Review of Provisions on Corrosion Fatigue and Stress Corrosion in WWER and Western LWR Codes and Standards

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ABSTRACT

Results are presented from a collaborative project performed on behalf of the European Commission, Working Group Codes and Standards. The work covered the contents of current codes and standards, plant experience and R&D results.

Current fatigue design rules use S-N curves based on tests in air. Although WWER and LWR design curves are often similar they are derived, presented and used in different ways and it is neither convenient nor appropriate to harmonise them. Similarly the fatigue crack growth laws used in the various design and in-service inspection rules differ significantly with respect to both growth rates in air and the effects of water reactor environments. Harmonised approaches to the effects of WWER and LWR environments are possible based on results from R&D programmes carried out over the last decade. For carbon and low alloy steels a consistent approach to both crack initiation and growth can be formulated based on the superposition of environmentally assisted cracking effects on the fatigue crack development. The approach indicates that effects of the water environment are minimal given appropriate control of the oxygen content of the water and/or the sulphur content of the steel. For austenitic stainless steels a different mechanisms may apply and a harmonised approach is possible at present only for S-N curves. Although substantial progress has been made with respect to corrosion fatigue, more data and a clearer understanding are required in order to write code provisions particularly in the area of high cycle fatigue.

Reactor operation experience shows stress corrosion cracking of austenitic steels is the most common cause of failure. These failures are associated with high residual stresses combined with high levels of dissolved oxygen or the presence of contaminants. For primary circuit internals there is a potential threat to integrity from irradiated assisted stress corrosion cracking. Design and in-service inspection rules do not at present provide quantitative treatments of stress corrosion crack initiation and growth. Code provisions are limited to advice on avoidance by materials selection, stress control and water chemistry control. Upper bound stress corrosion crack growth laws for austenitic stainless steels have been published by Regulatory Authorities. They have limited relevance in the light of subsequent developments in water chemistry control.

KEY WORDS: nuclear, LWR power plant, design codes, corrosion fatigue, stress corrosion cracking.

1. INTRODUCTION

This paper reviews provisions in current Codes and Standards covering corrosion fatigue and stress corrosion cracking (SCC) in steels for LWR, BWR AND WWER. In addition a review of WWER and LWR plant experience has been performed together with an assessment of R & D data. The main purpose is to compare current provisions and recommend improvements based on a harmonised approach.

The work was done within a collaborative study [1] lead by NNC who covered Western LWR Rules. WWER Rules were covered by experts from E-N-E-S of Russia and from Vitkovice and Dukovany of the Czech Republic. The study was initiated and financed by the Working Group Codes and Standards (WGCS), an advisory group of the European Commission.

2. DESIGN AND IN-SERVICE INSPECTION CODES

2.1 Identification of Design and In-Service Inspection Codes

The WWER reactors in operation in the Russian Federation and elsewhere are designed and constructed according to the Soviet (Russian) PNAE Codes with some changes used in a few countries (i.e. Czech Republic) where a new design code is being introduced. Russian in-service inspection procedures include fatigue crack growth laws. Western LWR codes on the other hand have a strong dependence on the ASME Boiler and Pressure Vessel Code. Design rules for the most important components appear in ASME III while the in-service inspection rules of ASME XI contain crack
growth laws. The RCC-M rules represent a European code based originally on ASME but with some changes based on European practice and R and D inputs.

### 2.2 Corrosion fatigue provisions

#### 2.2.1 Endurance curves

LWR rules based on the ASME Code provide design fatigue curves derived from fully reversed, strain controlled tests in air at room temperature. Mean curves for material types (mild steel, low alloy steel, austenitic stainless steels etc.) are fitted to collected data. The design curves are then derived by applying reduction factors of 20 on cycles or 2 on stress whichever gives the lower endurance at a given stress amplitude. A mean stress correction at high cycles is then applied, based on the Goodman diagram.

Design curves for four material types at different temperatures are given which extend up to $10^9$ cycles and in some cases up to $10^{11}$ cycles depending on material. In the high cycle regime up to three curves are provided to cover different levels of the maximum stress in the cycle.

In the Russian rules design fatigue relationships are presented and used in equation form that allows the designer considerable flexibility. A full description of their derivation and application to corrosion fatigue is given in another paper at this conference [2]. It is noted here that temperature dependent fatigue curves are calculated using equations of the Coffin-Manson type. Rules are provided so that designer may determine the parameters in the Coffin-Manson equation from the measured or specified tensile properties of his material (Yield Stress, UTS, % Reduction of Area and Modulus of Elasticity). Comparisons with fatigue data for particular grades of steel confirm that curves based on specified tensile properties provide a lower bound to measured endurances. A term is included in the equation for the effect of cycle asymmetry (mean stress) based on the Savelyev-Gillemot diagram (modified Goodman diagram). Additional life reduction and/or strength reduction factors may also be incorporated to allow for the presence of welds and the water environment. Factors of 2 on stress amplitude and 10 on cycles are incorporated into the equation to give the code allowable number of cycles. Lower factors may be used in some circumstances e.g. when thermal stresses dominate the loading.

At low cycles the ASME factor of 20 on cycles is intended to cover data scatter (x2), size effects (x2.5) and surface finish /‘mild environmental’ effects (x4). It is therefore to be expected that a factor of 10 applied to the lower bound Russian curve should produce a similar design curve to ASME and this is usually found to be the case.

#### 2.2.2 Crack growth laws

Fatigue crack growth laws appear in either code provisions or in special procedures associated with in-service inspection requirements and take the form of a ‘Paris Law’:

$$\frac{da}{dN} = C_0 \cdot (\Delta K)^n$$

Both Western and Eastern European codes define reference curves that are upper bounds for combinations of material type (carbon, low alloy, stainless steel) and environment (air, low or high oxygen water at LWR temperatures). Russian practice also allows use of the air curves for preliminary assessments of water-exposed flaws with crack growth rates increased by a factor of 10 in the case of carbon and low alloy steels.

The effects of the cycle asymmetry, $R = K_{\min}/K_{\max}$, may be included by specifying appropriate values of $C_0$ and $n$ or by using an effective value of $\Delta K$. For low values of $R$, Figure 1 shows that there is close agreement between the ASME, RCC-M and AME laws for crack growth in air over most of the range of $\Delta K$ values considered. The AME code includes a steeply rising line ($n = 15.2$) at low $\Delta K$ based on near threshold behaviour. Growth rates according to the original Russian M-02 procedure and its proposed modification were higher than in the other codes. For values of $R$ up to 0.7 the ASME code, the revised M-02 procedure and the RCC-M code agree quite closely. At high values of $R$ the three codes diverge, the revised M-02 code giving large shifts as $R$ approaches unity.

The fatigue crack growth laws for low alloy steels in water (see Figure 2) on the other hand differ markedly with respect to crack growth relationships for a given environment. The AME code uses very conservative upper bounds incorporating near threshold laws with high $n$ values for both air and water. Very high environmental factors (>100) are associated with these near threshold laws. The Russian code equations give the lowest crack growth rates in water but the crack growth rates in air are conservative when compared with other codes. Consequently environmental factors are well below the factor of 10 specified for preliminary assessments. The RCC-M code uses a conservative upper bound to water data when compared with ASME. This arises in part because the RCC-M laws are based on an earlier version of the ASME laws but with a modification having interim status pending completion of test programmes in France.
There is relatively little information on the effects of LWR environments on austenitic stainless steels. Only the AME code gives a crack growth law in water. It covers low values of R and indicates a modest increase in crack growth rate (up to a factor of five). The Russian procedure applies a factor of 10 to air data to allow for high oxygen water environments, consistent with the AME code, at least for low values of R. The Russian procedure applies a factor of 2 for low oxygen water environments. These factors are not consistent with the effects of water on the fatigue endurance curves of austenitic stainless steels.

**FIGURE 1. FATIGUE CRACK GROWTH RATES FOR LOW ALLOY STEELS IN AIR AND WATER**

![Graph showing fatigue crack growth rates for low alloy steels in air and water.](image)

### 2.3 Stress corrosion cracking

#### 2.3.1 Avoidance of crack initiation

Until very recently service degradation mechanisms such as stress corrosion cracking SCC were not addressed explicitly in design codes. In 1999 ASME published Appendix W ‘Environmental Effects on Components’ which provides designers descriptions of various damage mechanisms and identifies measures to avoid or mitigate damage based on the classical combination of materials selection, stress control and water chemistry control.

Materials selection examples include the use of L and Nuclear grade austenitic stainless steels, the avoidance of IGSCC in high strength bolting by specifying minimum yield strengths less than 840 MPa and modified heat treatment and composition of Alloy 600 for PWR steam generator tubes.

Stress control recommendations include minimising both stresses due to applied loads and residual stresses from welding, fabrication or installation. Shot peening, heat sink welding, induction heating stress improvement and mechanical stress improvement are identified as methods of inducing compressive residual stress states at the interface between the metal and the corrosive environment.

Water chemistry control measures include avoiding stagnant fluid regions and crevices including those produced at weld joints by integral back-up rings or bars. Cleanliness during fabrication is important in avoiding contaminants. It is emphasised that water chemistry control is vital at all stages of plant operation to maintain low oxygen levels and avoid contamination, particularly by sulphates, chlorides or fluorides.

#### 2.3.2 Crack growth laws

None of the main codes contain quantitative provisions on stress corrosion crack growth rates with respect to material, loading and environment as is the case for corrosion fatigue. Some upper bound crack growth laws for austenitic stainless steels under constant load have been published by American and Swedish regulators. Relationships between crack growth rate in mm/sec and the applied stress intensity factor $K_I$ in MPam$^{1/2}$ take the form:

$$\frac{da}{dt} = A K^m$$
In 1988 the USNRC [3] recommended values of $A = 2.07 \times 10^{-10}$ and $m = 2.161$ based on data from the USA and Japan, covering ‘practical BWR conditions’. Recommendations by the Swedish Nuclear Power Inspectorate (SKI) in 1995[4] were based on data collected relating to three water chemistries. In each case $m = 3$ but values of $A$ varied widely depending on the conductivity $k$ in $\mu$S/cm and electrochemical potential (ECP) in mV (SHE):

- For high conductivity chemistry (HCC, $k > 0.3$): $A = 6.5 \times 10^{-11}$.
- For normal water chemistry (NWC, $k < 0.3$, ECP > -230): $A = 9.5 \times 10^{-12}$.
- For hydrogen water chemistry (HWC – $k < 0.3$, ECP < -230): $A = 2.57 \times 10^{-13}$.

3. PLANT EXPERIENCE

3.1 Generic problems in PWR steam generators and BWR’s

Stress corrosion cracking experience in the USA, Japan and Western Europe has been dominated by generic problems. These include inter-granular stress corrosion cracking at in austenitic stainless steel welds in BWR’s, primary and secondary side stress corrosion cracking in PWR steam generator tubing and stress corrosion cracking of ferritic/ martensitic steel bolting at LWR pressure boundaries. In each case the diagnosis of the problem and its solution has followed the classical route of improving material, stress and environmental factors. Water chemistry specification and control has taken a much more important role in recent years, particularly in cases (mill annealed steam generator tubing, BWR core shroud) where major economic penalties are associated with changing material or stress factors.

In the above cases the problems have been sufficiently widespread to impact on in-service inspection and assessment requirements, initially via special provisions in regulatory documents and subsequently in codes and standards. In the case of BWR piping ASME inspection requirements have been tailored in proportion to the assessed level of risk associated with the adopted mitigation measures.

3.2 Russian experience with Ti stabilised austenitic stainless steel

The review considered mainly experience in both stress corrosion cracking and intergranular cracking problems in the Ti stabilised austenitic stainless steel grade 08Kh18N10T. This steel grade has been used widely and successfully in reactor engineering but eleven cases of environmentally related cracking were described by Russian colleagues based on a survey of the ABM-200 and RBMK systems as well as WWER’s. SCC was identified as the failure mechanism in ten of the cases in each of which abnormal water chemistry conditions were present due to condensation/evaporation, crevices/stagnant regions, corrosion product deposition or inadequate control of water chemistry during testing and start-up. Residual stresses and/or sensitisation due to welding were also factors in eight of the ten cases of SCC.

Three cases were considered in which other materials were involved. In two cases stress corrosion cracking was associated with the use of austenitic stainless steels with higher (22 – 35%) Ni in crevice chemistry conditions. In the only case of stress corrosion cracking associated with a ferritic pressure vessel steel (10GN2MFA) very high residual stresses were induced in a crevice geometry by explosive expansion with no subsequent stress relief heat treatment.

4 R & D RESULTS LEADING TO HARMONISATION PROPOSALS

4.1 Corrosion fatigue design curves

A basis for harmonisation arises from substantial programmes of research and data analysis over the last decade in the USA and Japan. Critical environmental parameters for LWR’s have been identified and descriptions of their effects on fatigue endurance have been formulated. For carbon and low alloy steels, descriptions have been provided by Argonne National Laboratory (ANL) in the USA and by Higuchi and Iida in Japan. At the time of this study the most recent formulations from ANL [5] and Japan [6] had many features in common. The ANL approach (see Table 2) was considered preferable because it was based on a larger body of data, provided a clearer description of the effects of the various parameters and was also being applied to austenitic stainless steels.

The ANL model uses the following relationships between endurance $N$, strain amplitude $\varepsilon_a$ and environment:

For carbon and low alloy steels: $\log_e (N) = \alpha - \beta \cdot \log_e (\varepsilon_a - \gamma) + 0.101 \cdot S^* \cdot T^* \cdot O^* \cdot \varepsilon_{\gamma^*}$

For austenitic stainless steels: $\log_e (N) = \alpha - \beta \cdot \log_e (\varepsilon_a - \gamma) + T^* \cdot O^* \cdot \varepsilon_{\gamma^*}$

The parameters $\beta$ and $\gamma$ are based on the mean fatigue curve fitted to fully reversed, room temperature fatigue test results in air. Different values of $\alpha$ apply for room temperature air and high temperature water. The definitions of the environment parameters $T^*$, $O^*$, $S^*$ and $\varepsilon_{\gamma^*}$ in Table 2 above are such that major effects on fatigue life are indicated only when each of three thresholds (temperature, oxygen content and strain rate) is breached. There is also a critical
strain amplitude (~20% above fatigue limit, most likely corresponding to the rupture strain of the surface oxide film) below which environmental effects are not significant.

**TABLE 2. ANL ENVIRONMENTAL FACTORS FOR CORROSION FATIGUE**

<table>
<thead>
<tr>
<th>Effect</th>
<th>Parameter definition</th>
<th>Condition</th>
<th>Effect</th>
<th>Parameter definition</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Carbon and Low Alloy Steels</strong></td>
<td></td>
<td></td>
<td><strong>Austenitic Stainless Steels</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sulphur</td>
<td>S* = 0.015</td>
<td>DO &gt; 1.0 ppm</td>
<td>Temperature</td>
<td>T* = 0</td>
<td>T°C &lt; 180</td>
</tr>
<tr>
<td></td>
<td>S* = %S</td>
<td>DO &lt;= 1.0 ppm and 0&lt;S&lt;=0.015%</td>
<td></td>
<td>T* = (T-180)/40</td>
<td>180&lt;T°C&lt; 220</td>
</tr>
<tr>
<td></td>
<td>S* = 0.015</td>
<td>DO &lt; 1.0 ppm and S&gt;0.015%</td>
<td></td>
<td>T* = 1</td>
<td>T°C&gt; 220</td>
</tr>
<tr>
<td>temperature</td>
<td>T* = 0</td>
<td>T&lt;150°C</td>
<td>dissolved oxygen</td>
<td>O* = 0</td>
<td>DO &gt; 0.05 ppm</td>
</tr>
<tr>
<td></td>
<td>T* = T-150</td>
<td>150&lt;T°C&lt;= 350</td>
<td></td>
<td>O* = 0.26</td>
<td>DO ≤ 0.05 ppm</td>
</tr>
<tr>
<td>dissolved oxygen</td>
<td>O* = 0</td>
<td>DO &lt;= 0.05 ppm</td>
<td>strain rate</td>
<td>ε γ * = 0</td>
<td>ε γ ≥ 0.4 %/s</td>
</tr>
<tr>
<td></td>
<td>O* = loge(DO/0.04)</td>
<td>0.05 ppm&lt; DO &lt;= 0.5 ppm</td>
<td></td>
<td>ε γ * = loge(ε γ)/(0.4)</td>
<td>0.0004 %/s &lt; ε γ &lt; 0.4</td>
</tr>
<tr>
<td></td>
<td>O* = loge(12.5)</td>
<td>DO &gt; 0.5 ppm</td>
<td></td>
<td>ε γ * = loge(0.0004/(0.4))</td>
<td>ε γ &lt; 0.0004 %/s</td>
</tr>
<tr>
<td>strain rate</td>
<td>ε γ * = 0</td>
<td>ε γ ≥ 1 %/s</td>
<td></td>
<td>ε γ * = loge(0.001)</td>
<td>ε γ &lt; 0.001 %/s</td>
</tr>
<tr>
<td></td>
<td>ε γ * = loge(ε γ)</td>
<td>0.001%/s &lt; ε γ &lt; 1</td>
<td></td>
<td>ε γ * = loge(0.0001)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ε γ * = loge(0.001)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3 compares the most recent versions of the ANL and Higuchi-Iida models under conditions (sulphur content, temperature, strain rate) selected to produce maximum values of $F_{cn}$ at given dissolved oxygen contents according to the ANL model.

- There is agreement between the models that power law relationships describe the effects of strain rate and dissolved oxygen content over critical ranges.
- The ANL model incorporates upper and lower thresholds on both strain rate and dissolved oxygen content.
- Maintaining dissolved oxygen below 0.05 ppm ensures that $O^* = 0$. Environmental effects are mild (about a factor of 2) under these conditions and may be covered by existing design factors.

**FIGURE 3. VALUES OF $F_{cn}$ FROM RECENT STUDIES**
4.2 Crack growth laws

In the USA and Western Europe research and development on fatigue crack growth laws has followed lines similar to those for fatigue design curves. For carbon and low alloy steels, a detailed description of the effects of rise time, cycle asymmetry, sulphur content and water chemistry on crack growth rates has been formulated by workers at EPRI [7] but not included in the ASME Code. Examples of the resulting curves are shown in Figure 4.

**FIGURE 4. CRACK GROWTH RATES ACCORDING TO THE EPRI EQUATIONS**

For carbon and low alloy steels there is broad agreement that the effects on fatigue crack growth rates of a well controlled water environment with low oxygen and sulphur can be encompassed by applying a factor of two on reference fatigue crack growth curves in air. This is in line with the provisions of the Russian code and the results obtained from a comparison of similar low alloy steels used in Russia and Western Europe.

For low sulphur/low oxygen environments crack growth relationships are defined by a threshold level of \( \Delta K \) and a single Paris Law. When environmentally assisted cracking (EAC) contributes, the description incorporates additional curves and transition values. Both fatigue crack growth rates and \( \Delta K \) values may depend not only on the cycle asymmetry factor \( R \) but also on the rise time, i.e. the time for \( \Delta K \) to increase from zero or \( K_{\min} \) (if greater than zero) to \( K_{\max} \). Although the EPRI formulation provides a convincing description of laboratory test results it is not clear how it can be used in code rules. It may be necessary first to define a limited number of combinations of water chemistry, steel sulphur content and rise time for which growth laws can be defined.

5 DISCUSSION

On the basis of the information collected and analysed during the collaborative study it is possible to go some way towards introducing harmonised rules covering the effects of environmental factors on the fatigue strength and reliability of components.

For carbon and low alloy steels the crack initiation models developed at ANL and in Japan identify similar processes and critical factors to the crack growth models developed at EPRI. In both cases environmental effects are modeled as a superposition of the effects of static (stress corrosion cracking) crack growth mechanisms on fatigue mechanisms. It is considered that fatigue cycles are the only loadings capable of crossing the stress thresholds for stress corrosion cracking. There is agreement as to the critical variables. An important finding, common to the ANL and EPRI work is that significant environmental effects in new plant can be avoided by maintaining any one of the above variables within acceptable limits. Temperatures and strain rates may be inherent to the design of existing plant but practical ranges can be set for both DO and in replacement components, for S.
Proposals for changes to design fatigue curves have not been adopted by ASME. Instead ASME III Appendix W advises designers to avoid potentially damaging parameter values while pointing out that no known cases of crack initiation or failure have been ascribed to non-conservatism of the design curves.

From the comparison of WWER and PWR/BWR rules it is clear that valuable savings are associated with the use of tensile data to derive the basic fatigue curves in the WWER Code. A major effort would be required however to adapt this approach for use in PWR/BWR design rules. An approach based on harmonised environment factors in existing design fatigue curves seems to have better prospects for success. It is however necessary to address imperfections in the ANL and Higuchi models before considering harmonisation of environmental factors.

An important consideration is the role of the oxide film in the development of corrosion fatigue flaws. A threshold strain range is attributed to the oxide film cracking strain. Research into the details of oxide film damage, in particular at strain amplitudes comparable with the film cracking strain in monotonic tension, is important for refining the position of the corrosion fatigue curve in the high cycle region, particularly with regard to the effects of stress cycle asymmetry. Application of a modified Goodman diagram in the ANL statistical model to account for the cycle asymmetry effect at the level of 3 mm deep cracks has not been experimentally confirmed to date. This seems necessary given that all tests (ANL, Higuchi) were performed under fully reversed controlled strain cycles. Fatigue curves for thin walled structural components in water environments (thickness of up to say 3 mm and cracks 0.1 mm at ‘initiation’) may require special consideration leading to higher factors. The loading history of the oxide film may affect the threshold strain amplitude value in the corrosion fatigue curve. It should be noted that the available data have all been obtained in pressurised high-temperature water. Different effects may well occur in steam and steam-water mixtures that have not yet been studied.

It follows from the above that it is necessary to focus future studies on strain amplitudes near the film cracking strain level. A significant effort will be required to refine the position of the fatigue curve (particularly for cracks with depths of around 0.1 mm) under asymmetric non-steady loading in terms of both loads and temperature, with static loading between half-cycles, etc.

It is likely that a considerable effort will be required in the future to establish a format for harmonisation of crack growth laws based on the EPRI formulation. The effort must first be directed to resolving differences between existing codes with respect to crack growth rates in air and water. A second step will require feedback from plant operation to ensure that relevant chemistries are covered.

In the case of austenitic stainless steel, service experience shows that in both WWER and LWR the dominant causes of failures are transgranular or intergranular stress-corrosion cracking. These failures were associated with:

- High levels of residual stress particularly at welded and expanded joints.
- High levels of dissolved oxygen in BWR’s.
- Deviations of pH and electro-chemical potential from acceptable ranges in PWR’s.

The ANL corrosion fatigue model for austenitic stainless steel on the other hand implies that a hydrogen embrittlement mechanism operates at low dissolved oxygen contents. This requirement focuses attention therefore on water chemistry control measures to meet both the oxygen level criterion and an electrochemical potential criterion to avoid stress corrosion cracking.

For LWR internals with a long service life (60 years and more), conditions for irradiation-assisted stress corrosion cracking (IASCC) initiation need to be analysed to determine threshold irradiation doses and stresses as functions of the LWR environment composition (electrochemical potential) and impurities in the metal. As a first stage, it is expedient to prepare analytical overviews by qualified specialists with respect to the dominant degradation mechanisms and their interaction (based on published results and experience of operation).

6. CONCLUSIONS AND RECOMMENDATIONS

The work has brought together and addressed the major design code issues associated with environmental effects in corrosion fatigue and stress corrosion cracking. A concentrated information base has been provided for the development of LWR component assessment methods that incorporate the effects of the water environment.

For low alloy steels used for reactor pressure vessels of the WWER’s, PWR’s and BWR’s, corrosion fatigue effects have been modeled successfully by considering a superposition of the stress corrosion cracking processes on the fatigue
process. The model indicates that one or both of two parameters, the oxygen content of the water and the sulphur content of the steel can be so limited that corrosion fatigue effects become minimal.

A significant number of LWR failures have resulted from stress corrosion cracking of austenitic stainless steels under combinations of static and cyclic loading. Relatively little progress has however been made in quantifying the effects of mechanical, environmental and material variables on crack initiation and growth. Corrosion fatigue initiation effects have been attributed to hydrogen embrittlement while avoidance of stress corrosion cracking requires low oxygen contents or other measures to control the electrochemical potential. Special provisions in the area of water chemistry can meet both of these requirements.

Threats to the integrity of LWR internals come from the potential impact of irradiation assisted stress corrosion cracking. Analytical overviews of the problem are required in order to provide a basis for development of calculation methods for fatigue and static cracking of such components.

Further collaborative studies can be recommended in a number of areas. A high priority should be given to the provision and understanding of fatigue data in the high cycle regime by calculation and/or statistical analysis of experimental data. The role of oxide film rupture, the effects of stress asymmetry in the cycle and non-steady loading have yet to be properly measured or understood. There is also scope for harmonisation of calculation methods for use in WWER, PWR and BWR design and structural integrity assessments. This work has to cover both fatigue crack initiation and crack growth under cyclic and/or static loading. Analytical overviews covering irradiation assisted stress corrosion cracking are required to support the development of calculation methods for LWR internals.

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8. **REFERENCES**


