U.S. Nuclear Regulatory Commission Public Meeting Summary

October 16, 2018

Title: Public Meeting on Environmentally Assisted Fatigue Research and Related ASME Activities

Meeting Identifier: 20180785

Date of Meeting: Tuesday, September 25, 2018

Location: Nuclear Regulatory Commission (NRC) Headquarters, Rockville, MD

Type of Meeting: Category 2

Purpose of the Meeting(s):

Discuss environmentally assisted fatigue (EAF) research and associated ASME activities that are sponsored by EPRI, discuss related activities and issues of interest to the NRC, and summarize progress on actions arising from the last NRC EAF public meeting that was held on June 30, 2016.

General Details:

The Nuclear Regulatory Commission (NRC) conducted a public meeting starting at 8:30 am eastern daylight savings time (EDT) where representatives of the commercial nuclear power industry and members of the public met with NRC staff to discuss ongoing and planned research activities related to EAF evaluation of nuclear components and structures and associated ASME Code activities. The meeting was scheduled from 8:30 - 5:00 p.m. EDT. Seventeen NRC staff members participated in the meeting along with twenty-seven nuclear industry representatives and other stakeholders. The lead industry contact for the meeting was Gary Stevens from the Electric Power Research Institute (EPRI). The meeting attendance list is attached. The meeting was led by Robert Tregoning from the NRC's Office of Nuclear Regulatory Research (RES).

The meeting began with an introduction of the meeting participants and a review of meeting ground rules. The meeting agenda was reviewed next. The initial agenda was provided as part of the meeting announcement which is available in the NRC's Agency Documentation and Management System (ADAMS) under accession number ML18256A115 or within the public meeting package found in ADAMS under accession number ML18289A322. For completeness, the final meeting agenda is also attached. The remainder of the meeting was dedicated to presentations that were provided by nuclear industry representatives and NRC staff. The meeting presentations are available in ADAMS within the public meeting package found under accession number ML18289A322.

Summary of Presentations:

In the first presentation, G. Stevens and R. Tregoning reviewed the status of the action items from the previous meeting on June 30, 2016. These actions are summarized in the meeting summary for that meeting, which is available in ADAMS under accession number

ML16197A023. Actions a. – e. and h. relate to ongoing research and ASME Code activities that were discussed and updated during this meeting, so these actions were considered closed as a result of this meeting. Action item f. requested EPRI to provide more explanation on their evaluation of irradiation effects on fatigue crack growth rate (FCGR) behavior. This action was closed by the submittal of the document "EAFCG in Irradiated SS.pdf", which is publicly available in ADAMS under accession number ML18284A002 or within the meeting package available in ADAMS under accession number ML18289A322.

Action item g. was for R. Tregoning to arrange a meeting between NRC, EPRI, and DOE to discuss possible research to address irradiation effects on fatigue after EPRI's study on irradiation effects on fatigue crack growth rates (FCGRs) is completed. Related work by EPRI is publicly available in PVP Paper PVP2016-63640, *Crack Tip Strain Rate Models for Environmentally-Assisted Fatigue Crack Growth in Light Water Reactor Environments*, Proceedings of the ASME 2016 Pressure Vessels and Piping Conference, July 17-21, 2016, Vancouver, British Columbia, Canada. A brief description of this work is included in the "EAFCG in Irradiated SS.pdf" document. This document can now be used to provide background for a follow-on meeting among NRC, EPRI, and DOE which will be arranged as an action stemming from this meeting. This follow-on action closes action item g. from the 2016 meeting.

Finally, action item i. was to create a standing agenda item on metal fatigue as part of the NRC/industry quarterly call to discuss activities related to materials issues. EPRI and NRC already discuss all significant materials issues during the quarterly call and it was decided that an additional standing item to single out fatigue related issues would be redundant. Hence, action item i. from the 2016 meeting is also closed.

G. Stevens next described the EPRI updated EAF gap report. The report was created initially in 2012. As summarized by Stevens, since the 2012 report, there has been extensive progress in EAF research aimed at closing some of the key gaps and developing improved assessment methodologies for EAF in light water reactor (LWR) environments. Some of the most significant and promising new assessment methods and supporting data are at differing stages of development: Several of these activities were discussed in more detail during this meeting. The latest revision of the EAF gap report includes a revised, condensed, and categorized listing of the remaining knowledge gaps. Subsequent to the meeting, this report was published by EPRI on September 28th, and is publicly available through the EPRI website.

Next, R. Tregoning made a presentation on the effects of irradiation on fatigue life. He summarized past fatigue crack growth rate and fatigue life testing programs and also discussed microstructural changes induced by irradiation that could affect fatigue life. There is a paucity of data under representative LWR conditions and therefore conclusive trends cannot be established. The data that does exist do not exhibit a significant effect of irradiation on FCGRs. However, some consistent effects of irradiation on fatigue life have been observed in the existing data. This data shows decreases in fatigue life at higher (i.e., > 0.35 to 0.6%) strain levels and increases in fatigue life at low (i.e., < 0.35 to 0.6%) strain levels. These initial results can be used to prioritize any subsequent testing. Initial testing should focus on evaluating the effects on low-cycle fatigue life, where irradiation may have a detrimental effect, and identifying the transition strain between low-cycle and high-cycle fatigue regimes. The NRC's latest summary of irradiation effects on fatigue initiation is contained in Section 1.3.2 of NUREG/CR-6909, Rev. 1, which was published in May 2018.

Kevin Mottershead of Wood PLC summarized the EAF database sharing effort among NRC, Europe's Joint Research Center (JRC), and the 16 organizations that comprise the INCEFA-PLUS (Increasing Safety in Nuclear Power Plants by Covering Gaps in Environmental Fatigue Assessment) project. The objective of this effort is to create an international database of EAF testing data. The agreement is currently undergoing final review by all sides and final agreement signing is planned for Fall 2018. The current agreement contains a provision that allows additional signatories upon unanimous consent of existing signatories. Once the agreement is initiated, it will be circulated to other organizations such as EPRI for their review to determine if they want to participate.

The next agenda topic summarized ongoing EPRI EAF specimen testing. The first talk on this topic was given by Seiji Asada of Mitsubishi Heavy Industries, Inc. discussed non-isothermal EAF testing of 316 stainless steels in a simulated pressurized water reactor (PWR) environment. The objective of the work is to evaluate the effects of complex, in-phase and out-of-phase temperature and strain transients compared to the same strain transients under isothermal conditions. The results show that the phase of the temperature and strain transients can affect fatigue life and that the results are conservatively predicted by NUREG/CR-6909, Rev. 1 equations. A prediction method to account for non-isothermal effects was described and provided a more accurate prediction of the experimental data.

Jean Smith of EPRI next summarized the following EPRI research activities related to specimen testing: The first activity is studying water chemistry effects, specifically the addition of zinc in PWR environments, on EAF. Initial results indicate that zinc additions increase the fatigue resistance of stainless steels. More work is being planned to better understand this phenomenon and identify its limitations. The second activity is investigating EAF under plant-like conditions, particularly the effects of hold-time. Results to date do not conclusively demonstrate that hold-time has a beneficial effect on fatigue life. Finally, J. Smith discussed research to further understand the EAF short crack growth regime that bridges fatigue crack initiation testing (i.e., ε vs. N) and classical FCGR testing. Commissioning tests on the experimental set-up and approach have been successfully completed, while the bulk of the testing will initiate in late 2018. Tests in the remainder of 2018 and throughout 2019 will include a comparison of FCGRs in air and PWR environments and a study of rise time effects for environmental enhancement.

The next presentation was also by J. Smith and discussed EPRI's EAF component testing research. The objectives of this research are to understand the effect of LWR environments on the fatigue life and resultant cumulative usage factor (CUF) on component materials, reconcile the differences between the current CUF methodology results and the fleet operating experience with respect to EAF failures, and provide the technical basis for an improved CUF analytical methodology for EAF. The presentation described the test component, test fixtures and the proposed loading transients. The five-year program will begin in 2018 and consists of four phases: finite element analysis modeling and design; commissioning of the experimental set-up; testing; and integration of the results into EAF models. Each phase was outlined.

The next presentation, by S. Asada, detailed the development and validation of new design fatigue curves in Japan. The new best-fit design curves - for carbon and low-alloy steels, and stainless steels - were based on traditional small-specimen, fully reversed fatigue specimens and explicitly consider the materials' ultimate strength. Small specimen testing was also used to evaluate several different mean-stress correction methods and the Smith-Watson-Topper (SWT) approach was selected as the better method. The results from two large-scale fatigue testing programs were evaluated and compared with predictions from the new design curves. The fatigue lives of the large-scale tests, adjusted as needed by the SWT mean-stress correction, are close to the new best-fit design curves.

After the lunch break, Steve Gosselin of Lucius Pitkin, Inc. (LPI) discussed the development of a CUF life and gradient factor concept for reducing the conservatism in typical fatigue evaluations. ASME Code fatigue rules are based on testing performed on small cylindrical specimens under alternating, uniform membrane loading in an air environment. However, these rules are typically applied to larger components which have differing thicknesses compared to test specimens, and are loaded non-uniformly through the component thickness. Ignoring thickness and through-wall stress gradient effects can lead to fatigue life predictions that are much less than actual component fatigue lives. The approach, as described in NUREG/CR-6909 Rev. 1, separates fatigue life into Stage I (i.e., crack initiation to a depth between 10 μm to 200 μm) and Stage II (i.e., subsequent crack propagation to depths from 200 μm to the depth corresponding to a 25% load drop). The gradient factor accounts for the increase in Stage II life associated with through thickness stress gradient loading. The life factor corrects fatigue usage estimates to account for the additional crack growth needed in a thicker component to reach a 25% load drop, compared to a smaller-scale test specimen.

The presentation also discussed recent work to quantitatively define the Stage I and Stage II portions of fatigue life. A large matrix of piping geometries and applied cyclic strains were then analyzed for carbon, low-alloy and stainless steels. The results were then regression-fit to develop closed-form solutions for the life and gradient factors. The method was demonstrated on an example problem for a reducing elbow piping component. A Code Case on this approach has been drafted and is under consideration by the ASME Code Section III.

The next presentation was provided by Sam Ranganath of XGEN Engineering on an alternative, simplified approach for performing elastic-plastic (EP) analysis with the ASME Code fatigue evaluation. The current simplified EP analysis within the ASME Code is often the largest source of conservatism in a linear-elastic fatigue analysis. The ASME Code currently allows an updated EP analysis to be used. However, this analysis is expensive because it requires a new finite element analysis and significantly more effort compared to a linear elastic analysis. Also, the rules for performing the analysis are not explicit, and it is difficult to apply this analysis in piping evaluations because of the large number of locations and number of piping systems evaluated in a typical nuclear plant. The presentation next summarized the development of the current EP method in the ASME Code and discussed alternative approaches in the various international codes and standards.

The proposed approach follows the Welding Research Council (WRC) Bulletin 361 method that uses a weighted average approach for the thermal and mechanical portions of stresses and includes a notch factor. Proposed K_{ε} factor equations were developed for both vessel (i.e., ASME Section III NB-3200) and piping (i.e., NB-3600) analyses. The proposed method was next applied to four NB-3200 example problems, some with notches and some without notches: the Bettis stepped pipe test, a notched beam, an axial groove in a pipe with mechanical and thermal loading, and a pipe taper. In all cases, the proposed simplified method proposed was equal to or less conservative than the current ASME Code approach while still bounding the results from more rigorous EP finite element calculations. Two piping example problems were also discussed. The proposed Code Case on this method has been extensively discussed at ASME Code meetings, and important comments have been addressed. The technical basis document and the Code Case have been completed. Subsequent to this meeting, the draft Code Case was sent out for ballot to relevant ASME Code working groups during the first week of October.

The next presentation, by S. Ranganath, described the development of modified fatigue design curves for stainless steel materials for use in vibration, or high-cycle, fatigue evaluations. This is intended for applications such as boiling water reactor (BWR) steam dryers to remove excess margins in the tail ends of existing ASME Code fatigue curves (i.e., cycles to failure greater than 10^6). The approach described in the presentation uses temperature dependent properties for the mean stress correction and the correction for the modulus of elasticity rather than the room temperature values used to develop the curves. The high cycle portion of the stainless steel fatigue design curve was developed by applying the mean stress and the Young's Modulus (E) correction on the reversing load mean data curve and applying a factor of 2 on stress. The proposed revised curves were compared with existing ASME design curves as well as curves developed from the mean data curves in NUREG/CR-6909, Rev. 1, with mean stress correction based on temperature dependent properties. The proposed Code Case on this method has been extensively discussed at ASME Code meetings and important comments have been addressed. Subsequent to this meeting, the technical basis document and the draft Code Case were sent out for ballot to relevant ASME Code working groups during the first week of October.

The final presentation from S. Ranganath described a more recent EPRI-sponsored project to develop updated corrosion FCGR curves for low-alloy steel components in BWR environments. This work is building on earlier work to develop corrosion FCGR curves for BWR environments, and is based on an improved superposition model to account for material sulfur content and chloride intrusions associated with BWR environments. As described in the presentation, the initial predictions of the model to available data are promising. The next steps are to develop a more rigorous statistical fit of the model to all available data and then prepare the technical basis document and proposed ASME Code Section XI Code Case for review and balloting within ASME.

After the break, G. Stevens summarized the Boiling Water Reactor Vessel and Internals Project (BWRVIP) approach for managing EAF in internals. The motivation for the effort is that many BWR internal components do not have CUF values and the objective is to demonstrate that existing inspection programs provide adequate aging management of the EAF degradation mechanism applicable to BWR internals. The basis of the approach is to demonstrate that intergranular stress corrosion cracking (IGSCC) and irradiation-assisted stress corrosion cracking (IASCC), which are explicitly addressed and are the limiting degradation mechanisms upon which the current inspection guidance is based, are significantly more limiting than cracking caused by EAF. The presentation described the six elements of the EAF technical basis and concluded that existing inspection programs adequately account for EAF. EPRI is documenting this work in Appendix D of a new report for BWR internals for extended plant operation, which is planned for NRC submittal at a later time.

A joint NRC/EPRI presentation was provided by G. Stevens and Mike Benson (NRC) to discuss the basis of the high energy line break (HELB) limit of 0.1 on CUF. The presentation described the prior work and public meetings on this topic dating back to 2012. It is anticipated that this topic will be an issue facing both BWR and PWR plants that apply for subsequent license renewal (SLR). Recent work at NRC on this topic initiated in 2015 with the objectives to document the basis for the current CUF criterion, develop options for revising the criterion, evaluate existing water jet force models (i.e., in ANSI/ANS Standard 58.2 and NUREG/CR-2913), and make recommendations for revised regulatory positions. The history of the CUF criterion of 0.1 has been traced back to 1972; however, a robust technical basis does not exist for this criterion. As part of the review of the Economic Simplified Boiling Water Reactor (ESBWR) design, the NRC accepted a CUF criterion of 0.4 when environmental effects were addressed. The basis for this decision is not clearly documented, but it is associated with a 1986 letter from Houston Lighting and Power to the NRC that is available within the ADAMS legacy library. That letter was placed in the main ADAMS library subsequent to the meeting, and can be found at ADAMS accession number ML18284A024 or within the meeting package available in ADAMS under accession number ML18289A322.

The jet-force modeling work has just been initiated at NRC although NRC (A. Tsirigotis) identified that as part of an internal review of a Westinghouse jet force model completed in 2012, the ANSI/ANS 58.2-1988 jet model was found to provide a conservative estimate of impingement pressures within the jet. The NRC technical review and the basis for this conclusion is contained in a memorandum that also contains proprietary Westinghouse information and is therefore not publicly available. Discussion of this topic identified a proactive need for a public meeting on HELB to understand the industry needs and also determine appropriate future actions.

The final presentation provided the status of previous EPRI EAF efforts that were not discussed earlier during the meeting. G. Stevens summarized four on-going or completed EPRI projects: 1) Probabilistic Determination of Margins in ASME Code Section III CUF Calculations, 2) FCGRs for Austenitic Stainless Steels in BWR Environments, 3) BWR Subsequent License Renewal EAF Database, and 4) International Collaboration Group. The first project developed a simplified engineering approach based on probabilistic methods that quantifies the uncertainties of inputs in CUF and environmental CUF (CUF_{en}) calculations and is documented in EPRI Report No. 3002012326, which is publicly available on EPRI's website. The second project is developing FCGR curves for austenitic stainless steels in BWR environments that will be used to develop a complementary code case to Code Case N-809, which provides FCGR curves in PWR environments. The third project developed a database of BWR EAF estimations for 80 years of operation for the entire U.S. BWR fleet to identify potential EAF issues and needs for 80 years of operation. The results will be documented in an Appendix to BWRVIP-316, *Reactor Pressure Vessel Inspection and Evaluation Guidelines for Long Term Operation*, which is planned for publication in December 2018.

Finally, the fourth project is an international EAF collaboration group hosted by EPRI. The group's purpose is to periodically meet to exchange EAF information, research and data, coordinate research efforts to the extent practical, review on-going research and provide constructive input and direction, and provide insight and ideas for new research projects. The group currently consists of seven participating organizations that have signed a non-disclosure agreement (NDA) to facilitate exchange of information and data. This group meets approximately once each year. They met on September 26-27, 2018 in Washington, DC after the NRC public meeting.

Action Items/Next Steps:

The following action items were identified during the meeting and resulted from discussion held in concert with the presentations previously summarized.

1. NRC (Tregoning) will review document supplied by EPRI in response to June 30, 2016 meeting Action Item f, make that document publicly available, and provide the ADAMS accession number as part of meeting summary. NRC (Tregoning) will also identify any follow-up questions or actions related to the report.
2. NRC (Tregoning) and EPRI (Stevens) will meet with DOE (Leonard/Hahn) to discuss the potential for DOE-sponsored research to evaluate irradiation effects on fatigue.
3. NRC (Tregoning) and EPRI (Stevens) will discuss the need for a possible scoping effort to determine if there is a driver for evaluating irradiation effects on fatigue.
4. NRC (Tregoning) will provide EPRI (Stevens) with a final draft of the international fatigue database participatory agreement when available (Fall-Winter 2018).
5. NRC (Hsu) will develop a question related to differences between the fatigue crack growth vs. temperature relationship from Code Case N-809 and the MHI test results for EPRI/MHI to address.
6. EPRI (Stevens) and MHI (Asada) will address the question in Action #5 by considering test data and other available technical information.
7. Rolls-Royce (Twite/Morley) will provide available technical papers related to differences observed between testing and the fatigue crack growth temperature relationship for Code Case N-809.
8. EPRI (Smith) will determine if KHNP is accounting for crack growth during hold periods.
9. LPI (Gosselin) will investigate data or test results to substantiate the assumption of a circular crack profile for thicknesses greater than typical solid pin test specimens.
10. NRC (Tregoning) and EPRI (Stevens) will jointly plan for a public meeting on HELB issues.
11. NRC (Tregoning) will check on public availability of HELB jet force reaction memo and, if it is publicly available, provide the ADAMS Accession Number as part of the meeting summary.
12. NRC (Benson) will place the HELB Rodabaugh letter in the ADAMS main library and provide the accession number as part of the meeting summary
13. NRC (Tregoning) and EPRI (Stevens) will plan for the next EAF Public Meeting

Public Comment

No comments or questions were provided by members of the public during the public comment portion of the meeting.

Attachments:

- Attendance list
- Meeting agenda
- Meeting announcement - ML18256A115
- Meeting presentations and other meeting-related documents - ML18289A322

Attendance List

Public Meeting on EAF Research and Related ASME Activities

NRC Headquarters, Rockville, MD
Tuesday, September, 2018
8:30 AM to 5:00 PM

Name	Organization	Email Address
Rob Tregoning	Nuclear Regulatory Commission	robert.tregoning@nrc.gov
Alexander Tsirigotis	Nuclear Regulatory Commission	axt4@nrc.gov
Chakrapani Basavaraju	Nuclear Regulatory Commission	cxb10@nrc.gov
Allen Hiser	Nuclear Regulatory Commission	allen.hiser@nrc.gov
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Ian Tseng	Nuclear Regulatory Commission	ian.tseng@nrc.gov
Stewart Bailey	Nuclear Regulatory Commission	stewart.bailey@nrc.gov
Gary Stevens	Electric Power Research Institute	gstevens@epri.com
Jean Smith	Electric Power Research Institute	jmsmith@epri.com
Kawaljit Ahluwalia	Electric Power Research Institute	kahluwal@epri.com
Wynter McGruder	Electric Power Research Institute	wmcgruder@epri.com
Robert Carter	Electric Power Research Institute	bcarter@epri.com
Peter Gill	Wood	peter.gill@woodplc.com
Kevin Motterhead	Wood	kevin.mottershead@woodplc.com
Drew Odell	Exelon	andrew.odell@exeloncorp.com
Sam Ranganath	XGEN Engineering	sranganath@sbcglobal.net

Attendance List (continued)

Public Meeting on EAF Research and Related ASME Activities

NRC Headquarters, Rockville, MD
Tuesday, September, 2018
8:30 AM to 5:00 PM

Name	Organization	Email Address
Steve Gosselin	Lucius Pitkin Incorporated	sgosselin@lipny.com
Seiji Asada	Mitsubishi Heavy Industries, Ltd	seiji_asada@mhi.co.jp
Daniel Leary	Rolls-Royce	daniel.leary@rolls-royce.com
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Liu Chang	SNERDI	liuchang@snerdi.com.cn
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George Abatt	Becht Engineering Company	gabatt@becht.com
Tim Austin	JRC	simon.austin@ec.europa.eu
Jana Bergman	Curtiss Wright	jbergman@curtisswright.com

PUBLIC MEETING AGENDA

Environmentally Assisted Fatigue (EAF) Research and Related ASME Activities

September 25, 2018, 08:30 AM to 05:00 PM

NRC One White Flint North, 10 B4
11555 Rockville Pike
Rockville, MD

Time	Topic	Speaker
8:30 am	Introductions and Introductory Remarks	R. Tregoning, NRC
8:40 am	Review of Actions from June 30, 2016 Meeting	R. Tregoning, NRC G. Stevens, EPRI
9:00 am	Overview of EPRI Updated Gap Report	G. Stevens, EPRI
9:15 am	Effects of Irradiation on Fatigue Life	R. Tregoning, NRC
9:45 am	EAF Database Sharing	K. Mottershead, Wood
10:00 am	**Break**	
	Ongoing EPRI EAF Specimen Testing	
10:15 am	a. Non-Isothermal EAF Testing for 316 Stainless Steel in Simulated PWR Environment	S. Asada, MHI
10:30 am	b. Hold Time and Water Chemistry Effects	J. Smith, EPRI
10:45 am	c. EAF Short Crack Growth	J. Smith, EPRI
11:00 am	EPRI EAF Component Testing	J. Smith, EPRI
11:30 am	Development of New Design Fatigue Curves in Japan - Discussion of Best Fit Curves Based on Fatigue Test Data	S. Asada, MHI
12:00 pm	**Lunch**	

PUBLIC MEETING AGENDA (continued)

Environmentally Assisted Fatigue (EAF) Research and Related ASME Activities

September 25, 2018, 08:30 AM to 05:00 PM

NRC One White Flint North, 10 B4
11555 Rockville Pike
Rockville, MD

Time	Topic	Speaker
	Ongoing EPRI EAF Analyses	
1:00 pm	a. Fatigue Usage Gradient and Life Factor Concept	S. Gosselin, LPI
1:30 pm	b. Alternative Approaches for Simplified Elastic-Plastic Analysis	S. Ranganath, XGEN Engineering
2:00 pm	c. Fatigue Limit of Stainless Steel for Use in Vibration Evaluation	S. Ranganath, XGEN Engineering
2:30 pm	d. Corrosion fatigue crack growth of low alloy steel in BWRs	S. Ranganath, XGEN Engineering
3:00 pm	**Break**	
3:15 pm	BWRVIP Approach for Managing EAF of Internals	G. Stevens, EPRI
3:45 pm	Discussion of High Energy Line Break (HELB) Limit for CUF = 0.1	M. Benson, NRC G. Stevens, EPRI
4:15 pm	Status of Previous EPRI EAF Efforts a. Probabilistic Determination of Margins in ASME Code Section III CUF Calculations b. Fatigue Crack Growth Rates for Austenitic Stainless Steels in BWR Environments c. BWR Subsequent License Renewal EAF Database d. International Collaboration Group	G. Stevens, EPRI
4:45 pm	Meeting Summary and Next Steps	R. Tregoning, NRC
4:50 pm	Public Comment Period	R. Tregoning, NRC
5:00 pm	**Adjourn**	