B. 14 "Fatigue,"

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Fatigue life evaluation (S-N approach)

High-cycle fatigue

The most 'classical' fatigue-related degradation mechanism is high-cycle (HC) fatigue. HC fatigue involves a high number of cycles at relatively low stress amplitude (typically below the material's yield strength but above the fatigue endurance limit of the material).[i] The crack initiation phase is dominant here, since crack growth is usually fairly rapid. High cycle fatigue may be:

Mechanical in nature, i.e. vibration or pressure pulsation, or due to flow-induced vibration (FIV). FIV can induce HC fatigue in otherwise normally passive components merely through interaction of flow adjacent to the component or within the system, establishing a cyclic stress response in the component. Power uprates are of some concern here, as an increase in flow may change the acoustical characteristics of the system and excite a HC mode where a resonant frequency is achieved.

Thermally induced due to mixing of cold and hot fluids, where local instabilities of mixing lead to low-amplitude thermal stresses at the component surface exposed to the fluid.

Due to combinations of thermal and high cycle mechanical loads, such as might occur on pump shafts in the thermal barrier region.

Low-cycle fatigue

Low cycle fatigue is due to relatively high stress range cycling where the number of cycles is less than about 10^4 to 10^5. To induce cracking at this number of cycles requires that the stress/strain range causes plastic strains that exceed the yield strength of the material. Cycling thus causes local plasticity leading to more rapid material fatigue degradation. In reactor coolant system components, the cumulative combined effects of reactor coolant system pressure and temperature changes are considered in the component design analysis. The stress or, more correctly, strain cycling that contributes to low cycle fatigue is generally due to the combined effects of pressure, piping moments and local thermal stresses that result during reactor operation. The latter are usually highest in connection with transients (such as plant start-up/shut-down or hot stand-by). Particular attention must be paid to the possibility of locally high component stresses (e.g. from notch effects at welds or from piping restraints), even though nominal system design criteria are met.

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[i] One of the recent concerns for fatigue cracking is "Giga Cycle" fatigue, which may take place beyond the 10^6 cycles usually used to define fatigue endurance guidelines. There are several observations showing a change in the mechanism of crack initiation. In Giga Cycle fatigue, cracks initiate inside the material, not from a surface, as commonly observed in normal HC fatigue Also, there is almost no data on environmental effects for Giga Cycle fatigue, which may be related, for example, to the failure of socket welds.

The major difference between high and low cycle fatigue is that, for low cycle fatigue, it is the crack growth rate which dominates component life, since crack initiation can occur after relatively few loading cycles. Fatigue crack propagation is discussed separately in Section II.

Thermal fatigue

Thermal fatigue is due to the cyclic stresses that result from changing temperature conditions in a component or in the piping attached to the component. Thermal fatigue may involve a relatively low number of cycles at a higher strain (e.g., plant operational cycles or injection of cold water into a hot nozzle) or due to a high number of cycles at low stress amplitude (e.g. local leakage effects or cyclic stratification). Although such issues have been known (and intensively studied) for many years, fatigue damage sometimes still occurs (see Section 6) when unexpected thermal loading is encountered, e.g. due to thermal stratification arising from incomplete mixing of water streams at different temperatures, which has led to significant incidents (e.g. at feedwater nozzles).

Environmental fatigue

Environmental fatigue concerns the reduction in fatigue "life" in reactor water environments compared to "room temperature air" and is also known as corrosion fatigue. It involves two primary aspects: the effects of a reactor water environment on the overall fatigue life of reactor components (i.e. both crack initiation and crack growth), and the potential accelerated growth of an identified or assumed crack-like defect due to cyclic loading in high-temperature water environments. Important examples of the effects on overall life for carbon and low-alloy steels (C&LAS) and for stainless steels (SS) are to be found in the references.[1, 2] Another reference [3] contains extensive discussion of corrosion fatigue crack growth for C&LAS, while the workshop presentations in reference 4[4] give a good overview of what is known here for SS and nickel-base alloys.

With regard to the evaluation of fatigue for component aging management, consideration of the effects of a particular environment on the overall fatigue life is usually more relevant (see Section 5). Environmental acceleration of fatigue crack growth is also important, however, in dispositioning detected/postulated flaws in a component so as to permit continued operation.

It should be noted that confusion often arises through the (unrecognized) use of different definitions for fatigue crack initiation in terms of flaw size. In laboratory studies of low-cycle corrosion fatigue at constant strain amplitude, initiation is usually taken to correspond to a certain load drop (typically 25%) during testing. However this already corresponds to a relatively deep crack, and recent studies[5] confirm that incipient flaws form much earlier during cycling, although they may often not continue to grow. In the field, "initiation" is usually more arbitrarily defined as the crack length/depth that can reliably be detected during non-destructive component examination.

Fatigue crack initiation and crack growth rates are governed by a number of material, structural and environmental factors, such as stress (or, more fundamentally, strain) range, temperature, ECP (usually categorized only approximately as dissolved oxygen content), mean stress, loading frequency (although strain rate and wave form are more fundamental parameters), surface roughness and number of cycles. A factor that has often been left out of consideration to date is degree of coolant purity, which is surprising given the attention paid to this key environmental variable in studies of SCC field behavior. Some data is now available showing just how important this can be, at least for low-alloy steel in oxygenated BWR environments.[6]

In the field, cracks typically initiate at local geometric stress concentrations, such as welds, notches, other surface defects, and structural discontinuities. The presence of pits in the surface of many alloys is often presumed to decrease corrosion fatigue life, since they can act as stress concentrators and potential fatigue crack initiation sites. In fact, however, pitting may often reflect environmentally assisted enhancement of fatigue cracking more indirectly (by indicating the local presence of an aggressive medium at the metal surface[7]) rather than being a fundamental stage in the corrosion fatigue process.

The major factor that has not received adequate consideration in laboratory investigations of environmental fatigue is undoubtedly flow rate. For C&LAS, the high flow rates typical of reactor operation are known to be very beneficial in reducing corrosion fatigue effects (with regard to both the initiation and growth of cracks). For stainless steels, the picture is more complex and experimental work in this area is still ongoing.[8, 9, 10]

Fatigue crack propagation (da/dN vs. ΔK approach)

As has been described above, fatigue life evaluation is based mostly upon S-N curves, but several modes of fatigue crack propagation should also be taken into account in proactive materials aging management. Fatigue crack propagation can be caused by mechanical or thermal fatigue loading, and environmental fatigue effects may contribute to crack growth in both cases. The crack growth characteristics are interpreted in terms of da/dN vs. ΔK, taking account of the stress ratio R and the frequency of loading. Such curves are, of course, dependent upon both materials and the environment.

If environmental effects are present, the flow rate of the medium also affects the crack propagation rate and, in general, a higher flow rate results in a lower crack growth rate for pressure vessel steels in PWR environments. In the case of low alloy steels, local crack tip chemistry can be modified by dissolution of MnS inclusions, thus acidifying the crack tip environment and resulting in higher growth rates for high sulfur materials. Up to now, no systematic crack propagation testing in terms of flow rate effects has been done on austenitic alloys under PWR conditions.

Extensive research on fatigue crack propagation has been done for many years by members of the international cooperative group on cyclic crack growth (ICCGR, former name of the current ICG-EAC group). The outcome has been largely taken into account in ASME Section XI rules for flaw evaluation, although some aspects (e.g. with regard to rules for components exposed to NWC in BWR plants) are still a subject of debate. For PWR environments, in particular, da/dN vs. ΔK curves have been developed based upon a more mechanistic approach, i.e., time domain analysis.

One important issue, which was pointed out already in the 1970s, is the effect of ripple loading on crack growth rate, when the environmental effects associated with simultaneous stress corrosion cracking have to be considered. Such synergy of effects must be taken into account in the PMDA program. For example, low-alloy steels, which have a rather high resistance to SCC in LWR environments, showed crack growth at a stress ratio of 0.98 and high frequency, even in pure water at 85C.

Crack propagation caused by thermal stress is another important area. Many field incidences of cracking are associated with initiation from local thermal stresses due exposure to water streams of different temperatures. However, these thermal stresses cause mostly very shallow cracks, because the temperature changes due to such water mixing are surface phenomena. However, such shallow cracks may start to propagate by other structural loads (including the effects of weld residual stress).

Significant reduction in the fatigue life of stainless steels has been observed in PWRs, but there is currently no mechanistic interpretation of these phenomena. Fatigue crack growth behavior in PWRs has been observed with mainly marginal enhancement, but it may be important to examine a possible impact on accelerated crack growth in PWR components due to this mechanism and studies are ongoing.

Synergistic effects of microstructural changes by aging at operating temperature and environmental effects can be a potential issue associated with license renewal. One example of such synergy involves dynamic strain aging and environmental fatigue crack propagation. Thermal aging of duplex SS, hydrogen entry into structural materials and irradiation can be other important microstructural changes with aging.

ASME Code rules on fatigue

Design against fatigue damage is based primarily on the fatigue curves in Section III, Appendix I (e.g., Figures I-9.1 and I-9.2) of the ASME Code. These curves indicate the number of stress cycles at a given amplitude of cyclic stress that is required to reach a so-called usage factor of 1.0. The fatigue curves are based on test data taken in air at room temperature, but reduced by a factor of 2 on stress range or 20 on cycles to failure (whichever is most conservative) to account for scatter of data, size effects, roughness, and non-laboratory environments. For carbon and low-alloy steel materials, the most adverse conditions of mean stress are used to correct the test data prior to applying these factors. The exact interpretation of the extent to which so-called "moderate service environments" were already taken into consideration when the ASME Code rules were drafted continues to be a major source of contention (see, e.g., reference 11[11]). Despite many years of development,[12,13] more appropriate treatment of reactor water effects by the application of a so-called environmental fatigue multiplier (F_{en} factor) has not (yet?) found favor in the US within the ASME Code, although it is being applied on a plant-specific basis in the context of license renewal applications.[14] Such approaches are already used in Japan, however,[15] and incorporate specific consideration of key factors such as strain rate, temperature, oxygen content and (for C&LAS) sulfur content of the material.

The ASME Code includes analytical approaches and criteria for determining usage factors for Class 1 components. For Class 1 code components, the cumulative usage factor must be shown to be less than 1.0 for the component life. However, a fatigue usage factor of unity does not imply actual crack initiation both because of the safety factors applied to the stress amplitude or number of allowed cycles for the Code fatigue curves and because of the often conservative nature of the design-basis loads that have been assumed. Fatigue monitoring of real components can be valuable to reveal margins in this context. The assumed load pairs present a particular challenge in evaluating environmental fatigue, where realistic strain rates are a key consideration.[16]

The crack growth that follows fatigue crack initiation can be predicted if the crack can be characterized and if the cyclic stress field is known. Procedures for performing crack growth analyses are contained in Section XI of the ASME Code. Again, the consideration given to environmental effects has sometimes been controversial and the present disposition lines do not necessarily reflect the current state of knowledge.[6] Significant progress has been made, however, for the specific case of LAS in PWR reactor water through the introduction of Code Case N-643,[17] which is currently undergoing further refinement. Work is ongoing to develop analogous cases for SS in PWR environments and for all classes of material in BWR reactor coolant.

Service experience of fatigue

Mitigation of fatigue damage for existing components is accomplished by reducing the magnitude of the applied loads or thermal conditions or reducing the number of cycles of loading. For thermal transients, reduction in the rate of temperature change for extreme temperature cycles can be effective (although it should be noted that this can also increase any environmental component of damage, if present). However, the normal operating cycles are not generally the source of significant fatigue damage in nuclear plants. The observed fatigue cracking in service has mostly been due to high cycle fatigue as a result of conditions not anticipated at the time of original plant design. Some instances of (very) low-cycle fatigue cracking (with a significant environmental contribution) have also been reported, mainly in Germany.[7]

Major areas of plant where fatigue failures and leakage have occurred are as follows:

<u>RCS Piping</u>

A number of fatigue issues have been identified, as described below.

The major occurrence of leakage has been due to mechanical vibration-induced cracking of small attached lines (primarily socket welded instrument lines). Power uprate has contributed to a number of recent incidences.

Thermal fatigue has also caused cracking in normal flowing lines where relatively colder water is injected into flowing RCS lines.

Thermal fatigue has also occurred in a number of normally stagnant branch lines attached to flowing RCS lines. The source has been thermal stratification/cycling due to valve in-leakage in up-horizontal running safety injection line configurations and swirl-penetration thermal cycling in down-horizontal drain/excess letdown lines. This is being addressed by the MRP Fatigue ITG and new guidelines are to be issued in mid-2005.

Although no occurrences of leakage have been identified, an issue related to surge line stratification was identified in 1988. The issue was resolved by analysis; however, the computed usage factors were quite high. Environmental fatigue effects are potentially significant for these lines.

Other potentially susceptible locations include PWR charging nozzles and BWR RHR tees, where significant thermal transients can occur in some plants.

<u>Reactor Pressure Vessels</u>

The effects of fatigue are adequately managed by adherence to the plant design basis, where thermal transients were considered in the original plant designs. The notable exception was BWR feedwater nozzles and control rod drive nozzles, where the effects of cold water injection caused cracking early in the life of some plants. Mitigating actions and continued monitoring have been implemented and have proved to be effective.

Pressurizers

There have been no known fatigue failures in pressurizers. However, recent considerations of cold water insurge to pressurizers have been identified that may be a contributing factor to leakage that has been observed in pressurizer heater sleeve welds. The pressurizer spray nozzle is also affected by some significant thermal transients. Pressurizer surge nozzles can be affected by thermal stratification conditions in the surge line.

Steam generator shell, tubes, and internals

Steam generator feedwater nozzles have exhibited cracking as a result of thermal stratification and cycling, but high oxygen content of the feedwater for low-power conditions may have also increased environmental effects. Girth weld cracking of the steam generator shells and cracking at feedwater nozzle blend radii have also been observed, where both hot/cold water thermal fatigue and an environmental contribution were identified.

RPV internals components

The major issue identified has been that due to flow induced vibration of BWR steam dryers following power uprates. This has led to cracking of the vessel-attached support brackets at several plants.

Areas for further research

Although fatigue is not perceived to be an issue of safety consequence based on the studies reported in,[18] the combined effects of adverse loadings and environments may lead to more cracking in the future than has been observed in the past. In addition, the effects of power uprate have increased the occurrences of flow induced vibration failures and related damage to component supports. Thus, research in the following areas is recommended:

Develop a better understanding of the relationship between laboratory environmental testing and actual reactor water conditions. The conditions in laboratory testing are often significantly different than those observed in actual flowing reactor water (flow rate is a key variable deserving closer attention here)[ii].. In addition, material conditioning between the extremes of actual cyclic conditions may be beneficial in reducing environmental effects. Although this has been primarily identified as a License Renewal issue, the laboratory effects are real and indicate that the fatigue resistance in a water environment is not as good as was originally thought.

Understand better the extent to which laboratory test data (usually on small specimens) can really be transferred to complex component geometries.

[ii] Most of the experimental work on flow rate effects has been done in BWR environments, where effects of flow rate on fatigue life are very complicated. Sometimes higher flow rate seems to be beneficial and sometime harmful, depending upon materials, DO and corrosion potential. Flow rate affects the thickness of the surface boundary layer, supply rate of oxidants to the surface, removal of corrosion products from surfaces, flush out of cracks and, clearly, local water chemistry. Some experimental data obtained in the EFT program in Japan revealed such complicated effects of flow on fatigue life. More details in Japanese at http://www.jnes.go.jp/katsudou/seika/2003/pdf_kikaku/04kizai-0006.pdf

Investigate high cycle fatigue effects due to hot and cold water mixing. Several incidences of cracking in France have led to EdF embarking on major research programs in this area.

Improve methods for predicting and quantifying flow-induced vibration and acoustic loadings. A number of cases have been identified that have resulted in component wear and failure. Giga Cycle fatigue at very small amplitudes is one of the issues for further investigation here (including environmental effects).

Past attention to fatigue issues has related primarily to pressure-retaining components. Additional, more detailed, evaluations are probably needed to determine flow-induced fatigue effects and safety consequences for reactor internals (and possibly other support components).

Consider whether random loading spectra (which may be more typical of some plant components) are properly represented in the fatigue testing database.

Synergistic effects of various forms of material degradation, such as thermal aging, on fatigue need to be studied, with special emphasis on the effect of ripple loading together with time dependent (SCC) crack growth.

References for B.14

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