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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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Fatigue of Nuclear Reactor Components

Proceedings of the 4th International Conference
28 September-1 October 2015
Seville, Spain

The presentations provided during the workshop will be available on the NEA website.

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

The OECD is a unique forum where the governments of 35 democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

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NUCLEAR ENERGY AGENCY

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The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;
– to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The Committee on the Safety of Nuclear Installations (CSNI) shall be responsible for NEA programmes and activities that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations, with the aim of implementing the NEA Strategic Plan for 2017-2022 in its field of competence.

The Committee shall constitute a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development and engineering, to its activities. It shall have regard to the exchange of information between member countries and safety R&D programmes of various sizes in order to keep all member countries involved in and abreast of developments in technical safety matters.

The Committee shall review the state of knowledge on important topics of nuclear safety science and techniques and of safety assessments, and ensure that operating experience is appropriately accounted for in its activities. It shall initiate and conduct programmes identified by these reviews and assessments in order to confirm safety, overcome discrepancies, develop improvements and reach consensus on technical issues of common interest. It shall promote the co-ordination of work in different member countries that serve to maintain and enhance competence in nuclear safety matters, including the establishment of joint undertakings (e.g. joint research and data projects), and shall assist in the feedback of the results to participating organisations. The Committee shall ensure that valuable end-products of the technical reviews and analyses are provided to members in a timely manner, and made publicly available when appropriate, to support broader nuclear safety.

The Committee shall focus primarily on the safety aspects of existing power reactors, other nuclear installations and new power reactors; it shall also consider the safety implications of scientific and technical developments of future reactor technologies and designs. Further, the scope for the Committee shall include human and organisational research activities and technical developments that affect nuclear safety.

The Committee shall organise its own activities. Furthermore, it shall examine any other matters referred to it by the Steering Committee. It may sponsor specialist meetings and technical working groups to further its objectives. In implementing its programme, the Committee shall establish co-operative mechanisms with the Committee on Nuclear Regulatory Activities in order to work with that Committee on matters of common interest, avoiding unnecessary duplications.

The Committee shall also co-operate with the Committee on Radiological Protection and Public Health, the Radioactive Waste Management Committee, the Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle, the Nuclear Science Committee, and other NEA committees and activities on matters of common interest.

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EXECUTIVE SUMMARY

This workshop was the fourth in a series of Nuclear Energy Agency (NEA) workshops on fatigue (Napa, California, United States, August 2000; Snowbird, Utah, United States, July 2002; Seville, Spain, October 2004), dedicated to Fatigue of Reactor Components. The fourth NEA workshop dedicated to Fatigue of Reactor Components was held on 28 September-1 October 2015 in Seville, Spain, hosted by the CSN. Over 90 specialists from 21 countries attended the workshop. The workshop focussed on the various subjects relating to environmental assisted fatigue and thermal fatigue as well as to the methods for assessing, predicting and monitoring fatigue, and detecting cracks caused by fatigue.

The main objective of the conference was to bring together the results of international research on the topic of fatigue with a special focus on the methods for evaluating environmental effects. The goal was to address the current status of the regulatory arena, identify and recommend good practices for member countries and explore R&D to be developed on this topic.

The recommendations of previous fatigue workshops for improving the transferability of test results to real nuclear power plant (NPP) structures remain valid after this fourth workshop on fatigue of reactor components. It is important to strengthen the route from research to codification and to integrate the results of new experiments into the existing test and operating experience data. The identification of the critical locations should be based on operating experience and lessons learned on assessment of the decommissioned plants. After collecting this new data, and rigorously assessing all existing data, the design rules for fatigue and especially for environmentally assisted fatigue (EAF) could be updated.

Another issue for preventing the fatigue incidents of new and operating plants is the need to recognize the stratification locations, where thermal fatigue could be critical. Improvements in fatigue monitoring and knowledge on sensor locations should be developed based on detailed assessment of the operating experience and lessons learned from decommissioned plants.

Based on the workshop, it is obvious that additional research is necessary to understand the mechanisms of damage and continue to address the mitigation of thermal fatigue. Combining the research results with the results from operating experience, the fatigue management guidelines could be updated.

Based on conference results, the following technical suggestions for decreasing the number of plant incidents related to fatigue by clarifying and increasing the design margins could be assessed:

- Material examination is an important consideration and some good suggestions are now available for use of such information to aid data interpretation. As an example, presentations in this conference have shown that decrease of strain rate in elevated temperature can promote hardening of steel material used in main components of the primary circuit.

- The number of safety related incidents of NPPs caused by thermal stratification could be decreased by improving the operating procedures based on results of monitoring, as well as on detailed assessment of the operating experience and lessons learned from decommissioned plants. Improvements with monitoring systems are effective in recognising low-cycle fatigue, provided the sensors are placed at adequate locations and that their measurement uncertainty is accounted for. Results may also have an effect on machining process (surface finish) to prevent crack initiation.

Proposals to reduce the conservatism in the existing ASME Code procedures were discussed in the fourth conference. Additional assessments of the potential reasons for the disparity between operating experience and laboratory test results could help in understanding and defining the necessary level of conservatism for environmental factors. Some of the reasons are the differences in mechanical and chemical loadings between lab specimens and real components. In addition, conservatism in design regarding assumptions for levels (i.e., strain amplitudes) and frequency of loadings may enhance this discrepancy.

Based on the conclusions of the Seville workshop, the following recommendations were made for international work looking at the possibilities to decrease unnecessary conservatism in design:

- Work to reduce conservative assumptions in analyses based on existing fatigue standards or comparison of standard models could be supported internationally (e.g. in future activities under NEA CSNI). The differences between conditions producing environmental fatigue damage in plant and laboratory tests could be assessed and the understanding of sensitivity to these differences shall be improved. It is recommended that an international team develop a report analyzing differences in the communicated results and design curves. The team could also look into possibilities to carry out more extended (and relevant) testing in PWR environments and assess these experimental results and evaluate how to integrate them into the engineering methodologies and design standards.

- Reduction in conservatism could be associated with required target reliability values for avoidance of through wall leakage, dependent upon the consequences of leakage occurring at the location of interest. Work is required to establish internationally what these reliabilities could be rather than the current use of unquantified margins.

- Environmental effects measured in various laboratories and experimental programs report variations in environmental correction factor (F_{en}). The environmental correction factor is used in design for ensuring necessary safety margins of structures against environmental effects. Therefore, establishment of an international task group with a mission to compare the data and search for a correlation between test boundary conditions and results is recommended. The assessment of the realistic environmental effect data from components of retired plants could help with this target.

- Testing of (standardized) components instead of laboratory specimens might help improve the transferability from research data to plant applications and support reducing conservatism in the design codes. In particular, an international round-robin analytical ‘blind-prediction’ of such tests could be used to validate improved methodologies. Further, an international benchmark for establishing the reliability of detecting existing cracks could be started. The benchmark could include the comparison of the detection techniques, calibrating procedures of the equipment for plant environment, and the ultrasonic examination procedures. A mixing tee mockup could be used to investigate up-stream cracking in this benchmark.

It was proposed that the discussions on fatigue evaluation methods and design curves be continued in international workshops in future.

ACKNOWLEDGEMENTS

Gratitude is expressed to the CONSEJO DE SEGURIDAD NUCLEAR (CSN, Spain) for hosting the Conference and to the Workshop Organising Committee, the Session Chairpersons and the workshop participants for their effort and cooperation.

The workshop organising committee lead by Carlos Castelao was as follows:

Name	**Country**	**Organization**
Carlos Castelao	Spain	CSN
Robert Tregoning	United States	NRC
Lubomir Junek	Czech R.	IAM
Peter Hähner	Netherlands	JRC
Matthias Bruchhausen	Netherlands	JRC
Karl-Heinz Herter	Germany	MPA
Isabelle Delvallée-Nunio	France	IRSN
Mike McDevitt	United States	EPRI
Seiji Asada	Japan	MHI
Olli Nevander	International	NEA

Chairpersons

General session: General Fatigue Program Overview
Javier Reig (NEA)

Session I Environmental Fatigue
Part A: Jürgen Rudolph (AREVA GmbH) and Al Ahluwalia (EPRI).
Part B: Karl-Fredrik Nilsson (EU-JRC) and Armin Roth (AREVA GmbH).

Session II: Thermal Fatigue
Robert Magnussen (Ringhals) and Mike McDevitt (EPRI).

Session III: Assessing and Predicting Fatigue
Part A -Normann Platts (Amec) and Philippe Spätig (PSI)
Part B - Thomas Métais (EDF/SEPTEN) and Mike McDevitt (EPRI).

SESSION IV: Codes and Standards
Nathan Palm (EPRI) and Karl-Fredrik Nilsson (EU-JRC).

Session V: Component Performance and Testing
Part A - Mike McDevitt (EPRI) and Ertugrul Karabaki (E.ON Kernkraft GmbH)
Part B - Xaver Schuler (MPA) and Isabelle Delvallée-Nunio (IRSN)
Part C - Thomas Métais (EDF/SEPTEN) and Matthias Bruchausen (JRC).

SESSION VI: Fatigue Monitoring and Crack Detection
Jennifer Correa (SIA) and Olli Nevander (NEA)

DEFINITIONS

Corrosion fatigue - is an environmental reduction of fatigue life (crack initiation) and environmental acceleration of fatigue crack growth in a material under the simultaneous and synergistic interaction of cyclic or fluctuating stress and corrosive environment.

Environmentally assisted fatigue (EAF) means reduction of fatigue life (initiation and crack growth) in material in a different environment (e.g. test environment is air and real NPP environment is liquid) at the same stress.

Environmental factor (F_{en}) is a parameter used in a method, where the effect of real LWR environment to the fatigue curve is taken into account by using a special correcting factor (F_{en}) for correcting the fatigue usage calculated with the “air” design fatigue curves. The method affords the designer greater flexibility to calculate the appropriate impacts for specific environmental parameters.

Fatigue is a process of progressive localized permanent structure change, occurring in a material subjected to fluctuating stresses and strains, which may culminate in cracks or complete fracture after sufficient number of fluctuations.

High-cycle fatigue (HCF) happens with high number of stress cycles, relatively low stress amplitude usually below yield strength, but above fatigue endurance limit of material.

Low-cycle fatigue (LCF) happens with high stress range, typically less than 100,000 cycles and with stress/strain above yield strength.

Stress corrosion cracking (SCC) is a progressive fracture mechanism in metals that is a result of the simultaneous interaction of a corroding and a sustained tensile stress. In materials where the maximum applied-stress-intensity factor exceeds the stress-corrosion cracking-threshold value, stress corrosion adds to crack-growth velocity. The boundary between SCC and corrosion-fatigue is sometimes vague. However, because the environments that cause SCC and C**orrosion Fatigue** are different, the two are treated as separate and distinct metal fracture mechanisms.

Thermal (thermo-mechanical) fatigue is the fatigue of a material mainly arising from cyclic thermal loading which may or may not exacerbate other cyclic loads.

Vibration fatigue damage occurs when a number of variable cycles, depending on the level of the applied stress, provide cracks in the newly plastic area, and when this cumulative phenomenon is accompanied by the reduction of strength.

LIST OF ABBREVIATIONS AND ACRONYMS

ANT	Advanced nuclear technology
AMPs	Ageing management programs
ASME	American Society of Mechanical Engineers
BWR-VIP	Boiling water reactors vessel integrity program
CAPS	CSNI Activity Proposal Sheet
CGR	Crack growth rate
CRP	Coordinated research program
CSN	Consejo de Seguridad Nuclear
CSNI	Committee on the Safety of Nuclear Installations
CUF	Cumulative fatigue usage factors
EAF	Environmentally assisted fatigue
ECP	Electro-chemical potential
EDF	Électricité de France
EPRI	Electricity Power Research Institute (United States)
F_{en}	Environmental correction factor
GALL	Generic Aging Lessons Learned
IAEA	International Atomic Energy Agency
IGALL	International Generic Aging Lessons Learned
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (France)
ISI	In-service inspection
LCF	Low-cycle fatigue
LCFG	Low-cycle fatigue growth
LTO	Long term operation
LWR	Light water reactor
MRP	Materials reliability program
NEA	Nuclear Energy Agency
NPP	Nuclear power plant
NRAJ	Nuclear Regulation Authority (Japan)
NRC	Nuclear Regulatory Commission
OECD	Organisation for Economic Co-operation and Development
POD	Probability of detection
PSCR	Primary systems corrosion research program

SCC	Stress corrosion cracking
SEM	Scanning electron microscopy
SSC	Systems, structures and components
TEM	Transmission electron microscopy
TLAA	Time limited aging analyses
TOFD	Time of flight diffraction
TSO	Technical support organization
VHCF	Very high-cycle fatigue
WGIAGE	Working Group on Integrity and Ageing of Components and Structures

1. INTRODUCTION

This is a summary report from the International Conference on Fatigue of Nuclear Reactor Components on 28 September-1 October 2015 in Seville, Spain. Over 90 specialists from 21 countries attended this workshop.

Fatigue is a primary degradation mechanism affecting nuclear power plant components worldwide. The effective management of fatigue is important to the continued safe and reliable operation of plant components during present, long-term and next-generation operation.

This was the fourth instalment of an NEA co-sponsored conference series on fatigue. The first conference in the series was held in Napa, California in 2000 and was attended by approximately 90 fatigue experts, representing 12 countries. The second conference, held in Snowbird, Utah in 2002, provided an excellent forum for the discussion of component fatigue issues. The third conference was held in Seville in 2004 and was attended by more than 90 experts. Since then, important research has been performed and different approaches have evolved internationally.

2. OBJECTIVES

The main objective of the conference was to bring together the results of international research on the topic of fatigue with a special focus on the methods for evaluating environmental effects. Several countries have already incorporated the results from new research into applicable codes and standards. Furthermore, many countries are requiring that environmental effects be considered by operating reactors as well as by new reactors.

The conference provided an opportunity to discuss and understand the different approaches for addressing fatigue effects and the rationale supporting the country, laboratory and plant specific approaches.

This conference brought together the international community to discuss significant fatigue issues that affect nuclear plant operations. The goal was to address the current status of the regulatory activities in each country, identify and recommend good practices among participating countries, and explore future developments on fatigue of reactor components.

3. SUMMARY OF THE RECOMMENDATIONS OF THE PREVIOUS WORKSHOP

The previous NEA workshop conclusions are presented in order to point out the main advances or findings on the topic available before this workshop.

Proceedings of the previous Fatigue Conferences of CSNI:

- Workshop on Experience with Thermal Fatigue in LWR Piping Caused by Mixing and Stratification, Proceedings, 1998, Paris, France; NEA/CSNI/R(1998)8
- Proceedings of the International Conference on Fatigue of Reactor Components, August 2000, Napa, California, United States; NEA/CSNI/R(2000)24
- Proceedings of the EPRI/USNRC/OECD International Conference on Fatigue of Reactor Components July 2002 Snowbird, Utah, United States; NEA/CSNI/R(2003)2
- Proceedings of the Third International Conference on the Fatigue of Reactor Components 3-6 October 2004, Seville, Spain; NEA/CSNI/R(2004)21

3.1 Summary of conclusions from the Workshop on Experience with Thermal Fatigue in LWR Piping Caused by Mixing and Stratification on 1998, Paris, France

The workshop concentrated on the recurring phenomena of thermal fatigue due to the stratification and mixing of hot and cold water. This workshop was an international precursor and starting point for the series of conferences on fatigue of reactor components. The need to develop further accepted methods to identify locations with potential risk of thermal fatigue was seen as important in the workshop. It was recommended that the best estimate analysis as well as probabilistic methods should be developed for this purpose. In addition, the risk of fatigue should be decreased by different methods and the NDE methods for detecting cracks should also be developed. The co-operation of plant owners and designers should be developed as well as the cooperation between different discliplines inside organisations e.g. maintenance and operation personnel of NPP's.

3.2 Main conclusions and recommendations from the proceedings of the International Conference on Fatigue of Reactor Components on August 2000 in Napa, California

The primary objective of the first conference on Fatigue of Reactor Components was to provide a forum for the technical discussion of fatigue issues that affect the integrity and operation of light water reactor components. Approximately 90 fatigue experts, representing 12 countries, participated in the conference. Strong representation was provided by nuclear operators, vendors, regulatory agencies, research and development organizations, and other experts.

Following the technical presentations, a general discussion was held to summarize major points identified by various speakers during the conference. The major discussion points identified by the participants are provided below.

1. Collaboration and cooperation on an international scale are critical to the success of resolving fatigue issues, including sharing of data, test programs, and theories.

2. It is recognized that conservatism exists in the ASME Code fatigue design procedures. Plant-specific analyses using actual plant operating parameters (transient occurrence and severity) may significantly reduce the conservatism in overall fatigue usage factor determination.

3. Significant advancements have been made in the international community regarding the effects of thermal fatigue and reactor water environment. Additional research and international collaboration are recommended in these areas in order to resolve technical issues and utilize the results of these efforts in various operating plant criteria.

4. An understanding should be developed between ASME Code analysis and laboratory testing regarding reactor water effects on fatigue life.

The characterisation of thermal hydraulic phenomena is complex and an important aspect in the quantification of thermal fatigue. Additional work regarding the proper characterisation of thermal hydraulic phenomena is recommended.

A background document regarding the development of implicit fatigue design criteria in B31.1 should be developed.

The following fatigue design Code changes/improvements were discussed:

- Modification of low cycle fatigue analysis procedures
- Addition of thermal fatigue analysis procedures for Class 2 piping
- Addition of “warnings” in Class 1, 2, and 3 design codes for dead legs/stratification and mixing tees with corresponding thresholds
- Changes in the existing Code fatigue design S-N curves based on additional data
- Further evaluation of the additional data
- Determination of updated reduction factors
- Differentiation between thermal and mechanical loads
- Consideration of surface striping/craze cracking

The development of expert tools is recommended to provide a better understanding of fatigue degradation mechanisms.

Weld overlay repairs were presented as an effective method for repairing leaking standard socket welds and providing sufficient fatigue resistance to operate to the next outage and beyond. In addition, welding process and geometry enhancements were reported to improve the fatigue life of socket welds.

Instrumentation and monitoring can confirm the existence of high cycle thermal loads, except for high frequency fluctuations.

Field experience indicates that the relatively limited numbers of locations that experience thermal fatigue are due primarily to the following:

1. Stratification

2. Dead legs and vortex conditions without a leak

3. Reversing zones with large temperature differences

Risk-informed considerations, including reactor operating experiences, should be applied to the management of fatigue technical issues.

3.3 Main conclusions and recommendations from the proceedings of the International Conference on Fatigue of Reactor Components on July 2002 in Snowbird, Utah

Following the technical presentations, a panel session was held to discuss key technical issues identified during the conference. As a result of these discussions, the following conclusions were developed

- Stronger U.S. utility participation in NEA and NEA/CSNI is encouraged regarding thermal fatigue technical issues,

- Similar efforts are underway by several organizations worldwide to understand the fundamental mechanisms associated with thermal fatigue and predict component susceptibility. Data sharing and collaboration are encouraged for the benefit of all organizations,

- International knowledge regarding the phenomena associated with thermal fatigue is progressing. Results of these studies should be incorporated into aging management programs, including in-service inspection (ISI) programs,

- Consideration should be given to the assessment and screening of Class 2 piping systems for thermal fatigue,

- International data efforts indicate that a change in the high-cycle end of the thermal fatigue mean data curve in the appropriate design code may be warranted. Generation of additional data beyond 10^6 cycles is recommended. This may also warrant a revision to fatigue evaluation procedures,

- Fatigue usage factor is not necessarily a good indicator of component degradation.

Environmental Fatigue

- The effect of flow rate on environmental fatigue for carbon/low-alloy steels has been shown by several organizations. Additional data are needed to characterize the effect for stainless steel materials,

- The effect of flow rate should be considered in environmental fatigue evaluations,

- International studies indicate that threshold conditions are necessary for environmental fatigue to occur,
- Development of a new fatigue design (S-N) curve that incorporates environmental effects is not recommended,
- For consideration of environmental effects, the present preferred approach is an application of an environmental factor, F_{en},
- Clarification of applicable environmental fatigue threshold parameters is needed, especially when the notion of "moderate" environmental effects is considered.
- Fatigue analysis procedures (including design curves) should not be revised without a thorough understanding of all relevant effects:
  - Applicability of load-controlled data was questioned; strain-controlled data are preferred,
  - Clarification of surface finish effects,
  - The measurement and reporting of water conductivity and electro-chemical potential (ECP) associated with environmental fatigue tests in boiling water reactor (BWR) environments are encouraged,
  - Further reconciliation between operating experience and laboratory/component structural data is recommended,
  - A more detailed evaluation of temperature/strain relationship in transient analysis (for example, the modified rate approach applied in Japan) should be considered for potential application.

Fatigue Monitoring/Evaluation

- Fatigue transient monitoring (both globally and locally) is an important tool for fatigue aging management that should be implemented as early in plant life as practical.
- Evaluation and assessment of data integrity are critical factors in the successful interpretation of fatigue transient monitoring results.
- Advanced methods for material condition monitoring are being developed and show promise for the successful monitoring of fatigue. Further development is encouraged.
- An overall integrated approach is critical to successful fatigue management of relevant structures. Training of plant personnel is an important aspect of any integrated approach.
- Additional discussion of fatigue evaluation of welds is recommended in future conferences.

Codes & Standards (American Society of Mechanical Engineers [ASME] Section XI)

- Improved in-service inspection (ISI) probability of detection (POD) is an important aspect in reducing component inspection frequency in flaw tolerance analyses.

- The crack aspect ratio of propagating flaws has been shown through analytical studies to vary as a function of transient.
- Multiple crack initiations may also need to be considered in a flaw tolerance evaluation.
- da/dN information is needed for austenitic stainless steels.

3.4 Main conclusions and recommendations from the proceedings of the Third International Conference on the Fatigue of Reactor Components on 3-6 October 2004 in Seville, Spain

Vibration is still the main cause of fatigue failure of components in NPPs for non-fatigue design components. Recent operating experience and potential modifications in plant operation (i.e., power uprates, component replacements, aging, material issues) shows that fatigue still warrants attention for many systems.

Thermal fatigue mechanism is understood. There is a general agreement on the swirl description and the origin of the cold fluid (heat loss or leakage through valves). Nevertheless predictability still remains an issue and caution should be exerted when applying methodologies to screen pipes.

There were still discussions within the community on the consideration of environmental factors. In particular, they should be compared with operating experience.

As to current Codes, appropriate warning could be in the Codes that there are other mechanisms that should be considered both at the design level and for component replacement (i.e., hot cold water mixing.). This is valid for all class of piping. Screening criteria are needed. Current ones should be improved based on operating experience and test results.

Guidelines on management of thermal fatigue and fatigue are under preparation by the EPRI and JSME/TENPES in Japan.

With regard to the transferability from test data to codes, the following statements were made:

1. Transferability of test results to real structures remains an issue. Additional efforts should be pursued.
2. How to go from research to codification should be investigated. Results of new experiments should be integrated.
3. Data quality issue: data generated to understand phenomenon should be clearly documented.

4. RECENT INTERNATIONAL ACTIVITIES ON FATIGUE OF COMPONENT AND STRUCTURES

Fatigue and Environmental Assisted Fatigue (EAF) are important phenomena for the Ageing Management Programs (AMPs) of components and structures of NPPs. The detailed knowledge of fatigue status of safety relevant Systems, Structures and Components (SSC) and minimizing thermal fatigue is an important safety issue for Long Term Operation (LTO).

The NRC report NUREG-1801, Revision 2, "Generic Aging Lessons Learned (GALL) Report," identifies acceptable aging management programs for fatigue and cyclic operation for the period of extended operation. It describes a process for assessing the impact of the reactor coolant environment on a set of sample critical components for the plant, examples of which are identified in NUREG/CR-6260. In international level, the methods for ageing predictions are documented in the IAEA "International Generic Aging Lessons Learned (IGALL)" report.

The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Section III, Subsection NB contains rules for the design of Class 1 components of nuclear power plants and recognizes fatigue as a possible mode of failure in pressure vessel steels and piping materials. However, the effects of light water reactor (LWR) coolant environments are not explicitly addressed by the Code design curves. The published data indicate that the existing ASME Code Section III curves are appropriate for austenitic stainless steels (e.g. Types 304, 316, and 316NG), and are conservative for carbon and low-alloy steels. The ASME Code fatigue design curves, given in Appendix I of Section III, are based on strain–controlled tests of small polished specimens at room temperature in air. The design curves have been developed from the best–fit curves to the experimental fatigue strain vs. life (e–N) data. These best-fit curves have been adjusted for the effects of mean stress on fatigue life and then reducing the fatigue life at each point on the adjusted curve by a factor of 2 on strain (or stress) or 20 on cycles, whichever is more conservative. As described in the Section III criteria document, these factors were intended to account for data scatter (including material variability) and differences in surface condition and size between the test specimens and actual components.

It has been recognized that the environmental impact on fatigue analysis of ASME Class 1 components in the real NPP environment (e.g. coolant environment, temperature) as well as real material data should be taken into account. However, it is overly complicated and conservative, if only one NPP environment fatigue curve is provided. The fatigue life of ASME Class 1 components in LWR environments is a function of several parameters; therefore, the development of several fatigue curves to address potential parameter variations is necessary. Another possibility is to use an environmental correction factor (F_{en}) for LWR environments by correcting the fatigue usage calculated with the ASME "air" curves.

As a consensus on the methods and fatigue curves has not been reached, NRC has published Regulatory Guide 1.207. In this guide the F_{en} method is presented as an acceptable method to incorporate the LWR environmental effects into fatigue analyses of ASME Class 1 components for new reactors. The technical basis document for Regulatory Guide 1.207, NUREG/CR-6909, and claims to validate the F_{en} methodology by comparing the results of five different experimental data sets obtained from fatigue tests that simulate actual plant conditions with estimates of fatigue usage adjusted for environmental effects using the updated F_{en} expressions. The potential effects of dynamic strain aging on cyclic deformation and environmental effects are also discussed.

However, a significant number of public comments were submitted regarding the draft update to NUREG/CR-6909 that has yet to be addressed. These include observations that the five different data sets claimed to validate the methodology did not consider through wall strain gradient effects typically associated with thermal shock loading.

Under high cycle fatigue conditions the curve in Regulatory Guide 1.207 predicts shorter fatigue lives than the previous ASME curve. It is significantly more conservative than the former ASME curve in the region of ~10^4 to 10^7 cycles, which can present problems for designers. The NRC requires license renewal applicants to assess the fatigue usage effects from a reactor water environment and demonstrate acceptable fatigue cumulative usage factors (CUF) with the effects of a reactor water environment considered for Class 1 components for the entire period of extended operation.

An international activity on fatigue of component and structures was initiated by a CSNI Activity Proposal Sheet (CAPS) on Fatigue of Components and Structures and it was approved in December, 2009. The CAPS was proposed and led by the EDF, France. The stated purpose of the CAPS was to collect information on code practices and existing test practices in different countries and to identify possibilities to define reference tests for comparing the rules in different laboratories and countries. The activity was based on the fact that even after a long process, mainly in Japan and USA, on fatigue of standard specimen, the work to transfer the test results to industrial components and structures needs still more work. The standards and results should consider all types of fatigue: high and low cycle fatigue, mechanical and thermal fatigue, and without or with environmental effects. The proposed plan for CSNI activity in year 2009 has the following steps:

1. Collect international code practices and the available fatigue test information provided for analyzing fatigue of components, and evaluate different codes and test methods that support the tests information.

2. Select the more effective programs and detailed experimental results and analysis, for comparative analysis.

3. Propose a synthesis of existing fatigue tests done on components and structures and select a set of reference tests for a benchmark exercise to check different proposed rules in different countries.

4. Develop conclusions and recommendations for code rules describing best practices for fatigue crack initiation and crack growth.

The technical goals of this activity were chosen because different leaks and deep cracks have been identified in the event information presented in meetings of CSNI working groups related to the ageing. As a result, large effort was made to implement ISI programs (list of location, frequency and performance) and monitoring systems in utilities to prevent fatigue events.

The work on 2009 activity on fatigue was not completed in the metal sub-group of CSNI Working Group on Ageing of Components and Structures, therefore, the focus of the similar activities related on fatigue of reactor components should be discussed again in the metal sub-group. The working group is now determining the interest of member countries to take part to the development of a database on small-specimen fatigue tests in both air and light water reactor environments. An international database on fatigue testing, both specimens and structures, with and without environmental effects could be used for further assessment of the fatigue test results and operating experiences. The NRC (USA) and NRAJ (Japan) have already consolidated their data on stainless steel, carbon steel, low-alloy steel, and nickel-based materials into a combined database. The work to share the fatigue data for stainless steel materials in air together with EdF (France) is ongoing. This cooperation will help to get information on different materials used in Europe, the United States and Japan.

Another international activity on fatigue of component and structures was initiated by a CSNI Activity Proposal Sheet (CAPS) on Fatigue of Components and Structures in June 2015. This activity proposal on vibration fatigue has not yet approved by CSNI. The activity proposal targets to the vibration fatigue of different sizes of safety related piping. The degradation effect of acoustic resonance and flow-induced vibration in fluid systems to the safety related systems will be evaluated in this activity.

In the Seville workshop on September 2015, it was recognized that with more and more test results to compare and discuss, harmonization of test methods and implications to real plant environment needs more international co-operation.

5. SESSION SUMMARIES

5.1 General session: General Fatigue Program Overview

Session G was chaired by Javier Reig (NEA). The presentations were titled as follows:

1. Development and Application of Fatigue Assessment Procedures and Consideration of Environmentally Assisted Fatigue Effects in the European Framework. S. H. Reese; W. Mayinger. EON.

2. Overview of Fatigue Evaluation Methods and Mechanistic Study in Japan. Prof. T. Shoji. Tohoku University.

3. Fatigue Management- an EPRI Perspective. J.P Sursock. EPRI

4. CODAP Project Operating Experience Insights Related to Fatigue Mechanisms. B. Lydell et al.

5. NEA (presented by Carlos Castelao).

Conclusions of the general session

The operators of NPP's have a great interest to have detailed knowledge of fatigue status of safety relevant SSC and minimizing thermal fatigue. This interest is related to the operator interest to reduce the amount of potential NDT efforts. The locations most at risk of fatigue damage during operation are identified by designer by operating experience and temperature measurement are installed at fatigue relevant locations to be able to measure since beginning of plant operation.

Germany has considered the Environmental Assisted Fatigue (EAF) to NPPs in operation in standard KTA 3201.2 / 3201.4 (2013-11). The standard includes e.g. definition of "attention threshold" CUF_{thr}, additional measures if CUF>0.4 for austenitic SS. National individual approaches for EAF are in use e.g. US, France, Germany.

Usually the F_{en} factors are based on laboratory investigations and on an empirical derivation of the numerical correction factor. In practice, the detailed fatigue assessment helps the operator improve the plant in general with optimizing maintenance activities and with minimizing radiation exposure of the personnel as well as to improve integrity of pressurized components. F_{en} approaches usually lead to more conservative results in comparison to certain traditional and conservative methods. Therefore, precise application and understanding of the numerical F_{en} approach is necessary. Internationally there is a need to improve transferability of laboratory data to fatigue assessment of plant components.

Environmental influence on life time is crucial and needs more R&D in connection to SCC at the lower strain rate. There is need for more worldwide integration of knowledge and information exchange.

5.2 Session I: Environmental Fatigue

<u>Session I Environmental Fatigue part A was chaired by Jürgen Rudolph (AREVA GmbH) and Al Ahluwalia (EPRI).</u>

This dedicated session on Environmentally Assisted Fatigue (EAF) part A issues consisted of five presentations from different viewpoints and institutions. It covered EAF approaches for WWER-440 Nuclear Power Plants, the observed mismatch between the largely investigated environmental Fatigue behaviour of laboratory specimens on one hand and field experience of plant components in real environment on the other hand, an overview of the ASME Working Group on Environmental Fatigue Evaluation Methods, an INCEFA-PLUS project and the consideration of EAF in specific TLAA's (Time Limited Aging Analyses) for Long Term Operation (LTO) in Spain.

The presentations were titled as follows:

1. Corrosion Fatigue Evaluation: Czech Proposal for WWER-440 Nuclear Power Plants. L. Vlcek, Institute of Applied Mechanics Brno.

2. Consideration of the Mismatch between Environmental Fatigue Behaviour of Laboratory Specimens and Plant Components in Real Environment. J. Solin et al. VTT, AREVA.

3. An Overview of the ASME Working Group, Environmental Fatigue Evaluation Methods, Fatigue Action Plan. K. Wright. Rolls-Royce.

4. INCEFA-PLUS (INcreasing Safety in NPPs by Covering Gaps in Environmental Fatigue Assessment). K. Mottershead et al. Amec Foster Wheeler.

5. Environmentally Assisted Fatigue Assessment in Time Limited Aging Analyses for Extended Operation in a Spanish PWR Plant. M. Álvaro et al. G. TECNATOM, CNAT

All presentations found a highly interested audience and the available time for discussion was used for questions. The first presentation by Mr. Vlcek gave an overview of the specific approach to EAF for WWER-440 reactors and some differences to the other international developments. In the second presentation, VTT from Finland presented latest experimental results on the complex specimen behaviour under different loading and environmental conditions deriving evidence for mismatches with component behaviour. The on-going work and development lines within the ASME Working Group, Environmental Fatigue Evaluation Methods, Fatigue action plan was presented by the chairman of this working group, Keith Wright. The issue of covering gaps in Environmental Fatigue Assessment was addressed by Amec Foster Wheeler in presenting the INCEFA-PLUS project. The session was closed by a practical explanation of how EAF is addressed in the aging management of Spanish NPP's. The session was closed with a good discussion and by thanking all the presenters, authors and the audience for questions.

<u>Session I "Environmental Fatigue" part B was chaired by Karl-Fredrik Nilsson (EU-JRC) and Armin Roth (AREVA GmbH).</u>

The presentations were titled as follows:

1. K. Mottershead et al., Amec Foster Wheeler (AFW), presented by Norman Platts, Environmentally-assisted fatigue assessment – the European view of the state of the art for stainless steels in LWR environments.

2. K. Ahluwalia et al., EPRI, Testing to Address Environmentally Assisted Fatigue Degradation in LWR Plants.

3. F. J. Perosanz, et al., CIEMAT, Corrosion fatigue behaviour of alloy 690 in simulated PWR primary water.

4. D. Tice et al., Amec Foster Wheeler, presented by Norman Platts, Mechanistic Studies on Environmentally Assisted Fatigue crack growth in light water reactor environments.

5. F.H.E. de Haan et al. NRG, Petten, Quantitative Comparison of Environmental Fatigue Methods.

<u>K. Mottershead et al., Amec Foster Wheeler (AFW), presented by Norman Platts, Environmentally-assisted fatigue assessment – the European view of the state of the art for stainless steels in LWR environments.</u>

In the first paper presented by Mr. N. Platts a review on European approaches (in UK, France, Germany, Finland, Czech Republic and Switzerland) to advance test data as well as to understand and assess environmental effects in fatigue curves and crack growth rates is provided. The European approach is compared with relevant approaches in the US and in Japan. These approaches comprise the control of data as well as the effects of surface condition, spectrum loads (including holds), material composition, and alternative assessment methods for total life assessment. Concerning data from the presenter (AFW), an important observation was that high-sulphur steels obviously exhibit lower environmental crack growth rates under PWR conditions than low-sulphur steels. It was stated that industry programmes are funded on the premise that plant performance is not consistent with laboratory test results.

<u>K. Ahluwalia et al., EPRI, Testing to Address Environmentally Assisted Fatigue Degradation in LWR Plants.</u>

In the second paper current efforts by EPRI to deal with environmentally assisted fatigue are summarized in this contribution. For EPRI, the main objective of their programme is to address EAF in both current and new plants consistently in order to meet nuclear safety while assuring an appropriate level of conservatism. The current perspective with regards to plant application is on license renewal (up to 60 years), second license renewal (up to 80 years), new plants, and flexible operations (e.g. for load following operational mode). EPRI has performed a gap analysis based on the state of technology and has then established a road map to address the existing gaps. These gaps are considered in several programs which fund EAF activities. These comprise the materials reliability program (MRP), the boiling water reactors vessel integrity program (BWR-VIP), the advanced nuclear technology program (ANT), and the primary systems corrosion research program (PSCR). In its experimental activities, EPRI is currently establishing a stakeholders database which consists of all published data regarding crack initiation and growth, BWR & PWR environments, carbon and low-alloy steels, austenitic stainless steels and nickel-based alloys. Regarding complex loading, EPRI is sponsoring mixed wave tests. In LCFG test using 316 SS, EPRI sponsored tests revealed consistently higher fatigue specimen lives than predicted based on the ANL model (NUREG/CR-6909). The EPRI sponsored hold-time test did not reveal beneficial effects to fatigue life. However, based on existing data, hold-times (60s / 300 s) are expected to be too short to observe relevant changes through thermal recovery. Complex loadings and non-isothermal behaviour are also addressed in EPRIs test programme, however these projects have just started and have yet to produce relevant data.

<u>F. J. Perosanz, et al., CIEMAT, Corrosion fatigue behaviour of alloy 690 in simulated PWR primary water.</u>

Paper of Mr. F. J. Perosanz, et al is based on observations in stress corrosion cracking, where Ni-base alloy 690 revealed some susceptibility to SCC in extremely cold worked conditions. The objective of this paper was to verify that the corrosion fatigue methodology analysis provides also insights into the SCC of alloy 690 in simulated PWR primary water. The work was performed using CRDM tubes with 20% of cold work to simulate the strain level expected in the heat affected zone of welds. Cold work was applied in two deformation methods, rolling and tensile straining. Crack growth tests were carried out at several temperatures and at constant corrosion potential. Tests were carried out by applying cyclic load, trapezoidal load (constant load with periodic partial unloading – PPU) and pure constant load. At the current state there obviously exists a big scatter in results. For instance, some environmental fatigue crack growth rate (CGR) tests revealed lower growth rates than tests in air. With applied hold times, an enhancement of CGRs was observed. This is explained by a small contribution of SCC growth at hold times with constant load. Weld material exhibited similar behaviour for plates and mock-up.

D. Tice et al., Amec Foster Wheeler, presented by Norman Platts, Mechanistic Studies on Environmentally Assisted Fatigue crack growth in light water reactor environments.

The fourth paper presented by Mr. Platts covers work in high temperature water aimed at understanding enhancement and retardation of crack growth due to EAF by crack growth studies and supportive microstructural studies. In addition, comparative studies in high temperature air and argon environments were performed to gain insight into the mechanism of environmental enhancement. Strong evidence was received that EAF of stainless steels is associated with enhanced planar slip that may be supported by hydrogen effects, based on literature data. Retardation of EAF has been observed for most series 300 SS with sulphur contents > 0.003% S. Retardation is favored by longer rise or hold times and higher temperatures. It is also associated with blunter, i.e., more heavily oxidized crack tips. Despite these phenomenal facts the mechanism of retardation is still unclear.

F.H.E. de Haan et al. NRG, Petten, Quantitative Comparison of Environmental Fatigue Methods.

In the fifth paper by Mr. de Haan a quantitative comparison was made for the calculation of the cumulative usage factor including environmental effects using several existing codes worldwide. This calculation was performed for a spray nozzle as an example. The materials were varied between carbon steel, low-alloy steel, austenitic stainless steel and Ni-base alloy. Significant differences for calculated usage factors were observed, depending on the code calculation method that was used.

Session I conclusions

There is a worldwide consensus that safety of nuclear components with regards to EAF is of highest priority and that a consistent approach for the assessment of environmental effects is desirable. However, there is also a wide agreement among certain stakeholders that sufficient safety should not be achieved by unnecessary over-conservatism when considering environmental effects.

This session has also highlighted once again that it is a common opinion among the industry worldwide that current environmental factors as set by Appendix A of ANL-report NUREG/CR-6909 are not representing the operational reality of components and thus create an unnecessary over-conservatism in the design of components or the assessment of plant life extension. Potential reasons for this obvious mismatch between operating experience and laboratory test results are significant differences in mechanical and chemical loadings between lab specimens and real components. In addition, conservatism in design regarding assumptions for levels (strain amplitudes) and frequency of loadings may enhance this discrepancy.

However, the dissatisfaction of the industry with the current situation is not fully reflected by the intensity of their common efforts to address open issues in their programmes worldwide. At the moment, Europe, the US and Japan are pursuing their individual approaches, whereas a worldwide cooperation would be desirable.

Based on the current rate of data generation it can be expected that operating experience from long-term operation of plants with increasing plant life will complement the lack of laboratory data, which is increasing more slowly. Therefore, the emphasis of efforts should not only be on the laboratory testing side, but should also comprise component fatigue monitoring in plants. This may serve as a practical baseline to identify true cumulative usage factors in comparison to those which are based on multiply conservatisms of the current design base.

A reliable but not overly conservative methodology to address environmental effects on fatigue is crucial to justify life extensions and for design of new reactors by ensuring sufficient safety margins and whilst also reducing overall costs. A key factor towards the development of improvements lies in better understanding of the discrepancies between laboratory tests and behaviour of components under operational conditions. Further work is therefore needed to address issues not covered by the lab tests such as strain gradients, non-isothermal conditions, variable amplitude and multi-axial loadings. This requires more plant representative tests supported by work on the underlying mechanisms.

Another key issue is the time factor where accelerated laboratory test never can completely represent the long-term degradation and monitoring of component behaviour is therefore a key aspect. The works needs to be done in close collaboration between operators and the research community and preferably in an international context.

5.3 Session II: Thermal Fatigue

Session II was chaired by Robert Magnussen (Ringhals) and Mike McDevitt (EPRI).

The session had the following presentations:

1. Analysis and Impact of Recent Thermal Fatigue Operating Experience in the United States. M. McDevitt et al. EPRI.

2. Short crack Behaviour of Austenitic Stainless Steels in Simulated PWR Primary Water During Fatigue Damage and Monotonic Deformation. C. Shim et al. Tohoku University.

3. Effect of Shoulder Extension Control on Fatigue Endurance Testing of Stainless Steels. C. Austin et al. Rolls-Royce.

4. Thermal Fatigue at Elevated Temperatures for 316L and P91 Thick-Walled Steel Tubes. K. Nilsson et al. EC, JRC, Institute for Energy and Transport.

In first paper by EPRI Management of Thermal Stratification Fatigue was presented. The paper describes large amount of some recent thermal stratification fatigue operating experiences in US and results of the assessment of these operating experience. The paper concludes the causes of the fatigue management program deficiencies. Based on the example cases in the paper in was concluded that the fatigue management program changes as well as additional research are needed to improve understanding the NPP's and to prevent future cracks from exceeding code allowable limits. The paper also noted that these recent events may indicate an emerging population of components reaching their fatigue life.

In the second paper by Mr. C. Shim et al. presented that the results of investigation of short fatigue crack growth behaviour on 316 stainless steel in simulated PWR, water at 325˚C and air at room temperature re investigated and comparison to SSRT test in a simulated PWR environment. According to the paper the following conclusions can be derived from these tests:

- Although cracks below 5 μm existed, Cracks can be easily observed by SEM, so that it is possible to express the histogram using crack distribution. Crack distribution behaviour observed on the surface of the four cross sections shows similar behaviour, therefore it was possible to express a representative crack distribution in order to compare crack distribution at each given cycle.

- Most of cracks were initiated in the early stage and cracks can be continued to initiate in the end of the test although many cracks were predominantly propagated
- Crack initiation-dominant region, transition region and crack propagation-dominant region can be separated and defined by using a representative crack distribution in simulated PWR water.
- Few cracks tend to be propagated intensively in air at room temperature. However, many cracks tend to be propagated in simulated PWR water relatively.

In the third paper the fatigue life of LWR reactor components in water environments are assessed against design codes (e.g. ASME Section III) based on test data in air ambient. As a conclusion the paper present that a single correction factor generated from a calibration curve represents a good solution giving a reasonable approximation of cyclic strain conditions for a practicable level of expenditure.

In the fourth paper characteristics of thermal fatigue at elevated temperatures for 316L and P91 thick-walled steel tubes are discussed. As a conclusion the paper presents that thermal fatigue cracking gives rise complex crack configurations and the cracking can be reasonably well be monitored with various replica techniques, with time-of-flight diffraction ultrasonic (TOFD) technic or with X-ray tomography. The paper also noted that a very basic crack propagation model could predict the crack propagation reasonably well.

Session II conclusions

The detailed assessment of the operating experiences could lead changes to the fatigue management program in NPPs in order to prevent future cracks from exceeding allowable limits. There is need for additional experiment results to generate data for the hardening model in design codes. However, the existing cracking in piping can be reasonably well be monitored with various replica techniques, time-of-flight diffraction ultrasonic (TOFD) technique, or X-ray tomography.

5.4 Session III Assessing and Predicting Fatigue

Session III "Assessing and Predicting Fatigue" part A was chaired by Normann Platts (Amec) and Philippe Spätig (PSI) and part B was chaired by T. Métais (EDF/SEPTEN) and M. McDevitt (EPRI).

Five papers were presented in part A: one from Germany, one from Spain, one from The Netherlands, one from the United States and one from Korea; in part B there was one presentation from the United States. The titles of papers are as follows:

1. Schuler et al paper on Fatigue design curve for SS in German Nuclear Safety Standard KTA.
2. Fernandez de Rucoba et al paper on Fatigue evaluation of component with environmental effects.
3. Holmstöm et al paper on Creep-fatigue models for P91 steel design rules.
4. Palm paper on Development of Fatigue Usage Gradient factor
5. Hong et al paper on Fatigue crack growth rate of 347 and 347N stainless steels under PWR water conditions

Schuler et al paper on Fatigue design curve for SS in German Nuclear Safety Standard KTA.

Presentation on fatigue analysis methods in nuclear codes and standards took into account the effects influencing fatigue life. Based on the large database of MPA Stuttgart, MPA Darmstadt and Areva of austenitic stainless steels X10CrNiNb18-9, X6CrNiNb18-10, X10CrNiTi18-9, new fatigue mean curves in air at room and elevated temperature were determined, from which new design curves were derived considering shifts toward lower cycle numbers and lower strain amplitudes. These new fatigue design curves are included in in the German Nuclear Safety Standards KTA 3201.2 and 3211.2 (Ed. 11/2013).

Fernandez de Rucoba et al paper on Fatigue evaluation of component with environmental effects.

A case study was presented of the application of a fatigue monitoring algorithm to a feedwater nozzle of a BWR reactor. The algorithm developed is capable of monitoring the actual fatigue of a component in service by means of mathematical models during its lifetime. This new method was compared in terms of stress level with the results of FE models for the complete transient, showing good correlation.

Holmstöm et al paper on Creep-fatigue models for P91 steel design rules.

Models of interactions models between cyclic softening/hardening behaviour and creep behaviour were discussed. For the interaction diagram based models, the challenge of acquiring representative creep damage fractions from the dynamic material response, i.e., cyclic softening with changing relaxation behaviour is addressed. It was shown that simplified models based on a reference state and on a relaxation time has the largest potential for design applications.

Palm paper on Development of Fatigue Usage Gradient factor

This presentation was focused on the effect of the through component thickness stress/strain gradient on the cumulative fatigue usage factor. These gradients arise as a result of thermal transient events. A methodology was presented to take these stress gradients into account in fatigue-life assessments based on tabulated factors for a range of membrane to gradient strain ratios.

Hong et al paper on Fatigue crack growth rate of 347 and 347N stainless steels under PWR water conditions

The fatigue crack growth rates in high purity water were investigated under different conditions: DO content, DH content. Effect of DO on FCGR was attributed to oxide induced crack closure. Due to the higher strength of 347N with respect to 347 steel, the FCGR of 347N was lower in hydrogenated water. It was shown that the JSME-BWR FCGR curve could be used as a conservative upper bound for the 347 steel.

The session III part B has one presentation:

Industry's First NRC Approved Appendix L Flaw Tolerance Evaluation to Manage Environmental Fatigue in a Surge Line - D. Gerber (SIA – United States).

The presentation in part B of session III was a practical illustration of the methodological evolutions being discussed internationally in fatigue. These proposals are more precisely being addressed by a dedicated ASME Fatigue working group (WGEFEM – Working Group on Environmental Fatigue Evaluation Methods).

Session III conclusions

The conclusions of the session III are:

- New methodologies can be applied to extend NPP license beyond 40 year life and receive approval from Safety Authorities (in this particular case, the NRC);

- The calculation using Flaw Tolerance Approach is a good way of meeting the safety requirements and needs to be led in conjunction with an efficient fatigue monitoring program.

The Flaw Tolerance approach has been made into a code-case that will be soon integrated to the ASME code.

5.5 Session IV: Codes and Standards

SESSION IV "Codes and Standards" was chaired by Nathan Palm (EPRI) and Karl-Fredrik Nilsson (EU-JRC).

The session consisted of five presentations:

1. "Alternative Approaches for ASME Code Simplified Elastic Plastic Analysis" by S. Ranganath and N. Palm (Presented by N. Palm)

2. "Code Evolution in European Research for Innovative Nuclear Reactors" by K-F. Nilsson (presented by K-F. Nilsson)

3. "Overview of Recent Modification Proposals In Fatigue in the RCC-M Code" by T. Metais et al (presented by T. Metais)

4. "Development Status of Design Fatigue Curves" by S. Asada et al (presented by S. Asada)

5. "Impact of the Newly-Revised Environmentally Assisted Fatigue Guidance in NUREG/CR-6909" by J. Correa (presented by J. Correa)

The presentation, "Alternative Approaches for ASME Code Simplified Elastic Plastic Analysis," by S. Ranganath and N. Palm discussed the potential for reducing conservatism in the ASME Section III elastic plastic correction factor K_e. Comparison was made of the Code K_e definition to finite element analysis results, actual test data, and approaches taken in other Codes. Previous efforts to reduce the conservatism of the K_e approach were discussed. Many of these approaches are difficult to use and require new stress analysis. An alternative was proposed that reduces the conservatism in the current approach while maintaining simplicity by only requiring stress inputs that are available from existing Code stress reports. Application of a K_e factor with reduced conservatism would reduce CUF values and offset penalties for environmental effects.

The second presentation, "Code Evolution in European Research for Innovative Nuclear Reactors," by K.-F Nilsson described the fast neutron reactor types being considered in the European Sustainable Nuclear Industrial Initiative. The RCC-Mx Code is being used to design these reactors for a 60 year design life but additional changes are needed to address new materials, operating environments, and degradation mechanisms and to ensure an acceptable 60-year design life. These new reactor designs will expose materials to irradiation, temperatures, and coolant types for which very limited data is available. As such, research is being performed to obtain data that can be used in the design efforts but obtaining data applicable for 60 years in an accelerated timeframe is a significant challenge.

The presentation, "Overview of Recent Modification Proposals in Fatigue in the RCC-M Code," by T. Metais discussed changes to the RCC-M Code to update the fatigue curve and incorporate environmental effects. The update of the fatigue curve adopts the mean air curve from NUREG/CR-6909, Revision 1, and applies a factor of 10 on cycles and a factor of 1.4 on strain amplitude. To incorporate environmental effects, the NUREG/CR-6909, Revision 1, approach was used with consideration of AREVA test data.

The approach uses a F_{en} factor but also considers environmental effects already considered in the fatigue curves through the use of an integrated environmental factor.

The presentation, "Development Status of Design Fatigue Curves," by S. Asada discussed efforts by the Japan Welding Engineering Society to develop design fatigue curves. Design curves were developed that consider mean stress effects; data scatter and surface finish effects. Size effects were also considered but it was determined that an adjustment was not needed to the design curve. The curves are valid for up to $1x10^8$ cycles. Work on large scale testing is underway to verify the new fatigue design curves.

The presentation, "Impact of the Newly-Revised Environmentally Assisted Fatigue Guidance in NUREG/CR-6909," by J. Correa provided a history of the different guidance that had been developed in U.S. for addressing EAF and discussed the evolution of the methods. A comparison of EAF results based on real plant instrument data as a demonstration of the effects of the changes presented in NUREG/CR-6909 Revision 1 was provided. The comparison addressed limiting PWR and BWR locations. The results showed that the guidance in NUREG/CR-6909 Revision 1 increases CUF for the PWR locations evaluated and decreased CUF for the BWR locations evaluated.

Session IV conclusions

One challenge for the new reactor designs is that very limited data to irradiation, temperatures, and coolant types is available for new materials used in new reactor types. Research and assessments for getting covering data for new reactor types as well as for getting data to the design of operating or new plants for the long term operation applicable for 60 years or more is a significant challenge. Work on large scale testing is underway to verify the new fatigue design curves in some countries, but there is need for international cooperation to validate these results.

5.6 Session V: Component Performance and Testing

Session V "Component Performance and Testing" part A was chaired by Mike McDevitt (EPRI) and Ertugrul Karabaki (E.ON Kernkraft GmbH), part B was chaired by Xaver Schüler (MPA) and Isabelle Delvallée-Nunio (IRSN) and part C was chaired by T. Métais (EDF/SEPTEN) and M. Bruchhausen (JRC).

Part A presentations

The part A of the session V consisted of following three presentations:

1. A Device for Studying Very High-cycle Fatigue at Asymmetric Push-Pull Mode. M. Bruchhausen et al. JRC.
2. Low Cycle Fatigue Behaviour of Modified 9Cr-1Mo Steel at Elevated Temperature. P. Verma et al. Centre of Advance Study, Dep. Of Met. Eng. Indian Institute of Technology.
3. Thermal Stress Investigation by Wall Temperature Measurements for Mixing Flow at T-junction. K. Miyoshi et al. Institute of Nuclear Technology Japan.

The presentation: A Device for Studying Very High-cycle Fatigue at Asymmetric Push-Pull Mode by M. Brüchhausen et al discuss on need of component testing for high numbers of cycles. This kind of test results is necessary for example for assessing the thermal stress in T-shape mixing connection of pipes. According to the authors ultrasonic very high-cycle fatigue (VHCF) testing is useful for such purposes to test a high number of cycles in reasonable time.

The presentation on Low Cycle Fatigue behaviour of Modified 9Cr-1Mo Steel at Elevated Temperature by P. Verma et al. discussed on challenges of design the steam generators of Prototype Fast

Breeder Reactor with sodium cooling against the stress corrosion cracking. The challenge is that in steam generator only a single wall is separating the water/steam from the sodium. According to the presentation the material selection of modified 9Cr-1Mo steel seems to be suitable against the challenges caused by low cycle fatigue.

The presentation on Thermal Stress Investigation by Wall Temperature Measurements for Mixing Flow at T-junction by K. Miyoshi et al. describes numerical simulations for predicting the stress fluctuation induced by mixing flow. Especially the information on the stress fluctuation induced by mixing flow has recognized to be difficult to predict. According to the numerical results of the presentation the stress and temperature fluctuation range on the inner surface of the pipe became large locally in the region from the outlet of the branch pipe to downstream.

Part B presentations

The part B of the session V consisted of following five presentations:

1. Mean stress effect on fatigue life and dislocation microstructures of 316L austenitic steel at high temperature in air and water environment; P. Spätig, H.P. Seifert, Paul Scherrer Institut; M. Heczko, T. Kruml, Institute of Physics of Materials

2. Study and Methodology Development for Cyclic Loading Application to Probabilistic Fatigue Analyses. O. Cronvall. VTT.

3. Fatigue Damage Assessment by Crack Growth Prediction for Type 316 Stainless Steel. M. Kamaya et al. Institute of Nuclear Safety System Inc., Japan Nuclear Safety Institute

4. Experimental and Numerical Analyses of Turbulent Mixing of Coolant Streams in a Mixing Tee. P. Karthick et al. Institute of Nuclear Technology and Energy Systems (IKE).

5. AdFaM (Advanced Fatigue Methodologies) Project – Effects of Elevated Temperature Holds on Fatigue of Stabilised and Non-Stabilised Austenitic Stainless Steels. E. Karabaki et al. EON, VTT, AREVA, Rolls-Royce.

Mean stress effect on fatigue life and dislocation microstructures of 316L austenitic steel at high temperature in air and water environment, P. Spätig, H.P. Seifert, Paul Scherrer Institut; M. Heczko, T. Kruml, Institute of Physics of Materials

The purpose of the study was to analyze the impact on fatigue life of two coupled parameters: mean stress and water environment / air environment. In air, mean stress increases the fatigue life. In water, it has not been possible to draw clear conclusions due to the difference of specimens used to perform the tests: massive cylinder in air and hollow cylinders in water. It reflects the complexity of comparisons of results from tests not totally similar and hence transferability of laboratory results to operating structure.

Study and Methodology Development for Cyclic Loading Application to Probabilistic Fatigue Analyses. O. Cronvall. VTT.

Standard methods in ASME, KTA, RCC-M or BS codes are not suitable to evaluate fatigue life of NPP components under high-cyclic thermal loadings such as those present in mixing zones. In the framework of THERFAT project, different suitable methods have been developed but they appears too costly and time consuming or too conservative. To estimate the fatigue life of T-junctions, VTT presents a new method based on a realistic approximation of the cyclic loading and a probabilistic application of cyclic loading.

Fatigue Damage Assessment by Crack Growth Prediction for Type 316 Stainless Steel. M. Kamaya et al. Institute of Nuclear Safety System Inc., Japan Nuclear Safety Institute

This study focusses on the role of stress and strain ranges on fatigue life. For Kamaya, fatigue life is better correlated with strain range than stress range. Therefore, he proposes to use a strain intensity factor instead of a stress intensity factor to estimate crack growth propagation.

According to Dr Solin this observation would be acceptable only for small crack, not for deep cracks.

Experimental and Numerical Analyses of Turbulent Mixing of Coolant Streams in a Mixing Tee. P. Karthick et al. Institute of Nuclear Technology and Energy Systems (IKE).

It is reminded that thermal fatigue damages induced by fluid turbulence and local thermal loading in mixing zone have been observed in the very beginning of life of NPP as well as after a long period of operation. The study presented aims at investigating numerically and experimentally complex local loadings in the vicinity of fluid mixing zones like a T-junction piping. The complex loadings are simulated by Large Eddy Simulation and validated by experimental data. The influence of increase flow rate in the main pipe on flow mixing behaviour is also investigated: temperature gradients inside the pipe wall are attenuate by nearly 90 % and therefore the thermal stress amplitude is greatly attenuated.

AdFaM (Advanced Fatigue Methodologies) Project – Effects of Elevated Temperature Holds on Fatigue of Stabilised and Non-Stabilised Austenitic Stainless Steels. E. Karabaki et al. EON, VTT, AREVA, Rolls-Royce.

AdFaM project confirmed the Hold-time effect on fatigue life: small hot hold-times - like those met in normal operation of NPP - are sufficient to increase fatigue life by strain relaxation and hardening.

Part C presentations

The part C of the session V consisted of following three presentations:

1. Fatigue behaviour of Dissimilar Weld and Cladding Material of Nuclear Components - K.H. Herter et al. (MPA-Stuttgart – Germany)

2. Experimental Evaluation of Fatigue in Welded Austenitic SS pipe components - M. Dahlberg (Inspecta Technology AB – Sweden)

3. Environmental Effects on the Fatigue Behaviour of Nuclear Materials – X. Schuler (MPA-Stuttgart – Germany)

Fatigue behaviour of Dissimilar Weld and Cladding Material of Nuclear Components - K.H. Herter et al. (MPA-Stuttgart – Germany)

The paper discusses the specific requirements of different piping and welds materials, which are used in NPPs. According to the paper it may not be assumed that the fatigue life curves of the various austenitic and ferrite product forms used in the different Codes and Standards are also representative for the fatigue behaviour of dissimilar welds and cladding material. The paper presents comparison of the results on the experimental determination of a fatigue life curve of a dissimilar welds and cladding material with available database of the stabilized austenitic stainless steels and fine grained ferrite steel used in German nuclear power plants.

Experimental Evaluation of Fatigue in Welded Austenitic SS pipe components - M. Dahlberg (Inspecta Technology AB – Sweden)

The paper describes experimental studies on realistic austenitic SS components with focus on High Cycle Fatigue (HCF) and Variable Amplitude (VA) loading. The conservatism of the design curves compared to the test results is discussed.

Environmental Effects on the Fatigue Behaviour of Nuclear Materials – X. Schuler (MPA-Stuttgart – Germany)

The paper assesses the environmentally assisted fatigue (EAF) in the design curves for different materials in nuclear codes and standards. The paper also discusses the differences between the design curves for EAF in standards and in the test curves based on the plant environment.

Session V conclusions

The uniqueness of this session lies in the nature of the experimental work presented: these presentations give an overview of testing using conditions and specimens aiming at being more representative of real life.

For instance, some experiments were led on welded specimens (MPA-Stuttgart and Inspecta Technology AB) as well as on cladding (MPA-Stuttgart) while some other tests were run using loading signals with variable amplitudes (Inspecta Technology AB).

The testing was conducted here in air, PWR and even BWR environment. The main conclusions are:

- Testing on lab specimens with standardized testing conditions and loadings match well with NUREG/CR-6909 whether it be in BWR or PWR;
- When testing is conducted in different conditions, the results indicate some un-conservatism (in the case of welded specimens) or in most cases heavy conservatism (for the variable amplitude signals) when compared to the NUREG/CR-6909;
- It is nevertheless reminded (by the audience) that when carrying testing on welded specimens, the strain amplitude measurement is difficult to carry out since there are different types of materials involved.

The next step will be to carry out more extended testing in PWR environment and to take advantage of these experimental lessons learnt and evaluate how to integrate them into an engineering methodology.

5.7 Session VI: Fatigue Monitoring and Crack Detection

SESSION VI “Fatigue Monitoring and Crack Detection” was chaired by Jennifer Correa (SIA) and Olli Nevander (NEA).

The session consisted of four presentations:

1. Improving Ultrasonic Examination Procedures for Detection of Thermal Fatigue. J. Spanner. EPRI.
2. Fatigue Monitoring of Equipment and Pipelines at Russian NPPS. Rubtsov V.S.; Korableva S.A. SEC NRS, Russia.
3. Technical Challenges for Long Term Operation. J. Correa. Structural Integrity Associates Inc.(SIA)
4. A Total Life Approach for Fatigue Design to a Target Reliability. K. Wright et al. Rolls-Royce.

Improving Ultrasonic Examination Procedures for Detection of Thermal Fatigue. J. Spanner. EPRI.

The paper presents methods to improve ultrasonic measurement procedures for detection of thermal fatigue.

Fatigue Monitoring of Equipment and Pipelines at Russian NPPS. Rubtsov V.S.; Korableva S.A. SEC NRS, Russia.

The paper presents two methods for monitoring of fatigue damage accumulation in metal of equipment and pipelines at Russian NPPs. The first method of monitoring is based on the requirements of the Russian national STO standard, according to which the number of realized design regimes of operation (loading cycles) for NPP equipment and pipelines should be recorded and assessed each year. The second method is based on application of the computerized monitoring system of fatigue damage accumulation of primary circuit components.

Technical Challenges for Long Term Operation. J. Correa. Structural Integrity Associates Inc.(SIA)

The paper presents technical challenges for operation over 40 or 60 years until 80 years. According to this paper, industry has learnt a lot about design margins and where conservatisms exist in the current analyses and how to implement programs that address passive long-lived components.

A Total Life Approach for Fatigue Design to a Target Reliability. K. Wright et al. Rolls-Royce.

The paper asserts that the traditional ASME one-size fits all approach in fatigue is too conservative. Deterministic approaches hide behind unquantified margins – not tolerable when compounded with environmental effects. The paper propose that a design factor for total life prediction to through wall leakage will need an improved mechanistic understanding and analytical prediction of nucleation and short crack behaviour so that a target reliability can be demonstrated probabilistically.

Session VI conclusions

The presentations described the different areas of fatigue monitoring and challenges for measuring fatigue effects during long life time operation.

The deterministic approaches hide behind unquantified margins which is not tolerable when compounded with environmental effects. There is a need to improved mechanistic understanding and analytical prediction of nucleation and short crack behaviour so that target reliability can be demonstrated probabilistically. It is necessary to translate plant level safety criteria to establish system and hence component target reliabilities, for avoidance of through wall leakage occurring, that considers the associated consequences. There is also need for covering EAF screening of each plant to identify sentinel locations as well as locations requiring more detailed analysis and on-line temperature measurements.

Based on insights from updated analyses and degradation research there is a need to modify operating practices and preventive maintenance activities to reduce the damage rate. Gathering and applying the relevant data based on plant specific environments and industry operating experience will reduce uncertainties in design analyses and improve effectiveness of Ageing Management Procedures (AMP’s).

The use of several methods for monitoring of fatigue damage accumulation help ensure the prevention of failures due to “macro-cracks under cyclic loading” in the equipment and piping within the primary circuit during operation.

6. CONCLUSIONS AND RECOMMENDATIONS

The fourth in a series of NEA workshops dedicated to Fatigue of Reactor Components was held on 28 September-1 October 2015 in Seville, Spain, hosted by CSN. Over 90 specialists from 21 countries attended to the workshop. The workshop concentrated on the various subjects on environmental fatigue and thermal fatigue as well as on the methods for assessing, predicting and monitoring fatigue, and detecting cracks caused by fatigue.

This fourth workshop on fatigue of reactor components has a special focus on the methods for evaluating environmental effects. Today many countries are requiring that environmental effects be considered by operating reactors as well as by new builds. However, the methods and approaches behind the new regulation and inside the new design codes have not yet been harmonized. Additionally, there is need for practical guidelines based on the existing operating experiences. With the operating experiences and information sharing, it could be possible to identify the most critical components susceptible to environmental fatigue in the new designs and maintenance programs of operating plants.

In all three previous workshops on the same subject, the transferability of test data to the design codes and to the real plant environment has been discussed. In the previous Seville workshop on October 2004 it was said that transferability of test results to real structures remains an issue and special effort should be pursued. It was also recommended that the route from research to codification should be investigated and results of new experiments should be integrated. It was also recognized that test data and operating experience data generated to understand environmental assisted fatigue (EAF) phenomenon should be documented in detail for adequate assessment of the results.

6.1 Conclusions of panel discussions of conference

During the conference and in the panel discussions it was concluded that the recommendations of previous fatigue workshops are still valid after this fourth workshop on fatigue of reactor components. However, it was mentioned that the work for collecting the international test data on a common international database on fatigue testing, both specimens and structures, with and without environmental effects, is going on between Japan, the United States and France, and more countries are expected to join this cooperation in the future. International activities for getting the fatigue data of components of decommissioned plants will also be started by IAEA in near future. After collecting new data and rigorously assessing all new and existing data, the design rules for fatigue and especially EAF could be updated.

The panel also agreed that for preventing the fatigue incidents of new and operating plants there is the need to recognize the stratification locations, where thermal fatigue could be critical. Improvements in fatigue monitoring and knowledge of sensor locations should be developed based on more detailed assessment of the operating experience and lessons learned from decommissioned plants. It was also noted that based on the workshop it is obvious that additional research is necessary to understand mechanisms of damage and continue to address the mitigation of thermal fatigue. With these research results and with results from operating experience, the fatigue management guidelines could be updated.

6.2 General conclusions

Based on conference results, the following technical suggestions for decreasing the number of plant incidents related to fatigue by clarifying and increasing the design margins could be assessed:

- Material examination is an important consideration and some good suggestions are now available for use of such information to aid data interpretation. As an example, presentations in this conference have shown that decrease of strain rate in elevated temperature can promote hardening of steel material used in main components of the primary circuit.

- Number of the incidents caused by thermal stratification could be decreased by improving the operating procedures based on results of monitoring as well as on detailed assessment of the operating experience and lessons learned from decommissioned plants. Improvements with monitoring systems are effective in recognising low-cycle fatigue, provided the sensors are placed at adequate locations and that their measurement uncertainty is accounted for. Results may also have an effect on machining process (surface finish) to prevent crack initiation.

- Proposals to reduce the conservatism in the existing ASME Code procedures should be discussed and defined internationally. For example, Japanese specialists will propose a new fatigue evaluation method in the future. This proposed design curve and other similar proposals could be discussed in a future international workshop.

For safety reasons the environmental factors as set by Appendix A NUREG/CR-6909 are include a large amount of conservatism compared to operating experience of environmental fatigue in actual NPP components. Therefore, it is possible that these factors, which are based on laboratory tests, could in some cases lead to unnecessary conservatism when they are used in the design of components or the assessment of plant life extension. Additional assessments of the potential reasons for the disparity between operating experience and laboratory test results could help in understanding and defining the necessary level of conservatism for environmental factors. Some of the reasons are the differences in mechanical and chemical loadings between lab specimens and real components. In addition, conservatism in design regarding assumptions for levels (i.e., strain amplitudes) and frequency of loadings may enhance this discrepancy.

Based on the conclusions of the Seville workshop, the following recommendations were made for international work looking at the possibilities to decrease unnecessary conservatism in design:

- Work to reduce conservative assumptions in analyses based on existing fatigue standards or comparison of standard models should be supported internationally (e.g. in future activities under NEA CSNI). The differences between conditions producing environmental fatigue damage in plant and laboratory tests shall be assessed and the understanding of sensitivity to these differences shall be improved. It is recommended that an international team develop a report analyzing differences in the communicated results and design curves. The team should look into possibilities to carry out more extended (and relevant) testing in PWR environments and assess these experimental results and evaluate how to integrate them into the engineering methodologies and design standards.

- Reduction in conservatism should be associated with required target reliability values for avoidance of through wall leakage, dependent upon the consequences of leakage occurring at the location of interest. Work is required to establish internationally what these reliabilities should be rather than the current use of unquantified margins.

- Environmental effects measured in various laboratories and experimental programs report variable F_{en} factors. Therefore, establishment of an international task group with a mission to compare the data and search for correlation between test boundary conditions and results is recommended. The assessment of the realistic environmental effect data from components of retired plants could help with this target.

- Testing of (standardized) components instead of laboratory specimens might help to improve the transferability from research data to plant applications and support reducing conservatism in the design codes. In particular, an international round-robin analytical 'blind-prediction' of such tests could be used to validate improved methodologies. Further, an international benchmark for establishing the reliability of detecting existing cracks could be started. The benchmark could include the comparison of the detection techniques, calibrating procedures of the equipment for plant environment, and the ultrasonic examination procedures. A mixing tee mockup could be used to investigate up-stream cracking in this benchmark.

APPENDIX 1 - LIST OF PARTICIPANTS

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Participants of the Workshop

Organising Committee and Session chairmen

APPENDIX 2 - WORKSHOP PROGRAMME AND LIST OF POSTERS

DAY 1. Tuesday 29th September

9:00-9:05 Welcome to Participants. Mr. Carlos Castelao, CSN local organizer

9:05-9:15 Opening of the Conference. Ms. Rosario Velasco, CSN Vice-president

9:15-9:25 A New Environment for Nuclear Safety: Main Challenges for NEA. Mr. Javier Reig, Director of the NEA Nuclear Safety Division

9:25-9:30 Conference General Remarks. Mr. Carlos Castelao, CSN local organizer

General Session: Fatigue Program Overview

Chair: Javier Reig (NEA)

9:30-9:50	5	Development and Application of Fatigue Assessment Procedures and Consideration of Environmentally Assisted Fatigue Effects in the European Framework. S. H. Reese; W. Mayinger. EON.
9:50-10:10	60	Overview of Fatigue Evaluation Methods and Mechanistic Study in Japan. Prof. T. Shoji. Tohoku University.
10:10-10:30	68	Fatigue Management- an EPRI Perspective. J.P Sursock. EPRI
10:30-10-50	32	CODAP Project Operating Experience Insights Related to Fatigue Mechanisms. B. Lydell et al. NEA.

Session I.a: Environmental Fatigue

Chairs: Jürgen Rudolph (AREVA); K. Ahluwalia (EPRI)

11:15-11:35	42	Corrosion Fatigue Evaluation: Czech Proposal for WWER-440 Nuclear Power Plants. L. Vlcek. Institute of Applied Mechanics Brno.
11:35-11:55	59	Consideration of the Mismatch Between Environmental Fatigue Behaviour of Laboratory Specimens and Plant Components in Real Environment. J. Solin et al. VTT, AREVA.
11:55-12:15	16	An Overview of the ASME Working Group, Environmental Fatigue Evaluation Methods, Fatigue Action Plan. K. Wright. Rolls-Royce.
12:15-12:35	10	INCEFA-PLUS (INcreasing Safety in NPPs by Covering Gaps in Environmental Fatigue Assessment). K. Mottershead et al. Amec Foster Wheeler.
12:35-12:55	12	Environmentally Assisted Fatigue Assessment in Time Limited Aging Analyses for Extended Operation in a Spanish PWR Plant. M. Álvaro et al. G. TECNATOM, CNAT

Session I.b: Environmental Fatigue

Chairs: Karl-Fredrik Nilsson (EU-JRC); Armin Roth (AREVA)

14:30-14:50	8	Environmentally-assisted Fatigue Assessment – the European View of the State of the Art for Stainless Steels in LWR Environments. K. Mottershead et al. Amec Foster Wheeler.
14:50-15:10	31	Testing to Address Environmentally Assisted Fatigue Degradation in LWR Plants. K. Ahluwalia et al. EPRI.
15:10-15-30	66	Corrosion-Fatigue behaviour of austenitic alloys in simulated PWR primary water. F. J. Perosanz, et al. CIEMAT
15:30-15:50	9	Mechanistic Studies on Environmentally Assisted Fatigue crack growth in light water reactor environments. D. Tice et al. Amec Foster Wheeler.
15:50-16:10	4	Quantitative Comparison of Environmental Fatigue Methods. F.H.E. de Haan et al. NRG, Petten.

Session II: Thermal Fatigue

Chairs: Robert Magnussen (Ringhals); Mike McDevitt (EPRI)

16:30-16:50	27	Analysis and Impact of Recent Thermal Fatigue Operating Experience in the United States. M. McDevitt et al. EPRI.
16:50-17:10	52	Short crack Behaviour of Austenitic Stainless Steels in Simulated PWR Primary Water During Fatigue Damage and Monotonic Deformation. C. Shim et al. Tohoku University.
17:10-17:30	56	Effect of Shoulder Extension Control on Fatigue Endurance Testing of Stainless Steels. C. Austin et al. Rolls-Royce.
17:30-17:50	62	Thermal Fatigue at Elevated Temperatures for 316L and P91 Thick-Walled Steel Tubes. K. Nilsson et al. EC, JRC, Institute for Energy and Transport.

DAY 2 (Wednesday 30th September)

SESSION III.a: Assessing and Predicting Fatigue

Chairs: Norman Platts (Amec); Phillipe Spätig (PSI)

8:30-8:50	50	Fatigue Design Curves for Austenitic Stainless Steels Grades 1.4541 and 1.4550 in German KTA 3201.2. X. Schuler et al. Institute MPA.
8:50-9:10	7	Fatigue Evaluation of Nuclear Plant Components with Environmental Effects. D. Fdez. de Rucoba et al. Fundación Centro Tecnológico de Componentes (CTC).
9:10-9:30	21	A Study on Creep-fatigue Models for P91 Steel Design Rules. S. Holmström et al. JRC.

9:30-9:50	15	Development of a Fatigue Usage Gradient Factor. S. Gosselin; N. Palm. LPI, Inc., EPRI.
9:50-10:10	37	Fatigue Crack Growth Rate of Type 347 and Type 347N Stainless Steels under the PWR Water Conditions. S. Hong et al. KAERI.

SESSION III.b: Assessing and Predicting Fatigue

Chairs: Dave Gerber (SIA); Thomas Metais (EdF)

10:30-10:50	46	Industry's First NRC Approved Appendix L Flaw Tolerance Evaluation to Manage Environmental Fatigue in a Surge Line. D. Gerber. Structural Integrity Associates Inc.

SESSION IV: Codes and Standards

Chairs: Nathan Palm (EPRI); Karl-Fredrik Nilsson (EU-JRC)

11:20-11:40	11	Alternative Approaches for ASME Code Simplified Elastic Plastic Analysis. S. Ranganath; Nathan Palm. XGEN Engineering, EPRI.
11:40-12:00	61	Code Evolution in European Research for Innovative Nuclear Reactors. K. Nilsson. JRC, Institute for Energy and Transport.
12:00-12:20	33	Overview of Recent Modification Proposals In Fatigue in the RCC-M Code. T. Metais et al. EDF, AREVA.
12:20-12:40	20	Development Status of Design Fatigue Curves. S. Asada et al. Toshiba Co., Kansai E.P.
12:40-13:00	47	Impact of the Newly-Revised Environmentally Assisted Fatigue Guidance in NUREG/CR-6909. J. Correa. Structural Integrity Associates Inc.

PANEL DISCUSSION SESSIONS G, I, II, III and IV

Panelists: Carlos Castelao (CSN), Al Ahluwalia (EPRI), Jussi Solin (VTT), Seiji Asada (MHI), Karl-Fredrik Nilsson (EU-JRC)

POSTER SESSION

Chair: Mike McDevitt (EPRI)

DAY 3 (Thursday 1st October)

SESSION V.a: Component Performance and Testing

Chairs: Mike McDevitt (EPRI); Ertugrul Karabaki (E.ON Kernkraft GmbH)

9:00-9:20	34	A Device for Studying Very High-cycle Fatigue at Asymmetric Push-Pull Mode. M. Bruchhausen et al. JRC.
9:20-9:40	25	Low Cycle Fatigue Behaviour of Modified 9Cr-1Mo Steel at Elevated Temperature. P. Verma et al. Centre of Advance Study, Dep. Of Met. Eng. Indian Institute of Technology.
9:40-10:00	38	Thermal Stress Investigation by Wall Temperature Measurements for Mixing Flow at T-junction. K. Miyoshi et al. Institute of Nuclear Technology Japan.
10:00-10:20		Questions and debate about presentation

SESSION V.b: Component Performance and Testing
Chairs: Xaver Schuler (MPA), Isabelle Delvallee (IRSN)

11:00-11:20	43	Mean Stress Effect on Fatigue Life and Dislocations Microstructures of 316L Austenitic Steel at High Temperature in Air and Water Environment. P. Späting et al. Laboratory for Nuclear Materials, Paul Scherrer Inst., Physics of Materials Brno.
11:20-11:40	30	Study and Methodology Development for Cyclic Loading Application to Probabilistic Fatigue Analyses. O. Cronvall. VTT.
11:40-12:00	39	Fatigue Damage Assessment by Crack Growth Prediction for Type 316 Stainless Steel. M. Kamaya et al. Institute of Nuclear Safety System Inc., Japan Nuclear Safety Institute.
12:00-12:20	40	Experimental and Numerical Analyses of Turbulent Mixing of Coolant Streams in a Mixing Tee. P. Karthick et al. Institute of Nuclear Technology and Energy Systems (IKE).
12:20-12:40	22	AdFaM (Advanced Fatigue Methodologies) Project – Effects of Elevated Temperature Holds on Fatigue of Stabilised and Non-Stabilised Austenitic Stainless Steels. E. Karabaki et al. EON, VTT, AREVA, Rolls-Royce.

14:10-15:10 SESSION V.c: Component Performance and Testing
Chairs: Matthias Bruchhausen (EC-JRC), Thomas Metais (EdF)

14:10-14:30	13	Fatigue Behaviour of DissimilarWeld and Cladding Material of Nuclear Components. X. Schuler et al. Materials Testing Institute (MPA)
14:30-14:50	23	Experimental Evaluation of Fatigue in Welded Austenitic Stainless Steel Pipe Components. M. Dahlberg et al. Inspecta Technology AB, TS Ingenjörsstatistik.
14:50-15:10	14	Environmental Effects on the Fatigue Behaviour of Nuclear Materials. X. Schuler et al. Materials Testing Institute (MPA).

15:30-16:50 SESSION VI: Fatigue Monitoring and Crack Detection

Chairs: Olli Nevander (NEA); Jennifer Correa (SIA)

15:30-15:50	35	Improving Ultrasonic Examination Procedures for Detection of Thermal Fatigue. J. Spanner. EPRI.
15:50-16:10	51	Fatigue Monitoring of Equipment and Pipelines at Russian NPPS. Rubtsov V.S.; Korableva S.A. SEC NRS, Russia.
16:10-16:30	45	Technical Challenges for Long Term Operation. J. Correa. Structural Integrity Associates Inc.
16:30-16:50	17	A Total Life Approach for Fatigue Design to a Target Reliability. K. Wright et al. Rolls-Royce.

PANEL DISCUSSION SESSIONS V and VI

Panelists: Jack Spanner (EPRI), Thomas Metais (EdF), Armin Roth (AREVA), Masayuki Kamaya (INSS), Keith Wright (Rolls-Royce)

Conference Closure

Carlos Castelao (CSN)

List of posters

ID number	**Title**
57	A Procedure to Predict Fatigue Life in Light Water Reactor 304 Stainless Steel. T.FO. Erinosho et al. Dep. of Mechanical Engineering, University of Bristol.
48	SI: FatiguePro 4.0 as part of a Fatigue Management Program. J. Correa. Structural Integrity Associates Inc.
49	Design and Implementation of a Fatigue Management Program. D. Gerber. Structural Integrity Associates Inc.
53	Fatigue Monitoring System for NPP in KHNP. M. Boo et al. Korea Hydro and N.Power.
1	Fatigue Analysis of Auxiliary Feedwater Line under consideration of stratification loads and EAF influence. B. Jouan et al. AREVA Gmbh, Axpo Poer AG (Swiss).
36	Thermal Stress Evaluation by Using Computational Fluid Dynamics Analysis Result and Green’s Function for a Nuclear Piping. M. Boo et al. KEPCO.
18	Effect of Boundary Conditions in Fatigue Thermal Analyses Using Monitoring Systems. R. Cicero et al. Inesco Ingenieros, Innomerics, Iberdrola Generación Nuclear.
44	Mechanical analysis for CRDM upper canopy seal weld Overlay. L. Pan. China GNP Group
63	Assessment of Resistance of VVER-440 Reactor Pressure Vessel Against Low Cycle Fatigue. F. Peter et al. UJV.
6	Operational Excellence by comprehensive temperature measurements and fatigue assessments. S. H. Reese et al. EON, Siempelkamp Prüf- und Gutachter-Gesellschaft.
26	Improvement in Fatigue Life of Particle Separator by Optimizing Local Design and Manufacturing Methods. A. Blom. AREVA
58	An analysis of nuclear plant leak-related events related to vibration-induced piping and tubing leaks. G. Schweitzer et al. INPO.
66	Corrosion-Fatigue behaviour of austenitic alloys in simulated PWR primary water. F. J. Perosanz, et al. CIEMAT
64	Experimental methods for direct strain controlled low cycle fatigue tests in simulated PWR water. T. Seppänen et al. VTT Technical Research Centre of Finland.

ID number	**Title**
65	Fatigue of stainless steel in simulated PWR operational conditions – LCF experiments in hot water. J. Alhainen et al. VTT, EON, EON Kernkraft GmbH.
7	Fatigue Evaluation of Nuclear Plant Components with Environmental Effects. D. Fdez. de Rucoba et al. Fundación Centro Tecnológico de Componentes (CTC).
24	Low cycle fatigue behaviour in air and in nominal PWR primary environment at 300°C of a 690 Ni-base alloy. W. Chitty et al. AREVA NP SAS.
67	Demonstration of Fatigue for LTO License of NPP Borsele. M.H.C. Hannik et al. NRG Petten and EPZ Borsele

APPENDIX 3 - LIST OF CONFERENCE PAPERS

1. **Fatigue Evaluation of Nuclear Plant Components with Environmental Effects**
   David Fernández de Rucoba
   Fundación Centro Tecnológico de Componentes (CTC), Spain
   Román Cicero González, Roberto Báscones Vega1, Iñaki Gorrochategui Sánchez, Víctor Gómez Fernández, Raúl Muñoz Roldán, Enrique Gómez Poncela.
   Equipos Nucleares, S. A. (ENSA), Spain

2. **Alternative Approaches for ASME Code Simplified Elastic Plastic Analysis**
   Nathan A. Palm, Electric Power Research Institute, United States;
   Sampath Ranganath, XGEN Engineering, United States

3. **Low Cycle Fatigue Behaviour of Modified 9Cr-1Mo Steel at Elevated Temperature**
   Preeti Verma, Department of Metallurgical Engineering, Indian Institute of Technology, Banaras Hindu University, Varanasi - 221005, India
   P. Chellapandi, Nuclear & Safety Engineering Group, Indira Gandhi Centre for Atomic Research, Kalpakkam, Tamilnadu - 603102, India.
   N.C.Santhi Srinivas, 1Department of Metallurgical Engineering, Indian Institute of Technology, Banaras Hindu University, Varanasi - 221005, India.
   Vakil Singh, Department of Metallurgical Engineering, Indian Institute of Technology, Banaras Hindu University, Varanasi - 221005, India

4. **Analysis and Impact of Recent Thermal Fatigue Operating Experience in the United States**
   Mike McDevitt, Electric Power Research Institute, United States
   Terry Childress, Duke Energy, United States Mike Hoehn, Ameren, United States
   Robert McGill, Structural Integrity Associates, United States

5. **Study and Methodology Development for Cyclic Loading Application to Fatigue Analyses**
   Otso Cronvall Otso Cronvall VTT, VTT Technical Research Centre of Finland Ltd., Espoo, Finland

6. **Mean Stress Effect on Fatigue Life and Dislocation Microstructures of 316L Austenitic Steel at High Temperature in Air and Water Environment**
   P. Spätig, H.-P. Seifert, Laboratory for Nuclear Materials, Nuclear Energy and Safety Department, Paul Scherrer Institute, 5232 Villigen-PSI, Switzerland
   M. Heczko, T. Kruml, Institute of Physics of Materials, Academy of Sciences of the Czech Republic, Zizkova 22, 616 62 Brno, Czech Republic

7. **Experimental and numerical analyses of turbulent mixing of coolant streams in a mixing tee**
   P. Karthick Selvam, Rudi Kulenovic, Eckart Laurien
   Institute of Nuclear Technology and Energy Systems (IKE), University of Stuttgart
   Pfaffenwaldring 31, 70569, Stuttgart, Germany

8. **Corrosion Fatigue Evaluation: Czech Proposal for WWER-440 Nuclear Power Plants**
   L. Vlcek, Institute of Applied Mechanics Brno, Ltd., Czech Republic
   M. Ernestova, UJV Rez, a.s., Czech Republic
   J. Ertl, Czech Energy Company, plc., Czech Republic

9. **Mechanical Analysis for CRDM Upper Canopy Seal with Weld Overlay Repair**
   Xiao XU, Dasheng WANG, Pan LIU, Ting JIN, China Nuclear Power Design Company, Ltd., Shenzhen 518172, China

10. **Short Crack Behaviour of Austenitic Stainless Steels in Simulated PWR Primary Water during Fatigue Damage and Monotonic Deformation**
    Choongmoo Shim, Tohoku University, Japan
    Yoichi Takeda, Tohoku University, Japan
    Tetsuo Shoji, Tohoku University, Japan
    Xiangyu Zhong, Tohoku University, Japan
    Shirish Chandarakant Bali, Tohoku University

11. **Effect of Shoulder Extension Control on Fatigue Endurance Testing of Stainless Steels**
    A McLennan, J Meldrum, J Holden, L McVey, C Austin and N Platts,
    Amec Foster Wheeler, 404 Faraday Street, Birchwood Park, Warrington, WA3 6GA, UK
    A Tweddle and M Twite
    Rolls-Royce plc, PO Box 2000, Raynesway, Derby, DE21 7XX

12. **Consideration of the Mismatch between Environmental Fatigue Behaviour of Laboratory Specimens and Plant Components in Real Environment**
    Jussi Solin, VTT, Espoo, Finland
    Armin Roth, AREVA GmbH, Erlangen, Germany
    Wolfgang Mayinger, E.ON Kernkraft GmbH, Hannover, Germany

13. **Experimental Methods for Direct Strain-Controlled Low Cycle Fatigue Tests in Simulated PWR Water**
    Tommi Seppänen, Jouni Alhainen, Esko Arilahti, Jussi Solin
    VTT Technical Research Centre of Finland Ltd., Espoo, Finland

APPENDIX 4 - FULL PAPERS

The full papers are published in the document NEA/CSNI/R(2017)2/ADD1.