Managing Environmentally-Assisted Fatigue in U.S. Plants

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Nuclear plants in the United States were originally licensed by the Nuclear Regulatory Commission (NRC) for 40 years of operation, but most of these plans have or are planning on renewing their license to 60 years. Plants are required by federal law to manage the aging effects of systems, structures and components in the scope of license renewal. One of the aging effects is environmentally-assisted fatigue of the primary system vessels and piping. This article discusses the strategies that U.S. utilities have utilized in order to satisfy NRC concerns with respect to fatigue damage in nuclear plants.

Las licencias de las centrales nucleares en los Estados Unidos fueron otorgadas inicialmente por la Comisión de Regulación Nuclear (NRC) para 40 años de operación, sin embargo la mayoría de estas centrales han renovado su licencia, o tienen previsto hacerlo, hasta los 60 años. Las centrales están obligadas por la ley federal a gestionar los efectos del envejecimiento de los sistemas, estructuras y componentes dentro del alcance de la renovación de licencia. Uno de los efectos del envejecimiento es la fatiga asistida por el medio ambiente de las vasijas y tuberías del sistema primario. En este artículo se exponen las estrategias que han utilizado las empresas eléctricas estadounidenses conel fin de dar respuesta a las exigencias de la NRC respecto a los daños por fatiga en las centrales nucleares.

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BACKGROUND

Extensive research conducted over the past three decades has shown that fatigue damage can be accelerated in a water environment due to corrosion effects. Temperature, loading rate, oxidant levels in the water, and the material properties of the component all influence to varying degrees the rate of fatigue damage. The ASME Code, Section III fatigue curves, widely used for the design of nuclear power plant components, did not explicitly account for these environmental effects. ASME has still not fully addressed environmental effects on fatigue to the satisfaction of the U.S. Nuclear Regulatory Commission (NRC). Utilities, therefore, rely on guidance from various published NRC reports to address the issue. Based on the formulations provided in these NRC reports, environmental penalty factors on fatigue can exceed 15 for stainless steel, and can theoretically be in the hundreds for ferritic components, depending on the temperature and oxidant levels present.

The NRC originally licensed nuclear plants for 40 years of operation. In the intervening time, they have expressed concern about these environmentally-assisted fatigue (EAF) effects, which were not well understood during design. Although the NRC concluded in a probabilistic risk study that EAF is not a safety issue during the original, 40 year licensing basis, they found an increasing probability of cracking and through-wall leakage of some components at 60 years of operation. The NRC, therefore, requires all license renewal applicants to assess the fatigue effects from the reactor water environment from the beginning of plant life through 60 years of operation.

Traditionally, a sampling of high fatigue locations included in NRC contractor report NUREG/CR-6260 needed to be evaluated for EAF. For a Westinghouse-designed plant, the sample locations typically include the reactor vessel shell and lower head, the reactor vessel inlet and outlet nozzles, the surge line, the charging nozzles, the safety injection nozzles, and the Class 1 portion of the residual heat removal system piping. For General Electric designed boiling water reactors (BWRs), sample locations typically include the reactor vessel shell and lower head, the reactor vessel feedwater nozzle and associated piping, the reactor recirculation piping, the core spray reactor vessel nozzle and associated piping, and the residual heat removal (RHR) nozzles and associated piping. Most recently, the NRC has expected plants to evaluate not only these sample components, but also other locations in the Class 1 pressure boundary that may be more limiting. Screening programs have, therefore, been developed to assist with appropriately selecting those additional limiting locations for further EAF evaluation.

For each Class 1 component of concern, the licensee must calculate the EAF usage projected to 60 years. If the usage exceeds 1.0 before 60 years, then a corrective action must be taken, such as (1) refined analysis or detailed fatigue monitoring to remove excessive conservatisms from the calculations and reduce the usage below 1.0, (2) inspection and flaw tolerance assessment, or (3) repair or replacement of the component. A discussion of these activities must be included in the license renewal application. EAF must be successfully managed in accordance with the above options, or commitments to do so must be provided in writing to the NRC as a condition to obtain a renewed license for operation past 40 years.

For vendors seeking a design certification for construction of new nuclear plants in the U.S., the NRC requires accounting for EAF effects in the fatigue design basis of all Class 1, primary side pressure retaining components.

For both the case of license renewal and new plant design, successfully addressing NRC requirements with respect to EAF for the few worst components may be challenging. Nevertheless, with enough work such efforts have generally been achievable. This article discusses some of the strategies utilities have employed to successfully address EAF for license renewal.

OPTIONS TO REDUCE EXCESSIVE CONSERVATISMS OF THE FATIGUE CALCULATIONS

To support license renewal, the utility first typically reviews the fatigue design basis of the plant. For some components, the fatigue usage factor (U) is low enough that a maximum environmental penalty factor (Fen) can be applied, and the resulting EAF usage factor (Uen) still remains below the limit of 1.0. A component like this may be managed for fatigue simply by ensuring that cycle counts remain below the number of cycles assumed in the design. Plant cycles are typically monitored using fatigue monitoring software, and in some cases are manually logged by plant personnel (Figure 1).

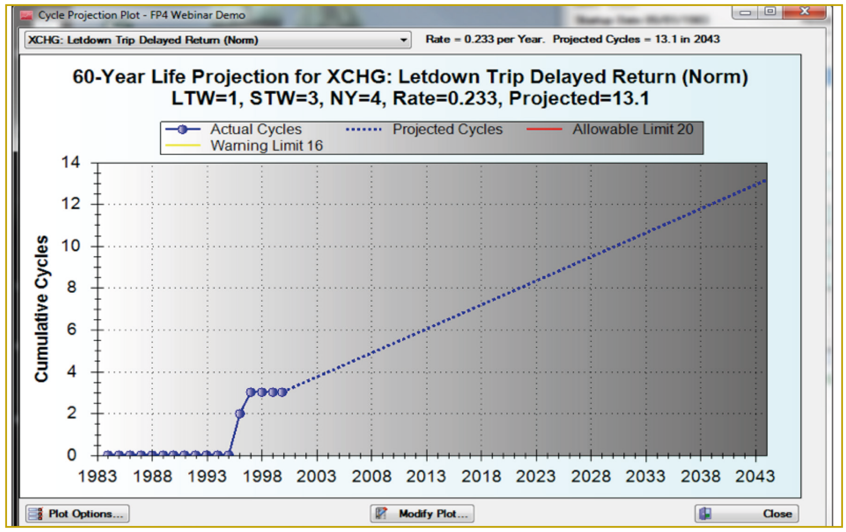
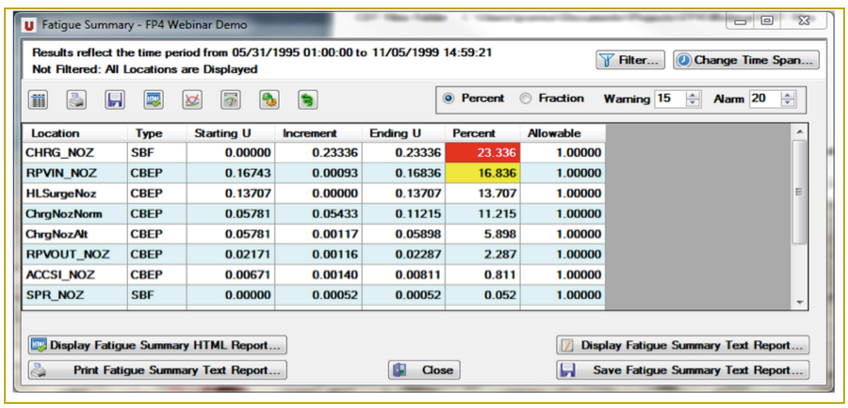


Figure 1. Projected Cycle Count to 60 Years.

For other locations that are not acceptable when using the simple screening method above, new analysis may still potentially be avoided by managing the component using cycle-based fatigue (CBF) monitoring. Some components experience significantly fewer plant transients than assumed by the original designers. CBF monitoring uses the results of that original analysis, but fatigue is recomputed by the monitoring system using the actual numbers of cycles instead of the numbers of design cycles. Most of the effort involved with CBF monitoring consists of reviewing the historical records and analyzing plant data to determine how many fatigue contributing transients actually occurred since the beginning of plant life. For BWRs with high fatigue locations composed of ferritic materials, it is also important to understand the various water chemistry conditions, as the Fen calculations are typically very sensitive to the varying oxidant levels through the plant life, e.g., normal water chemistry, hydrogen water chemistry, online noble chemical addition, etc. (Figure 2).



Location	Type	Starting U	Increment	Ending U	Percent	Allowable
CHRG_NOZ	SBF	0.00000	0.23336	0.23336	23.336	1.00000
RPVIN_NOZ	CBEP	0.16743	0.00093	0.16836	16.836	1.00000
HLSurgeNoz	CBEP	0.13707	0.00000	0.13707	13.707	1.00000
ChrgNozNorm	CBEP	0.05781	0.05433	0.11215	11.215	1.00000
ChrgNozAlt	CBEP	0.05781	0.00117	0.05898	5.898	1.00000
RPVOUT_NOZ	CBEP	0.02171	0.00116	0.02287	2.287	1.00000
ACCSI_NOZ	CBEP	0.00671	0.00140	0.00811	0.811	1.00000
SPR_NOZ	SBF	0.00000	0.00052	0.00052	0.052	1.00000

Figure 2: Monitoring of Fatigue Usage to Alarm Limits.

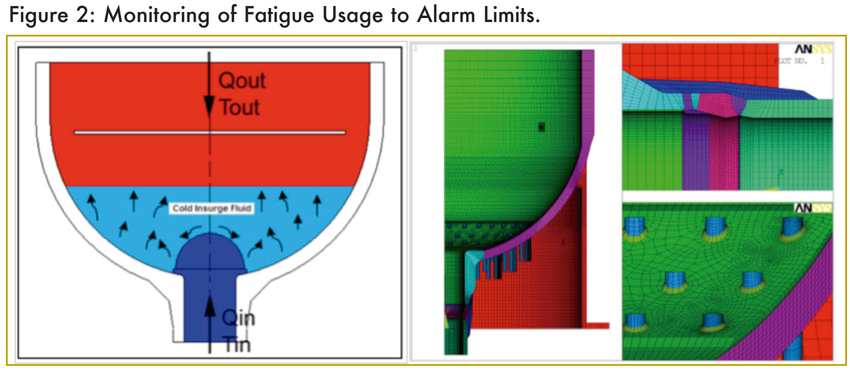


Figure 3. Advanced, 3-D Finite Element Model of PWR Pressurizer, Including Thermal Stratification Effects.

A third option to remove excessive conservatisms is to reanalyze the component using more modern methods of analysis. The goal of the original designers was to get the fatigue usage under 1.0 with the least amount of cost and effort. In doing so, the simplifications that they made were typically overly conservative. For example, all of the different types of transients may have been conservatively assumed to be represented by the most severe transient. Reanalyzing each transient separately, rather than relying on bounding assumptions, can significantly reduce excessive conservatisms. Analysis methodologies have also evolved over time, giving analysts more options to refine the results. For example, thermal stress analyses may be performed using detailed three-dimensional finite element analysis for each transient, and including nonlinear effects. Such an analysis was impractical or in some cases impossible when the plant was originally designed. Changes to the ASME Code have also provided analysts with opportunities to reduce excessive conservatisms. The end result of these refined analyses is that EAF may be successfully managed using cycle counting or CBF methodologies (Figure 3).

For some locations, cycle counting, CBF, or reanalysis using idealized design transient definitions may not be adequate to successfully manage EAF in the period of extended operation. NUREG/CR-6260 concluded that fatigue monitoring that accounts for actual tran-

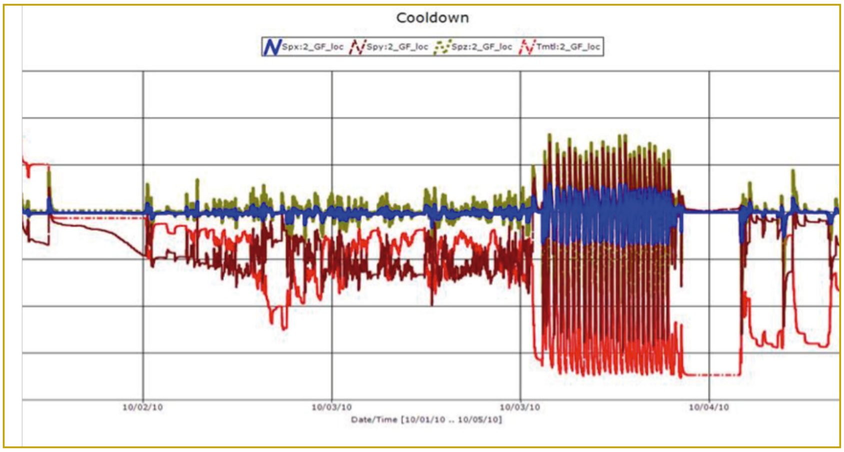


Figure 4: SBF Monitoring Example, Multiaxial Stress History.

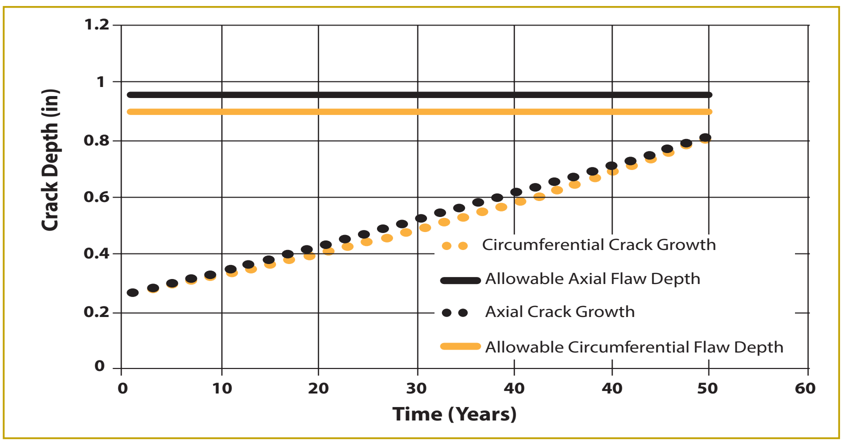


Figure 5: Fatigue Crack Growth Rate Example.

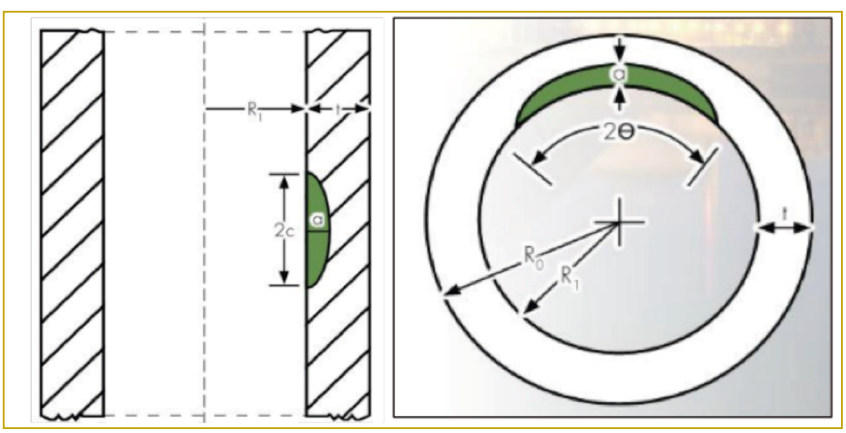


Figure 6: Postulated Cracks for ASME Code Section XI, Appendix L Evaluation.

sient severity appears to be the best option for the few worst locations. The most common methodology to do this is called stress-based fatigue (SBF) monitoring. With SBF, measured plant data such as temperatures, pressures, flow rates, and valve positions are used to determine local thermal and mechanical conditions at the locations of interest and ultimately compute a time history of the stresses. Based on the stresses, the EAF usage is computed. For BWRs, feedwater nozzles are typically monitored using SBF. For PWRs, SBF is typically used for the charging nozzles and the pressurizer surge line (Figure 4).

INSPECTION AND FLAW TOLERANCE

In the rare instances when fatigue usage factors cannot be calculated acceptably, or if the utility desires to rely on their inspection program instead of calculations, then a flaw tolerance approach is an acceptable method to manage EAF.

The basic methodology for a flaw tolerance analysis is provided in ASME Code, Section XI, Appendix L. The process consists of:

- performing an ultrasonic (UT) examination of the high fatigue location to verify the absence of a flaw,
- postulating axial and circumferential flaws, based on ASME Code, Section XI, Appendix L methodology and the detection threshold of the UT inspection,
- determining stresses and fatigue crack growth, including environmental effects, at the critical sections of the component,
- computing the time for the postulated flaw to grow to the maximum allowable flaw depth and determining the minimum time required between inspections (Figures 5 & 6).

Often times, a high fatigue location may already be included in the plant's 10-year in-service inspection (ISI) program. Unlike fatigue monitoring, it is not required to determine how many transients occurred in the past, or their severity. It is only necessary to postulate transient occurrences in the future (after the UT inspection).

At this time, only one plant in the U.S. has decided to use inspection and flaw tolerance to manage EAF in license renewal, instead of relying on EAF calculations and monitoring. One significant issue has been that the NRC requires consideration of environmental effects in the crack growth formulations. However, the ASME Code has not yet accounted for EAF in crack growth for stainless steel components. Much experimental research has been conducted in this regard, and a draft ASME Code Case has been proposed to provide guidance to perform flaw tolerance analyses, including environmental effects, for stainless steel components. Guidance from this work has been used to perform the first flaw tolerance analysis for license renewal and successfully address all NRC concerns.

CONCLUSIONS

Significant efforts have been applied by utilities to manage fatigue of U.S. nuclear power plants for license renewal to 60 years. In virtually all cases for all plant types, utilities have not needed to resort to repair or replacement of components because of EAF caused by plant transients. These results are consistent with the complete lack of service-induced fatigue failures of Class 1 nuclear components due to known transient loads. Research is currently being conducted to assess the feasibility and develop solutions to safely extend plant lives to 80 years. Based on the utilities' experiences with evaluating EAF for 60 years, it appears likely that with respect to EAF plant lives could be safely extended to 80 years, if sufficiently sophisticated analysis, monitoring and inspection programs are implemented accordingly.