will have no influence at low temperature where there is no creep.



(a) (b)

Figure 16 Distribution of the values of the two independent variables x1 and x2 when only a single parameter is varied (a) to a DoE based approach where several factors are varied simultaneously (b).

Design of Experiments is a means to optimize the distribution of (a limited number of) test runs in order to maximize the information than can be gained. It is, in principle, a better approach for a screening test program than varying a single variable at a time since it allows capturing interactions between several variables, although a statistical evaluation of the resulting data is required. A two-level screening experiment allows determining the major influences from main effects as well as from interactions with a reasonable number of tests (maximum 32 for 5 independent variables). For collaborative programmes across a number of laboratories the methodology enables an additional variable "laboratory" to be used to take the inter-laboratory variations into account. By including this variable directly into the experimental design a round robin exercise would be rendered unnecessary thus increasing the number of runs to be used for the actual test program.

4.2 Increased mechanistic understanding

As their contribution to the in-kind component of the INCEFA project [23], VTT performed a literature review gathering mechanistic insight from studies of Stress Corrosion Cracking (SCC) and considering possible relevance to studies of environmental fatigue. The review concluded that there are some issues that usefully could be examined more closely in future environmental fatigue experiments:

(a) Near -surface microstructural characterisation of specimens from tests interrupted at different points along the cyclic strain hardening curve could give important insight into the crack initiation precursors between the different LWR environments (PWR and BWR) which should provide insight into the rate controlling processes influencing fatigue as well as elevated temperature secondary hardening. Examination of fracture surfaces and cracks from fatigue initiation tests does not appear to be a very widely published activity. A few examinations are described in NUREG/CR-6787[47], but for only a few specimens. Some differences in the morphology of initiated cracks between air, BWR and PWR environments were found, but no strong conclusions were offered that could explain the worse corrosion fatigue performance in a PWR environment [47].

(b) The relevance of localised plasticity models in conjunction with hydrogen and/or vacancy injection could be tested for non-monotonic scenarios through a test matrix targeting regimes where hydrogen effects may be most important, with materials pre-fatigued in a manner promoting the formation of persistent slip bands, alpha martensite, and other localised deformation structures (perhaps in conjunction with DSA). If such tests were conducted with a focus on enabling microstructural characterisation rather than generating empirical data, the extent to which localization of strain may be an important precursor to crack initiation could possibly be determined. Factors to examine might include examination of surface features and characterisation of deformation microstructures at different key points along the evolving cyclic stress-strain curve. Murakami[48] performed studies similar to those suggested here. Hydrogen content was measured in various materials (including stainless steels) to assess the effects of hydrogen on fatigue crack growth behaviour. Hydrogen content was found to affect the sensitivity of the fatigue behaviour to load frequency and to localisation of fatigue slip bands.

(c) Another useful exercise would be a fracture-mechanics based comparison between the calculated crack-tip loading conditions under monotonic versus non-monotonic conditions, based on the typical test configurations and parameters in the different kinds of tests. In NUREG/CR-6787[47] Chopra points out that the presence of well-defined striations suggests that mechanical factors are of key importance, whereas a slip/dissolution mechanisms may not leave such clear striations. Likewise, scenarios with fully reversed loading cycles can produce more complicated plasticised zones ahead of the crack tip, including both compressive and tensile stress regions. A comparison of the stress intensity factors in different scenarios could reveal the regimes in which results from monotonically loaded test specimens are most relevant to a non-monotonically loaded specimen or scenario.

5 Conclusions

Throughout 2013, twelve organisations from ten European countries collaborated to develop the State of the Art from a European perspective with regard to EAF assessment for stainless steels in LWR environments. Contributions covered:

1. Status of EAF assessment methodologies, particularly in France, Japan, the USA, and the Czech Republic.
    a. Although many of the reviewed methodologies are broadly similar in concept, there are nonetheless some interesting variations in detail:

        i. Different transference factors used to derive air design curves from mean data curves.
        ii. Different approaches to calculation of environmental factor (F_{en}) produce different F_{en} factors for the same transients.
        iii. Some procedures assume a high level of conservatism to avoid the need to allow explicitly for environment, although it is difficult to quantify the degree of conservatism under all conditions using this approach.
    b. Current approaches to improving assessment practices include:
        i. Increased mechanistic understanding.
        ii. Justified reduced data scatter.
        iii. Data obtained under complex (plant relevant) lading transients
        iv. Introduction of better quantified transference factors, both for factors currently included in ASME and NRC procedures as well as for a range of issues not presently considered explicitly.
        v. Improving the reliability of transient modelling in assessments.
        vi. Allowing for phasing of thermal and environmental transients.
        vii. Allowing for non-uniform stressing.
    c. Through collaboration some of these initiatives are being combined to greater effect.
2. Data providing evidence of problems in current fatigue assessment procedures. Gaps in understanding which are being tackled to justify reduced conservatism include the effects of:
    a. surface condition
    b. load-form
    c. temperature
    d. non-unidirectional loading
    e. thermal and mechanical load phasing
    f. material condition
    g. hold time
    h. waveform effects
    i. mean strain/stress
    j. inter-dependence of sensitivities
3. Ideas for test programmes to maximise opportunities to reduce uncertainties:
    a. Maximising experimental benefit
    b. Increased mechanistic understanding

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