THIRD INTERNATIONAL CONFERENCE ON FATIGUE OF REACTOR COMPONENTS

EPRI/USNRC/CSNI

Seville, Spain
3-6 October 2004

The enclosed CD-Rom contains full papers and presentations.
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Foreword

The third International Conference on Fatigue of Reactor Components held in Seville, Spain on 3-6 October 2004 was sponsored by the EPRI, the U.S. Nuclear Regulatory Commission and the OECD - NEA/CSNI (Organisation for Economic Co-operation and Development/Nuclear Energy Agency/Committee on The Safety of Nuclear Installations) and hosted by the Consejo de Seguridad Nuclear (CSN), Spain.

Fatigue is a primary degradation mechanism affecting nuclear power plant components worldwide. The effective management of fatigue is important to the continued safe operation of plant components during present operation and as plants consider long-term operation. The first conference in this series was held in Napa, California, in 2000 and was attended by approximately 90 fatigue experts, representing 12 countries. The second conference was held in Snowbird, Utah, in 2002 and provided an excellent forum for the discussion of component fatigue issues. This third conference brought again together international experts to discuss significant fatigue issues that affect nuclear plant operations.

Utility and plant managers, system engineers, materials engineers, structural integrity engineers, licensing engineers, maintenance/repair engineers, and researchers discussed in depth:

✓ Reactor water environmental effects on fatigue design (S/N) and crack growth (da/dN)
✓ Thermal fatigue resulting from unsteady thermal stratification
✓ Thermal fatigue field experience and load evaluation through mockups
✓ Fatigue damage analysis
✓ Fatigue monitoring, in-service inspection (ISI), and mitigation actions
✓ Vibration fatigue
✓ High-cycle fatigue
✓ Fatigue-related Codes and Standards activities
✓ Nondestructive evaluation of fatigue cracks

The Conference provided an in-depth review of the progress made on fatigue and thermal fatigue issues over the last two years and provided a solid common ground and understanding on the issues and directions to address them.

This document contains the conclusions and recommendations from the Conference as well as abstracts of papers. A CD-ROM attached to this copy and prepared by EPRI contains full papers and presentations made at the Conference.
Acknowledgement

Gratitude is expressed to the Consejo de Seguridad Nuclear (CSN, Spain) for hosting the Conference and to Commissioner Barcelo, CSN for introducing the Conference. Special thanks to Mr Carlos Castelao, CSN for his help and support and for the excellent organization.

Thanks are also expressed to the Scientific Committee and to the chairpersons for their effort and co-operation.

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List of Participants

The enclosed CD-ROM contains papers and presentations.
Conclusions and Recommendations

Views expressed in this document reflect the opinion of the audience of the Conference. They do not bind any organizations or individuals. There are consensus and remarks on topics and papers discussed during this event.

General consideration

C. Faidy (EDF-FR), A. Deardorff (STA-USA), J. Carey (EPRI-USA), J. Solin (VTT-FIN), E. Mathet (OECD-FR)

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 warrant 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 pipings. 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:

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

Panel Discussion on Thermal Fatigue

Chairman: Mr Faidy (EdF-FR)

How to go from small specimen tests to structures, and is this mature enough to fully reproduce observed phenomenon in NPPs and draw conclusions as to the operation of NPPs? Large scale tests are considered as complementary and demonstrative tests. As all full scale tests, there are costly and should be carefully planned to be valuable and achieve their objectives. Although acknowledging the interest of such tests, the audience considered that there were still room for smaller scale tests to correctly understand separate effects. Large scale tests could then be a perfect candidate for an international program on thermal fatigue.

As said before many small tests have been carried out by the community. It was agreed that existing data bases need to be « understood » and the effects of the following parameters on initiation and crack growth need to be investigated further:

✓ Mechanism for SS in PWR environment;
Load / strain control tests;
Surface finish effects;
Mean stress and environmental effects;
Biaxial loading effects;
Threshold values;
Flow rate effects.

It was recommended that existing databases should be completed with
Variable amplitude tests;
Tests at temperature lower than 150°C;
High cycle data under strain control tests;
Tests to determine heat transfer coefficient.

Water chemistry should be carefully assessed and controlled during those tests.

It was recommended that a synthesis document with all existing information on analytical thermal tests should be prepared to check and validate different evaluation methods. The document could set up a common procedure allowing tests to be compared to each other.

Load monitoring is a key issue. Monitoring has to look at all local information and loads and water chemistry are considered of equal importance. No consensus could be reached on the decoupling of the two phenomena.

Highest uncertainties laid on the determination of the load, which is an extremely important parameter at high cycle regime. Thermal load computations have some limitations in the evaluation of fluctuations amplitudes and frequencies. However simulation capabilities have increased to the point that they could now be used for a wide range of complementary applications like fluctuation locations, mock-up to plant conditions transfer functions, interpolation rules on different geometry and different flow rates. Benchmarking of the models would be desirable to increase confidence in predictions.

Over the last few years, a lot of good scientific works have been made, but limited practical recommendations. A better knowledge has nevertheless been gained on identifying important parameters to monitor and to understand thermal fatigue phenomenon. From a utility point of view, monitoring, inspecting and changing operation procedures to avoid getting into those modes where thermal fatigue occurred are still part of thermal fatigue management. In that sense more discussion is needed between users (regulatory bodies, licensees) and researchers to assure adequacy of R&D investments.

Panel Discussion on Environmental Effects
Chairman: Mr Deardorff (SIA-USA)

There is a disconnect between fatigue testing and fatigue analysis. In environmental testing, each cycle is identical and follows immediately although fatigue analysis of plant transients is based on ranging of extreme stresses with no regard for sequence (similar concern could exist for crack growth analysis). Transient Linking is an Issue. “Linking” of transients pairs is not straight-forward and can lead to significant differences. For cases where starting and ending stress points are not equal, what rate of change do you assume for the discontinuity between transients, and what is strain rate?. There are also differences between fatigue analysis and real transients that are separated in time, involve various stress magnitudes and non-constant rise times. Hold time at an intermediate stress level or random load magnitude cycling has not been considered in environmental testing.

It is recommended that communication between the people performing tests and those who must perform the analysis be improved.

Several papers questioned the adequacy of Miner’s Rule for fatigue analysis and that perhaps Design Fatigue curves should have a factor to account for this. On the other hand,
methods such as Rainflow Cycle Counting will generally show that the use of Miner’s Rule with ASME Code analysis is conservative.

For purpose of component analysis for environmental effects, perhaps special stress indices and analytical methods need to be developed to distinguish between inside (fluid exposed) surfaces and external (air exposed) surfaces.

Several papers reported on strain hardening effects that may be affecting the results of fatigue testing at high cycles. This needs to be better understood.

There were several discussions on what constitutes the environment and how it may affect environmental fatigue. Environmental fatigue is typically linked to dissolved oxygen (Not ECP, Hydrogen water chemistry may produce much different results).

It was recommended to obtain more nickel alloy data.
Opening Address

Julio Barceló Vernet, Comissioner
Consejo de Seguridad Nuclear
Spain

Distinguished colleagues, all participants, ladies and gentlemen, thank you for your presence and for your assistance to the “III Conference on Fatigue of Reactor Components”, and also welcome to the beautiful and historical city of Seville host of this international meeting.

Today we open the third international opportunity to put together and enrich the worldwide knowledge on such a crucial field for the nuclear industry, as is the study of fatigue of components.

We could not present this Conference without necessarily going, although briefly, through what the two previous conferences have meant, and also remembering some of their conclusions.

As you all know, the First Conference was held in Napa, California, and was attended by up to 90 fatigue experts, representing 12 countries. The experience was repeated two years later, in Snowbird, Utah, were 60 experts, representing 8 countries, gathered. In 2004, we meet again, this time in Europe. We have also sought, and no doubt succeeded in bringing together most international experts on the areas covering fatigue reactor components. In fact the Conference was directed to an audience of utility and plant managers, system engineers, material engineers, structural integrity engineers, licensing engineers and researchers. Moreover, we come from different institutional structures, as are universities, nuclear operators and regulatory bodies. And it is up to fourteen countries that we come from.

The two previous international meetings shared, as it could not be otherwise, a common background, which is also the one of the Conference open today. That background tell us that fatigue is a primary degradation mechanism that affects nuclear power plant components worldwide. The effective management of fatigue is important to the continued safe operation
of plant components during present operation and as plants consider long-term operation. We all have in mind these days the grave accident occurred in Mihama, Japan, and, although there is not yet available a final assessment, no doubt fatigue was one of the factors involved.

The EPRI Materials Reliability Protram (MRP) organized the first Conference, as the following ones. OECD-NEA/CSNI and the U.S. Nuclear Regulatory Commission have provided co-sponsorship. CSN is proud to participate this time as local host.

The three conferences have also had common objectives:

- To provide a forum for the technical discussion of fatigue issues that affect the integrity and operation of light water reactor components.
- To share common experiences regarding fatigue of reactor components in order to assure safe operation, and
- To identify common areas of interest to foster future international research collaboration activities.

The topics treated in the first and second Conferences, are again scheduled for discussion through the sessions of the third one, and they have also been widened.

Interesting conclusions were already reached thanks to the first Conference, for instance, that:

- conservatism exists in the ASME Code fatigue design procedures. And that understanding should be developed between ASME Code analysis and laboratory testing regarding reactor water effects on fatigue life.
- Field experience indicates that the relatively limited number of locations that experience thermal fatigue are due primarily to: stratification; dead legs and vortex conditions without a leak; an reversing zones with large ΔT.
- Risk-informed considerations, including reactor operating experience, should be applied to the management of fatigue technical issues.
In the second Conference a wider range of conclusions were developed with the consensus of the conference participants. As for thermal fatigue is concerned, it was agreed, among others, that:

- Studies on thermal fatigue should be incorporated into aging management programs, including in-service inspection programs.
- Considerations should be given to the assessment and screening of Class 2 piping systems for thermal fatigue
- Fatigue usage factor is not necessarily a good indicator of component degradation.

On environmental fatigue, among the conclusions reached we can mention, that:

- International studies indicate that threshold conditions are necessary for environmental fatigue to occur.
- Clarification of applicable environmental fatigue threshold parameters is needed, especially when the notion of “moderate” environmental effects is considered
- A more detailed evaluation of temperature/strain relationship in transient analysis should be considered for potential application.

Those conclusions add to equal important ones on Fatigue Monitoring/ Evaluation and Codes and Standards.

There is a certainty evidenced by the summary reports of both Conferences, i.e., that “collaboration and cooperation on an international scale are critical to the success of resolving fatigue issues, including sharing of data, test programs, and theories”. Bearing that conviction in mind we have worked for the organisation of this event, so we are sure of its success if only it can represent one more step leading to cooperation on this field.

Additionally, we have the opportunity of holding the Conference in the magic city of Seville. We hope that the enchantment of its magnificent buildings, squares, parks and streets and, first of all, the imagination, friendliness and happiness of its people, inspire us all on the important job that has brought us here.

Again, welcome all and thanks for your participation.
SESSION I

General Program overview
Mr Castelao (CSN-SPN), Dr Schoeckle (AMTEC-GER)

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J. Bartonicek, F. Schockle-GER, and al.

-Overview of EPRI material reliability project fatigue activities 27
L.L. Spain-USA, and al

Session Summary:

The four papers in this introductory session give an overview of four major countries activities on fatigue program.

✓ France is focused on mixing SS tees on the major aspect of residual life evaluation procedure: complementary structure tests are needed, environmental effects for SS under PWR environments is probably limited, but remains an open point.

✓ Japan is focused on fatigue curve on small specimen including environment effects (PWR, BWR); the work is done in connection with USA (ANL, ASME, PVRC). Standard fatigue test on small specimen are well covered and will be completed in the next few years (up to 2006 in Japan...). In parallel to the activity on environmental effects, JSME has developed systematic guidelines for mixing tees under thermal fatigue.

✓ EPRI is more focused on dead legs and vortex in order to prepare guidelines and training of US utilities on thermal fatigue

✓ Germany focuses more on monitoring of thermal load in plants than on work on evaluation procedure
FATIGUE DEGRADATION IN PIPING SYSTEM OF GERMAN NUCLEAR POWER PLANTS

J. Bartonicek, EnBW Kernkraft- GER
W. Zais, EnBW Kernkraft- GER
F. Schöckle, Amtec Services- GER

Operation experience showed that failures could be found even in important piping systems where integrity should be guaranteed, by design. Generally, the parameters "material", "medium" and "stress" and their interactions are the reasons for damage. Regarding the operation parameters of nuclear power plants (in this case mainly the temperature) damage due to degradation of the material itself can be excluded, if the qualified recommended materials are used. Therefore simplified, if there are failures they can be grouped into failures due to medium (corrosion) and failures due to operational loads (fatigue). This paper concentrates on damage due to operational loads.

Supposed there was no mistake in the design procedure of the system the only reason remaining for a failure is that the loads have not been specified, at least not correctly (e.g. loads previously unknown, incorrect specification of stress level and/or number of cycles) or new loads occurred due to malfunction of components (e.g. internal leakage of valves). Changes in operation procedures or failures in switching systems can be the reason for additional not specified loads, too.

These loads can be of mechanical nature (steady dynamic loads like flow or pressure induced vibrations; single dynamic loads like water hammer or condensation; quasi-static loads as induced by internal pressure) or of thermal nature (non-uniform temperature distribution across the wall of components or along the cross section of a pipe or along the piping system). Depending on the type of load the resulting global and/or local stresses can be the reason for operational damage.

In the paper, the loads of the important piping systems (main coolant loops, surge line, feedwater system, charge lines, spray lines and the emergency cooling system) are reviewed, based on extensive monitoring experience in GKN (German npp). Examples for damage caused by operational loads are discussed. Finally, the GKN philosophy to guarantee integrity of components and systems is introduced.
OVERVIEW OF EPRI MATERIAL RELIABILITY PROJECT FATIGUE ACTIVITIES

Leslie L. Spain
Dominion Generation

John Carey
EPRI-USA

Art Deardorff
Structural Integrity Associates

Beginning in 1999, activities were initiated by the EPRI Materials Reliability Project (MRP) to address reactor coolant system fatigue issues. The initial focus on this project was to re-evaluate the potential for thermal fatigue in non-isolable branch lines of pressurized water reactor (PWR) plants. An interim guideline was issued in January 2001 that provided guidance for evaluating whether further action was required to evaluate or inspect safety injection lines and drain lines. Training on application of this guideline was conducted for all PWR sites. In efforts to develop final guidelines, additional tests have been conducted to support analytical model development to predict the effects of local swirl effects that can cause cycling in these lines. Final guidelines for thermal fatigue will be issued in 2005. The program is continuing to assess other fatigue issues that may affect the safety and reliability of both pressurized and boiling water reactors. This paper provides a historical perspective as and describes the ongoing efforts.
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Session Summary:

Thermal load determination remains a key issue for detailed evaluations in the future. Several simulations have been presented using different turbulence models (RANS and LES) for the computational fluid dynamic analyses performed at MIT (USA), CEA (France), FRAMATOME ANP (Germany) and VTT (Finland). Most of them represented mock-up results in order to validate the methodology used. From the presentations and the discussions, it can be concluded that:

✔ The definition of thermal hydraulic boundary conditions is very important.
✔ Low and high frequency coolant temperature oscillations are evaluated in different configurations.
✔ Additional benchmark analyses are needed for high frequency temperature fluctuations due to thermal striping.
✔ LES calculates coolant temperature fluctuations at near wall region and is now widely used by MIT, CEA, FRAMATOME ANP, and VTT for thermal load determination. International collaboration on mockup experimental data exchange would facilitate a larger scale validation of LES analyses.
✔ The unsteady heat transfer coefficient is evaluated and could be 2 to 3 times that of the Dittus-Boelter value at locations of high temperature fluctuations.

A lot of work has been done concerning thermal load evaluation. Nevertheless some parameters (e.g. heat transfer coefficient) are not yet fully assessed. One of the main advantages of using CFD methods are the direct transfer of the time dependent temperature fields and the relevant information of all thermo-hydraulic parameters to the structural model. Due to the progresses in the computer technology, CFD analyses became a significant tool for load determination.
HYDRO-THERMAL-MECHANICAL ANALYSIS OF
THERMAL FATIGUE IN A MIXING TEE

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Following the discovery of a leak due to a longitudinal crack at the outer edge of an elbow in a mixing zone of the Residual Heat Removal System of the Civaux NPP unit 1 in 1998, metallurgical expertises were carried out and highlighted that the origin of this degradation phenomenon was due to cracking by thermal fatigue. This article covers work carried out by the CEA to study the mechanisms leading to cracking in mixing zones of piping as a result of thermal loading. This work is supported by IRSN. The main goal of the work is to analyse, by calculation, the thermal loading caused by turbulent mixing in tees and to understand the mechanism of initiation and propagation of cracks in such components. This thermal fatigue phenomenon is still not fully understood. One of the main obstacles to its understanding resides in the multi-domain nature of the loading and associated damage, involving three complementary scientific disciplines: thermal-hydraulic field, thermo-mechanical field and materials science.

This article describes the approach adopted by the CEA to establish natural mechanisms (turbulence, pulsing and instability) which might be the cause of any substantial thermo-mechanical loading in the piping.

Although turbulence may be the cause of the thermal stripping (presence of high-frequency thermal fluctuations on the inner surface of the component), it cannot alone explain the propagation of deep cracks. The main reason is the “low-pass filter” effect of convection. The wall cannot be subjected to convection-related thermal fluctuations and frequencies less than the inverse of the turbulence transit time.

However, turbulence can give rise to flow instability (such as pulsing) of lower frequency. But this cannot explain everything. The geometry upstream of the tee, particularly the sequence of straight sections and elbows can, in certain cases, damp the pulses or greatly amplify them. The use of suitable thermal-hydraulic modelling is presented in the second part of this document.

Its application to the complex 3D geometry of the Civaux unit 1 case (which includes a mixing tee, elbows and straight sections) is described in the last section. Using the temperature fields obtained by the thermal-hydraulic calculations, a link-up was made with the thermo-mechanical analysis to determine the thermo-mechanical response of the structure. The stress and temperature fields are described in detail and propagation is analysed at certain characteristic points where cracks were observed in the field.

The final result of the thermo-hydro-mechanical link-up enabled the observations made in the Civaux 1 case to be highlighted and correlated. One of the originalities of this study is to have carried out the overall analysis (thermal-hydraulic and thermo-mechanical) with a single computer code, the CAST3M code developed by the CEA.
NUMERICAL SIMULATION STUDY OF HIGH CYCLE THERMAL FATIGUE CAUSED BY THERMAL STRIPING

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High cycle thermal fatigue is a challenging research subject for the life management of nuclear power reactor piping systems. Thermal striping is identified as one of the causes of thermal fatigue failure. Thermal striping characterizes the phenomenon where hot and cold flow streams join and result in random temperature fluctuations of the coolant near the piping wall. The coolant temperature fluctuations may cause cyclical thermal stresses and subsequent fatigue cracking of the pipe wall. Coolant temperature oscillations due to thermal striping are of relatively high frequency, which was reported previously on the order of several Hz. The current study addresses thermal striping high-cycle thermal fatigue that can result at tee junctions of the Light Water Reactor piping systems. Our study concentrates on numerical analyses of the temperature fluctuations and structural response of the pipes at a tee junction. The three key aspects of this study are: a) benchmark studies of small-scale thermal striping experiments using the Large Eddy Simulation (LES) model of a commercial CFD code – FLUENT, ii) development of a novel methodology that uses the temperature gradient predicted by RANS turbulent modeling to identify the locations that are most susceptible to thermal striping fatigue cracking, and iii) numerical evaluation of the pipe wall temperature response, thermal stress, and Stress Intensity Factor (SIF) for thermal stress fatigue cracking analysis. Results of the CFD simulations of the benchmark study and thermal fatigue cracking analysis will be presented at the conference.
LOAD DETERMINATION IN THERMAL FATIGUE USING COMPUTATION FLUID DYNAMICS ANALYSIS

Mr. Schippers- GER

Considering the load determination as one of the significant topics in the fatigue evaluation of components, the knowledge of environmental conditions and their influence is important. Complex fluid conditions that are not defined during the stage of design can result under specific conditions in stresses and strains which culminate in cracks. The phenomena of thermal fatigue caused by temperature stratification and striping are known. The different phenomena and their superposition can be analyzed using CFD.

In this paper, the numerical simulations of the following examples are studied:

- Thermal striping as a result of the mixing of hot and cold flow in pipe junction where Large Eddy Simulation (LES) is used for the modeling of turbulence.

- Thermal stratification effects due to the convection flow in the feed water nozzle of PWR steam generator using the k-ε model.

The results are compared with available data from mock-up or scale test configurations and published analytical approaches. The first example is studied within the European R&D project THERFAT. Also, conclusions for both examples concerning the accuracy of load determination and the use of the CFD analysis with its possibilities and limitations are discussed.
CASE STUDY ON THERMAL FATIGUE POTENTIAL IN A T-JOINT

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Ilkka Virkkunen; Helsinki University of Technology
Sari Vehkanen, Raimo Paussu; Fortum Nuclear Services
Yrjö Hytönen; STUK

A joint team consisting of experts from a utility (Fortum), research institute (VTT) and university (HUT) performed an extensive case study within the THERFAT project.

Calculational fluid dynamic (CFD) simulations using Large Eddy Simulation (LES) turbulence model were performed to evaluate operational thermal stresses in a T-joint. Mixing of cold water with low flow rate to hot flow in primary circuit was studied.

A full scale mock-up of the joint was thermal fatigue tested in laboratory. Induction coil heating and water cooling were used to generate severe thermal cycles in the inner corner of the joint. The test was interrupted after 30 000 cycles when largest cracks were 35 mm long.

The simulated and measured pipe surface temperatures were used as input values for thermal stress analyses (FEA) and fatigue assessment. Analysis of the experimental case showed that cyclic strain in tangential direction was dominant in the inner corner and the fatigue life predicted according to the ASME III mean curve was the same 20 000 cycles when notable cracks were observed during the experiment.

The finite element models for CFD (Fluent) and FEA (Abaqus) were rigorous, but the data was successfully transferred. Simulated steady state operational conditions resulted to high frequency thermal fluctuations unable to cause fatigue failure and even cycling between such operation and shutdown conditions would result to very long fatigue lives.
INVESTIGATION OF FLOW STRUCTURE AND TEMPERATURE FLUCTUATION IN A CLOSED BRANCH PIPE CONNECTED TO MAIN PIPE

A. Nakamura, N. Takenaka and M. Hase, Japan

Normally closed branch pipes are connected to main flow pipes in a nuclear reactor for coolant drain or safety injection. The branch pipe is often bended and connected to a horizontal pipe with a normally closed valve at the other end. Velocity and temperature of the main flow are around 300 °C and 10 m/s, respectively. The main flow initiates a cavity flow in the branch pipe and the hot water penetrates into the branch pipe. It has been reported that large temperature fluctuations with long periods occur when the penetration reach to the bent and causes thermal fatigue at the elbow. The purpose of this study is to clarify the mechanism of the large temperature fluctuations at the elbow of the branch pipe by experiments and numerical simulations.

A vertical straight pipe (the straight-pipe) and a vertical pipe with an elbow connected to a horizontal pipe (the bent-pipe) made from acrylic resin were used for a test section. Flow pattern visualization using a tracer method, velocity distribution measurement by LDV, liquid temperature measurement by thermocouples and visualization by liquid crystal were carried out for the uniform and non-uniform temperature conditions with various main flow velocities.
FATIGUE DAMAGE ANALYSIS OF UNEXPECTED THERMAL TRANSIENTS IN MIXING ZONE OF T-JUNCTION ON SURGE PIPING SYSTEM

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NPP Temelín has been finished the construction of both units and NPP starts a new stadium of operation. A new period can be started with NPP running - comparison and assessment measured data stored in databases. Measured data by installed Instrumental and Control system (I&C system) as well as monitoring and diagnostic systems are storing during operation of units. Thermocouples and strain gauges measurements are used as a local measurement near the assumed critical places of NPP important components. Saved data gives us the first useful information about unit components behaviour during real service operating condition. Measured values can be used for comparison of project and real service operating conditions, detection of unexpected transients and mainly for validation of previously analyses on numerical finite element models (FEM) done before operation. We have a first experience with real service operating conditions of NPP and we can do the first comparison of project presumptions with measured parameters.

The paper describes numerical analysis and assessment of detected unexpected thermal transients in T-junction mixing zone area on surge pipeline system. Could water is mixed with warmer water and it create non-linear thermal shock on surfaces of T-junction. Three-dimensional model of T-junction area with medium flows was created and flow analysis of medium mixture area was done first. Thermal transients on T-junction of surge line were calculated together with flow analysis. Two different zones of thermal transients were analysed. Stress analysis of mixing zone area was done subsequently. The main target of the task was determining the influence of unexpected thermal transients on lifetime of T-junction connection of surge line and to suggest the correction. The paper describes parts of analyses and comments obtained results.
### SESSION II B

**Laboratory experiments for thermal fatigue**  
Dr Chapuilot (CEA- FR), Mr Davis (Duke Energy- USA)

#### Session Summary

**Abstracts:**

- OECD benchmark on thermal fatigue problem  
  *S. Chapuilot and al., FR*
- INTEGRIPOL thermal fatigue test  
  *F. Curtit, FR*
- Advances in thermal fatigue investigations performed by CEA for French PWR pipings  
  *A. Fissolo and al., FR*
- Measurement of shallow crack growth during thermal fatigue of 316L tubular test pieces  
  *E. Paffumi, EC N. Taylor, EC, M. Bache*
- Fatigue-induced Martensite in Different Qualities of the Austenitic Stainless Steel AISI 321  
  *D. Kalkhoff, SWT*
- Non destructive characterisation of early fatigue damage in the austenitic stainless steels AISI 304L, AISI321 and AISI 347 by use of micro magnetic NDT  
  *G. Dobmann and al, GER*

#### Session Summary:

Several mock-up tests have been carried out in France, Japan, Germany, and by the EPRI to support transferability of small specimen results to structures. The main interest of these analytical tests lies in the investigation of different aspects related to thermal fatigue loading:

- Large scale or small analytical tests with local or overall thermal loading;
- Different kind of observations: multiple cracking, surface or through thickness cracking, main crack emergence;
- Indications on crack evolution on surface or through the thickness.
- However, these tests have some limitations:
- All are low cycle fatigue tests (only some of them reach 106 cycles);
- All are using cold water jet and no information is available on water chemistry;
- All are constant amplitude tests (no variable amplitude test);
- A coherent and homogeneous interpretation of these tests is needed to have a good understanding of all observed phenomenon.

In addition, two presentations discussed the possibilities to detect early changes in the micro structure of the material due to fatigue (martensite transformation and secondary cyclic hardening) using NDE techniques.
OECD BENCHMARK ON THERMAL FATIGUE PROBLEM

S. Chapuliot(1), O. Ancelet(1), T. Payen(2) and E. Mathet(3)

(1) CEA – FR
(2) IRSN – FR
(3) OECD/NEA – FR

Thermal fatigue in a fluid mixing area is a well-known phenomenon that has already been studied in the past. Generally, this phenomenon is linked to turbulent mixing of two fluids at two different temperatures and creates “elephant skin” type damage at the inner surface of the component and some cracks, which remain relatively small, compared to the thickness of the structure. However, as was the case for a Tee junction of the French Super Phenix fast breeder reactor (chosen configuration for an international benchmark study [1]) and more recently for a pressurized water reactor at Civaux Nuclear Power Plant [2], this kind of fatigue damage can create cracks that propagate through the entire wall thickness. To date the problem is not completely understood.

CEA considers that 3D mechanical loading is a major factor influencing crack propagation through the thickness, which is still poorly understood. This factor is linked to the complex thermal hydraulic loading and has an impact on the stress distribution in the structure and the damage or crack propagation estimates.

For this reason an R&D program, based on a test and numerical interpretations, was launched to quantify experimentally the influence of the 3D aspects on crack initiation and propagation. The main objective is to work on a configuration with a 3D thermal load easy to reproduce using numerical simulations, so that accurate mechanical studies can be carried out and the assessment methodologies validated or modified.

However, due to the complexity of the problem, it appeared necessary for the CEA to hold technical discussions with international partners to compare different approaches used for mechanical assessment of this 3D configuration. Under the auspices of the OECD/NEA Committee for the Safety of Nuclear Installations (CSNI) and its Working Group on Integrity and Aging (IAGE WG), a benchmark on the integrity assessment under thermal fatigue loading was launched in early 2002 and is still open for participation. Participation from the industry, research institutes and regulatory bodies is sought.

By now, the benchmark enters in its synthesis phase. Blind estimations of cracking (crack initiation on the inner surface of the mock up and crack propagation through the thickness) proposed by the participants are compared to experimental results.

The article and the presentation propose a description of the experimental observations, the different analyses made by the participants and the main conclusions of the benchmark.
INTHERPOL THERMAL FATIGUE TEST

F. CURTIT- EDF

The INTHERPOL testing facility, developed in MMC (Materials and mechanics of components) department of EDF R&D is designed in order to perform pure thermal fatigue test on tubular specimen.

INTHERPOL specimens consist of a 300 mm length section of pipe with an internal diameter of 386 mm and a thickness of 10 mm. Each specimen comprises a circumferential welding located at 200 mm from the bottom of the specimen. According to the test considered, the models can have various industrial surface finish brushed with flap wheel, shot blasted, rough-cast, grinded) and various configurations of welded joints (grinded or rough of realization, with or without taper).

Before beginning thermal cycling, the model is heated up to a homogeneous temperature of 230°C. Thermal cycling is carried out on a 70 mm broad sector of the internal surface of the specimen. The cold shock is generated by the pulverization of a cold-water spray while the hot shock is obtained by subjecting the cooled surface to an intense infrared radiation. The thermal amplitude is controlled by the regulation of the power of the infrared radiations and the pulverization time duration.

The tests were carried out with a thermal amplitude of 120 to 140°C and a cycle’s duration ranging of 5 to 8 seconds. The fatigue test is stopped periodically in order to detect the initiation and the evolution of the cracks by intermediate liquid penetrant inspections.

During all the test, the temperature of the sector submitted to thermal cycling is measured by using spot welded thermocouples. The evolution of the temperature recorded during the fatigue cycles are used to perform finite element simulations in order to obtain the stress and strain fields necessary to interpret experimental results.
ADVANCES IN THERMAL FATIGUE INVESTIGATIONS PERFORMED IN CEA FOR FRENCH PWR PIPING


Such a study has been made in the frame of the thermal fatigue damage that may occur in fluid mixing zones of nuclear reactors. Clearly, it appears that one of the main obstacles to understanding thermal fatigue resides in the nature of the loading and associated damage, involving three complementary scientific disciplines: Thermal-hydraulic field, thermal-mechanical field and science of materials. In that way, a multi-discipline strategy has been chosen by CEA to investigate thermal fatigue. This paper covers mainly work carried out by the CEA with the support of EDF and Framatome. Studies realised in the frame of CEA internal programmes are also presented.

Key words: Thermal fatigue, Crack initiation, Crack network, Crack propagation, RHRS pipes
MEASUREMENT OF SHALLOW CRACK GROWTH DURING THERMAL FATIGUE OF 316L TUBULAR TEST PIECES

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European Commission- The Netherlands.

Martin Bache
University of Wales- UK

As part of a study on improved methods for assessing thermal fatigue damage and cracking in light water reactor components, a special experimental facility has been developed to simulate cyclic down-shock thermal transients on tubular test pieces. The outer surface temperature is maintained constant (typically at 300°C) while the bore is subject to repeated quenching with room temperature water. The resulting cyclic thermal stresses cause the initiation of a network of cracks at the inner surface; some of these then propagate further through the wall thickness. To provide a basis for verifying models to simulate the crack growth process, it is necessary to be able to measure the position, depth and length of such cracks as they grow. Standard techniques such as potential drop are not suitable for measuring non-uniform or multiple cracks as in the present case, and hence an ultrasound time of flight diffraction technique (TOFD) has been applied with a resolution of ±0.5 mm. The measurements are taken during intermittent stops in the testing. The paper will describe the technique used and its application to two long-term thermal fatigue tests. The measurements are compared with crack growth predictions made using detailed models of the loading conditions and material behaviour.
FATIGUE-INDUCED MARTENSITE IN DIFFERENT QUALITIES OF THE AUSTENITIC STAINLESS STEEL AISI 321

D. Kalkhof, H. J. Leber and M. Niffenegger
Paul Scherrer Institute- SWT

It is well known that at room temperature in some meta-stable austenitic stainless steels a part phase transformation from austenite to martensite takes place under the influence of quasistatic or cyclic loading. In our previous investigations it was found that beside the loading parameters, like strain amplitude, cycle number and test temperature, the strain-induced martensite was influenced by certain material properties. The goal of the present paper is to investigate the effect of the material state in terms of the actual chemical composition, processing and final heat treatment condition on the martensite formation rate during fatigue. Specimens of different products (bar, plate, pipe) made of different heats corresponding to the same steel grade EN 10088-3 – X6CrNiTi18-10 (AISI 321) were analysed. The volume fraction of martensite was applied for lifetime assessment. The martensite content was measured by means of neutron diffraction, and advanced magnetic methods. The morphology of strain-induced martensite was characterized by optical metallography as well as by transmission electron microscopy.
NON-DESTRUCTIVE CHARACTERISATION OF EARLY FATIGUE DAMAGE IN THE AUSTENITIC STAINLESS STEELS AISI 304L, AISI321 AND AISI 347 BY USE OF MICRO MAGNETIC NDT

G. Dobmann, M. Kopp- GER

Austenitic stainless steel of the grade AISI 304 is common material in USA, Japan and France in nuclear power plants for primary circuit pipes, AISI 321 (German grade 1.4541 - Ti-stabilized and AISI 347 (German grade 1.4550 - Nb-stabilized) is often used in power station and plant constructions according to the Siemens design. The evaluation of early fatigue damage and thus the remaining lifetime of austenitic steels is therefore a task of enormous practical relevance. It is known that meta-stable austenitic steel forms by phase transformation ferromagnetic martensite due to quasi-static and cyclic loading. This presupposes the exceeding of the threshold value of cumulated plastic strain. The amount of martensite as well as its magnetic properties should provide information about the fatigue damage.

The contribution reports to investigations performed in a EURATOM project where the three mentioned steel grades were fatigued under LCF conditions at ambient temperature and at 300°C mainly under mean stress-free conditions up to different usage factors (0.0, 0.6, 0.8, and 1.0). The so obtained specimens were non-destructively tested by electromagnetic and micro-magnetic testing techniques. The fatigue damage observed is a strongly localized phenomenon. Therefore reliable results were obtained only if the measured parameters were averaged along the middle girth line in the measuring length of the hour-glass fatigue specimen where the fatigue effects are pronounced.

By data evaluation it was found that the ability of the material to form martensite by phase transformation is strongly affected by the local chemical segregation and heat treatment history of the specific heat. Only if the sensitivity for phase transformation exists, then the effect can be used to detect early fatigue damage by use of electromagnetic and micro-magnetic techniques, because the enhanced magnetic permeability by local martensite build-off is enhancing the contrast for detection. In that specific case a usage factor prediction by NDT can be performed.
SESSION III

Environmental effects
Dr Hickling (EPRI- USA), Mr Lapena (CIEMAT- SPN)
Dr Kalkhof (PSI- SWT), Dr Higuchi (IHHI- JPN)

Abstracts:

- Effects of LWR coolant environments on fatigue crack initiation in carbon and low-alloy steels, austenitic stainless steels and alloy 600
  O.K Chopra and W.J. Shack, USA - Presented by W. Cullen, USNRC
- Environmental Effects On Fatigue Life Of Type 316 Stainless Steel In High Temperature Water
  H. Cho and al., KR
- Environmental fatigue testing of stainless steel pipe bends in flowing, simulated PWR primary water at 2
  R. Killian, GER, and al.
- Low cycle fatigue behaviour of 316 NG alloy in PWR environment
  J. Solin and al., FIN
- Corrosion fatigue crack growth of austenitic stainless steel in PWR primary coolant at low frequency
  D. Tice, UK, and al.
- Strain controlled fatigue of 304L SS in air and PWR water
  H. D. Solomon, USA, C. Amzallag, FR and al.
- Development Of A Possible Bounding Corrosion Fatigue Crack Growth Rate Relationship For Low Alloy Steel Pressure Vessels Materials In Bwr Environments
  S. Ranganath, USA, and al.
- Crack growth rate of low alloy steels under BWR conditions. Effect of temperature and hold
  J. Lapena, SPN, et al.
- Low alloy steel EAC corrosion fatigue relationships for BWR environment
  H.S. Mehta, USA
- Corrosion fatigue crack growth behaviour of low alloy RPV and piping steels under BWR conditions
  H.P. Seifert, GER, and al.

Session Summary:

✓ Higuchi Paper from Initial Session
  - Summarized Japanese work and comparison of environmental curves/approach for fatigue initiation

✓ Chopra Paper (presented by W. Cullen, USNRC)
  - Summarized the Argonne-developed approach for fatigue initiation
    - Essentially the same as Higuchi approach
  - New data becoming available for roughness (NUREG/CR in process of being printed)
  - Conclude that Code Curves do not have conservatism in 2-20 factors
    - Some discussion of proposed factor for loading history (Miner’s Rule)

✓ Cho paper discussed 316SS testing
  - Showed minor environmental effect at 0.04%/sec strain rate
- How does this data compare with Argonne/Japanese data base?

✓ Killian paper discussed testing of prototypical SS components
- Current conclusion is that flow rate does not have a significant effect as was shown for CS/LAS
- Surface finish also had no significant effect
- Does this tell us something on required margins
- But, for component, cracked on both OD (air) and ID (water)
- Does this tell us something about the way we analyze components, especially piping?

✓ Solin paper discussed realistic loading spectra
- High-cycle low stress cycles may have an effect
- Spectrum of loads may reduce life by a factor of 5
- More tests may be needed

✓ Tice paper on 316SS crack growth in PWR environments
- Increased CGR for increasing rise times

✓ Solomon/Amzallag paper re 304L SS fatigue life in air and PWR environment
- Issue of secondary hardening at 300°C discussed (increased endurance life)
- 150°C endurances limit less than literature (and 300°C)
- Below 1,000,000 cycles, results are in agreement with literature

✓ Ranganath paper on LAS CRG in BWR environment
- What is the rise time for variable strain rate transients? In testing, rate of rise is constant, versus real stress responses are rarely this way!

- (Above shows actual transient versus two possible effective rise times for a surge line transient.)
- Working on simplifying Code approach
- Would add 4th Fundamental Corrosion Law to those proposed by Sam
  - Man has placed the elements of the Earth in a very un-natural state.
  - All metal wants to and will eventually become dirt! It is just a matter of time.

✓ Lapena paper on CGR of LAS in BWRs
- Scatter of relevant CGR data is very high
- Above ASME XI line
- Plus difficult to relate data to BWR conditions
  - E.g., effect of hold time
- Testing indicates da/dt growth during hold times for one test
- Some possible explanations offered
- Test sample size is small – more tests needed

✓ Mehta paper on LAS EAC corrosion fatigue in BWRs
- Presented evaluation of da/dN data as applicable to BWR conditions
- New curves could have an impact on inspection interval due to high CGRs + SCC may be an issue
- No adverse field experience – but work continuing
✓ Seifert paper on CGR in LAS vessel and piping for BWR conditions
- Attempting to develop more reliable CGR rules for certain conditions – large range of test conditions
- Very significant increases of CGR for ripple-load cases, especially for low rise time (low frequency) and high oxygen/ECP
  - But HWC/NMCA helps significantly
  - However, undue conservatism for high frequency and certain other conditions
The existing fatigue strain–vs.–life (ε–N) data illustrate potentially significant effects of light water reactors (LWRs) coolant environments on the fatigue resistance of pressure vessel and piping steels. Under certain environmental and loading conditions, fatigue lives of austenitic stainless steels can be a factor of 20 lower in water than in air. This paper reviews the existing fatigue ε–N data for carbon and low–alloy steels, austenitic stainless steels, and Alloy 600 in LWR environments to establish the effects of various material and loading parameters, such as steel type, material heat treatment, strain range, strain rate, temperature, and dissolved–oxygen level in water, on the fatigue lives of the steels. Statistical models are presented for estimating the fatigue ε–N curves as a function of material, loading, and environmental parameters. Methods for incorporating environmental effects into the fatigue evaluations of the American Society of Mechanical Engineers (ASME) Code are described. The influence of LWR environments on the mechanism of fatigue crack initiation is discussed. The decrease in fatigue lives of these steels is caused primarily by the effect of environment on the growth of short cracks that are <200μm deep. The effect of environment on crack initiation and crack growth rates is also presented.

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ENVIRONMENTAL EFFECTS ON FATIGUE LIFE OF TYPE 316 STAINLESS STEEL IN HIGH TEMPERATURE WATER

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Strain-life (S-N) curve tests of Type 316 stainless steel in 310 °C water were carried out to obtain data of fatigue life. In the tests, strain rate was 0.04 %/s and applied strain ranges were 0.4, 0.6, 0.8, and 1.0 %. Test environment was water at 310 °C water in temperature, 15 MPa in pressure, and < 1 ppt dissolved oxygen (DO) concentration. The cyclic stress response in 310 °C water showed a hardening at an earlier stage. The initial hardening was followed by continuous softening and saturation stage before the final load drop associated with fatigue crack initiation and propagation. On the other hands, the cyclic stress response in room temperature air exhibited continuous softening. Fatigue life of Type 316 stainless steel in 310 °C water was shorter than the statistical model in air, and the S-N curves in 310 °C water were located on a region above the ASME Code fatigue design curve.
ENVIRONMENTAL FATIGUE TESTING OF STAINLESS STEEL PIPE BENDS
IN FLOWING, SIMULATED PWR PRIMARY WATER AT 2

R. Kilian, F-ANP GmbH- GER
J. Carey and J. Hickling, EPRI- USA
R. Nickell, Applied Science & Technology-USA

The apparent reduction in component fatigue life due to laboratory-simulated reactor water environments, and the management of this phenomenon, has become a significant issue for those utilities seeking license renewal. An analysis and assessment of existing fatigue data for stainless steel exposed to the pressurized water reactor (PWR) primary water environment has identified a lack of information with respect to flow rate effects. The majority of existing data has been gained under static or quasi-static flow conditions, where – for carbon and low-alloy steels - the tendency to environmental enhancement of cyclic crack growth has been shown to be much higher. Environmental fatigue testing of austenitic stainless steel components under appropriate conditions of temperature, water flow rate, strain range and strain rate is being sponsored by the EPRI Materials Reliability Program (MRP) Fatigue Issue Task Group (ITG) to fill in some important gaps in the knowledge base.

The present paper describes production of the stainless steel U-bend specimens, detailed studies to optimize subsequent testing, information from baseline experiments in an inert medium at both room temperature and 240 °C, and the data recently obtained from comparison of several pairs of high/low flow rate tests in which environmental fatigue was observed.
LOW CYCLE FATIGUE BEHAVIOUR OF 316 NG ALLOY IN PWR ENVIRONMENT

Jussi Solin, Päivi Karjalainen-Roikonen, Esko Arilahti, Pekka Moilanen; VTT- Finland

Low cycle fatigue tests in low oxygen PWR water 320 °C were conducted for 316 NG stainless steel. The bellows loading technology presented in the previous Snowbird conference [1] was applied for a few constant amplitude and variable amplitude strain controlled tests.

Constant amplitude results at 0.01 Hz sinusoidal loading comply with predicted lives according to the EPRI/GE methodology (F_{eq} approach) as proposed by the CLEE of PVRC [2].

Variable amplitude straining with a block of 50 quasi-random cycles and strain amplitudes ranging from 0.19% to 0.78% lasted until the cumulative damage (fatigue usage factor) according to the ASME III design curve was exactly one.

The cyclic deformation mechanisms were monitored in terms of cyclic hardening and softening, hysteresis loops and CSSC’s aiming to clarify the currently unknown mechanism(s) of environmental effect in LCF for stainless steel and to be able to explain the influence of critical environmental and loading parameters.

The relevance of current and previously published results to Fatigue assessment of reactor components [3] will be discussed.
CORROSION FATIGUE CRACK GROWTH OF AUSTENITIC STAINLESS STEEL IN PWR PRIMARY COOLANT AT LOW FREQUENCY

David Tice and Keith Rigby, Serco Assurance- UK
David Swan, Rolls-Royce

The rate of growth of flaws in reactor circuit components by fatigue is usually determined using reference crack growth curves which describe the rate of propagation per cycle (da/dN) as a function of the applied stress intensity factor range (ΔK). Such curves are given in Section XI of the ASME Boiler and Pressure Vessel Code. For carbon and low alloy steels the ASME XI code provides separate curves for buried and surface-breaking defects to allow for the observed enhancement of growth of defects exposed to the high temperature reactor water environment. For austenitic stainless steels, no reference curves are provided for water-wetted defects. However, since the primary coolant in pressurised water reactors (PWR) has been shown to reduce the fatigue endurance of austenitic stainless steels significantly under low strain rate (low frequency) loading conditions, it is necessary to ascertain whether any enhancement of crack growth can also occur. Existing crack growth data for austenitic steels relate mainly to relatively high loading rates, under which the effect of the PWR environment on crack growth is relatively small. This paper describes the results of a test programme carried out to determine the rate of propagation of cracks in Type 304L stainless steel by corrosion fatigue in high temperature PWR coolant over a range of loading frequencies, with an emphasis on low frequency conditions. Tests were carried out on Type 304L stainless steel using conventional compact tension specimens over a range of frequencies, stress ratios (R) and temperatures. The data demonstrate that crack growth rates are significantly enhanced by the PWR primary coolant environment at both 250°C and 300°C. Within limits, the degree of enhancement increases with reducing loading frequency. The results will be presented both in terms of da/dN - ΔK curves and using the time domain (\( \dot{a}_e - \dot{a}_i \)) approach.
STRAIN CONTROLLED FATIGUE OF 304L SS IN AIR AND PWR WATER

By H. D. Solomon*, R. E. DeLair**, and C. Amzallag***
* GE Global Research Center, **Retired, formerly GE Global Research Center, ***EDF

This study of the fatigue behavior of type 304L stainless steel utilized strain controlled testing, with fully reversed total strain limits, with the extensometer placed on the specimen, in the environment. Tests were run in air and PWR water, at 150°C and at 300°C. Most of the testing was done using a strain rate of 0.4%/s, but several tests utilized lower strain rates to define the reduction of the fatigue life due to these lower rates. The most significant and novel feature of these tests was that they were run to $10^7$ cycles, at the relatively low strain rate of 0.4%/s. Few previous studies utilized such long lives, generated at so low a strain rate, to define an endurance limit. The overall fatigue lives were in general agreement with those in the literature (which are compared in the study), with several important new findings. At 150°C, the tests in air and PWR were similar but exhibited a lower endurance strain than has previously been reported (less than 0.1% versus over 0.11% for the literature). At 300°C, there was a decrease in the fatigue life in the low cycle fatigue regime in PWR water compared to that observed in air, with the results obtained in air being similar to that observed at 150°C. The endurance strain was, however, higher in both air and PWR water at 300°C than that observed at 150°C. This increase was due to the effects of secondary hardening at 300°C, which is shown by the increase in the stress range with cycling beyond about 1000 cycles. This increase in stress raised the elastic strain, concomitantly reducing the plastic strain and preventing failure when the plastic strain was driven to very small values.
DEVELOPMENT OF A CORROSION FATIGUE CRACK GROWTH RATE
RELATIONSHIP FOR LOW ALLOY STEEL PRESSURE VESSEL MATERIALS
IN BWR ENVIRONMENTS

Sam Ranganath, XGEN engineering
John Hickling, EPRI- USA

Fatigue crack growth tests on low alloy steel in simulated high temperature Boiling Water Reactor (BWR) environments have shown that, in addition to the conventional dependence on the stress intensity factor range, the crack growth rate is also strongly influenced by the frequency (or alternatively, the rise time), temperature and the mean stress (R ratio). While there is general agreement on the role of these variables on corrosion fatigue (CF) crack growth, a subset of environmentally assisted cracking (EAC), what is not clear is how to apply them to actual pressure vessel components. For example, the rise time for most loadingtransients in BWR operating conditions is not known a priori. In most cases, the ASME code stress and fatigue analyses assume a step change in temperature to calculate thermal stresses. While this may be conservative in terms of determining the stress range, it would also imply, by virtue of the step change, that the rise time is zero, with the result that any EAC effect is, by definition, negligible. However, using the conservative stresses (resulting from the step change assumption) in conjunction with long rise time assumptions can result in unrealistically high crack growth rates (CGR). Thus there are two competing effects: short rise time (low EAC effects) and high thermal stresses (resulting from the step change), and the converse: long rise time, or slow loading ramp rates (resulting in high EAC effects, but lower stress ranges).

Clearly neither of these approaches is effective in realistically predicting crack growth in pressure vessels. Similarly, when there are thermal transients in the vessel (the most common source of fatigue cycling in BWRs), the tests done under constant temperature conditions may not be adequate, since the temperature varies during the stress cycle. Specifically, what temperature is appropriate in predicting fatigue crack growth when the transients involve temperature cycling?

This paper describes the analytical study of stress transients and the resulting crack growth rates in pressure vessels under operating conditions. Stress analysis is performed to evaluate the CGR under the combination of different rise times. This will enable the determination the maximum CGR for a given plant transient regardless of the actual loading rise time. Similarly, the effect of temperature on fatigue crack growth (in events involving thermal cycling) is evaluated. Based on this study, a fatigue crack growth relationship that does not require prior knowledge of rise time and is not explicitly dependent on temperature is proposed. Predictions using the proposed relationship are compared with BWR feedwater nozzle data to benchmark the CGR model. The ultimate objective is to propose a CGR model for use in Section XI, ASME Code.
CRACK GROWTH RATE OF LOW ALLOY STEELS UNDER BWR CONDITIONS. EFFECT OF TEMPERATURE AND HOLD TIME

Jesús Lapeña, Dolores Gómez Briceño, Marta Serrano, Francisco J. Perosanz

CIEMAT. Nuclear Fission Department-SPN

Ageing processes decisively control the lifetime of a nuclear power plant, being the reactor pressure vessel (RPV) one of the most critical components. It is conservatively postulated that the RPV contains flaws, which have penetrated the austenitic stainless steel cladding. Therefore, environmentally assisted cracking (EAC) of the ferritic RPV material has to be considered as a major ageing process, but literature crack growth rate (CGR) data reveal a scatter of more than five orders of magnitude.

During operation, the effect of fatigue is considered in the Codes, but there are also transients (start-up/shut-down, hot stand-by, turbine trips, ...), followed by long periods of stationary transient-free where predominantly static loading of the RPV prevails. Fatigue crack growth rate has been determined in BWR conditions, and the possible influence of these transients on the crack propagation of low alloy steels has been also studied. The effect of temperature and hold time at constant maximum load on the crack growth behaviour has been considered. Main parameters were rise time, hold time and temperature of the coolant. Then, investigation of synergistic effects of load transients and temperature was carried out.

Two low alloy ferritic reactor pressure vessel steels have been tested: material A (20 MnMoNi 55, with a sulphur content 0,015 %) and material B (22 NiMoCr 37, with a sulphur content 0,007 %).

Some results of fatigue crack growth rate in the material with higher S content exceed the prediction line of the ASME Code, Section XI. Results of transients tests shows that for material A and hold times of $10^3$ seconds, CGR’s are above the BWRVIP-60 Disposition Line 2 for transients in load. But increasing hold time produces a decrease in CGR below that line.
LOW ALLOY STEEL EAC CORROSION FATIGUE RELATIONSHIPS FOR
BWR ENVIRONMENT

H.S. Mehta, R.M. Horn
GE Nuclear Energy- USA

J. Hickling,
EPRI- USA

The fatigue crack growth rates for ferritic steels in water environments given in A-4300 of Appendix A, Section XI, ASME Code, were developed from data obtained prior to 1980. Subsequently, updated assessments by Eason, et al. and recent laboratory test results from Seifert and Ritter demonstrated that under certain conditions, ferritic steels exposed to oxygenated water environments may be susceptible to high fatigue crack growth rates that exceed the current disposition curves. In the light of ASME adopting Code Case N-643 for PWRs, there is a need for a similar Code Case for the BWR water environments (for both the normal water chemistry and hydrogen water chemistry/NobleChem) that takes into account these findings. This could mean modification of current EAC curves in the ASME Code. A joint program of EPRI and GE was developed to address this need for updated evaluations of the corrosion fatigue. The program's first task has been to re-assess the role of rise time, environment, alloy, heat treatment and impurity levels on the established ASME codified disposition curves/methodologies. The data was then used as a basis to assess the impact of on modified cyclic curves on the disposition approaches that are currently used to evaluate postulated flaws in the BWR reactor pressure vessel or RPV head and the feed water nozzle regions. This paper includes a discussion of the appropriate BWR plant transients and the GE process for performing evaluations. The role of the evaluations on the establishment of inspection intervals currently determined using NUREG-0619 and the latest BWROG Report will also be presented. Finally, the relationship between cyclic load and constant load behavior in these steels will be discussed in the context of the mechanisms for environmental assisted cracking.
CORROSION FATIGUE CRACK GROWTH BEHAVIOUR OF LOW ALLOY RPV AND PIPING STEELS UNDER BWR CONDITIONS

H.P. Seifert, S. Ritter
Paul Scherrer Institut- SWT

Corrosion fatigue (CF) of carbon and low-alloy steels has been identified as a possible degradation mechanism for pressure vessel and piping in nuclear power plants. In the introductory part of this paper the research and service experience with CF crack growth of these materials in high-temperature water is briefly reviewed, with special emphasis on the primary pressure-boundary components of boiling water reactors (BWR). In the second part, the adequacy and conservatism of the current "ASME XI reference fatigue crack growth curves" are evaluated in the context of the most recent research results from a large PSI research programme and the CASTOC-project (5th EU FWP).

In summary, the current "ASME XI wet reference fatigue crack growth rate (CGR) curves" conservatively cover the CF CGR lab data under most combinations of loading, environmental and material parameters, even under BWR/NWC conditions, and might therefore be regarded as an adequate, general bounding curve. On the other hand, the most recent investigations also clearly reveal that the "ASME XI wet reference fatigue crack growth rate curves" can be significantly exceeded by cyclic fatigue loading at low loading frequencies (< 10³ Hz) and under ripple loading conditions, which might be characteristic for some specific BWR plant transients such as plant start-up/shut-down etc.
SESSION IV

Codes, rules and guidelines
Dr Nilsson (JRC- EC), Dr Carey (EPRI- USA)

Session Summary

Abstracts:

-Experimental database to evaluate different parameters influencing the S/N curve
  S. Krolop, GER, and al
-Thermal Fatigue Management Guideline For Normally Stagnant Non-Isolable RCS Branch Lines
  A.F. Deardorff, USA, and al.
-Thermal cycling Screening criteria and evaluation methodology and application to pressurized water
  reactor branch line piping
  J. D. Keller, USA, and al.- Presented by J. Davis, USA
-Thermal fatigue due to stratification and thermal shock loading in piping
  S. Krolop, GER, and al.
-Current status of development on codes for fatigue evaluation in JSME
  T. Nakamura, JPN, and al. - Presented by M. Higuchi

Session Summary:

The session consisted of six papers, with two from Japan, USA and Germany respectively:
✓ “Development and Evaluation Method of Fatigue Damage on Operating Plant
  Components Considering Environmental Effects” by M. Higuchi Japan.
✓ “Current Status of Development on Codes for Fatigue Evaluation in JSME” by T.
  Nakamura et al (presented by M. Higuchi)
✓ “Thermal Cycling Screening Criteria and Evaluation Methodology and Application to
  Pressurized Water Reactor Branch Line Piping” by J.D. Keller et al (presented by A.F.
  Deardorff)
✓ “Thermal Fatigue Management Guideline for Normally Stagnant Non-Isolable RCS
  Branch Lines” by J.D Keller et al (presented by M. Davis)
✓ “Experimental Database to Evaluate Different Parameters Influencing the S/N-Curve” by
  E. Roos et al (presented by S. Krolup)
✓ “Thermal Fatigue Due to Stratification and Thermal Shock Loading of Piping” by E.
  Roos et al.(presented by S. Krolup)

The paper “Development and Evaluation Method of Fatigue Damage on Operating
Plant Components Considering Environmental Effects” by M. Higuchi summarized the
Japanese work on considering environmental effects using environmental reduction factors,
Fem. Specific semi-empirical formulas for Fem were presented as function of temperature,
dissolved oxygen, sulphur content and strain rate for carbon steels and stainless steels. The
paper presented threshold values for strain amplitude and strain rate used in Japan and the
rationale for why no threshold values are used for temperature and dissolved oxygen. The
paper described three methods to account for strain rate effects; Average Strain Rate Model
(ASRM), which is a simple model to use; Time-Based Integral Model (TBI) and Strain-Based
Integral Model (SBI). The TBI model was not suitable as it gave very conservative results,
The SBI model provided very accurate results whereas the ASRM model gave moderately conservative predictions. The paper presented also a simplified and a detailed procedure for thermal transients with the number of segments used to discretize the transient as one of the most important differences. The difference between the methods could be small or relatively large depending on the nature of the transient.

The second Japanese paper, “Current Status of Development on Codes for Fatigue Evaluation in JSME” by T. Nakamura et al, described the thermal fatigue and environmental fatigue guidelines issued in 2003 and 2002 respectively. The Thermal Fatigue guidelines have three levels; a screening criterion based on a $\Delta T_{\text{fluid}} < \Delta T_{\text{er}}$, a simple stress criterion $\sigma_{\text{in}} < \sigma_{\text{er}}$, and a third analysis level where it must be proved the fatigue usage factor is below unity. The environmental fatigue guidelines use the fatigue reduction factors, $F_{\text{en}}$, as described by the Higuchi paper. The paper presented evaluation for design (40 years) and plant life management (60 years). A major difference is that the PLM analysis allows that the actual number of transients during operation is used rather than a conservative estimate, which gives a significantly lower usage factor. The environmental effects could increase the cumulative usage factor by an order of magnitude for certain cases but the usage factor remained below unity in all cases.

The two US papers “Thermal Cycling Screening Criteria and Evaluation Methodology and Application to Pressurized Water Reactor Branch Line Piping” and “Thermal Fatigue Management Guideline for Normally Stagnant Non-Isolable RCS Branch Lines” presented work which is done under the auspices of the EPRI Materials Reliability Program and with the aim to provide guidelines for evaluation, mitigation, monitoring and non-destructive examination. The Guidelines are currently under industry review with final release expected in 2005. The first paper described a methodology for screening and basic evaluation of thermal cycling in non-isolable branch lines attached to primary coolant piping and which uses scaled models of typical pipe configurations together with first-principles engineering modelling. The papers illustrated several examples of successful application of the method to predict location and time histories of thermal cycling and in-leakage ranges for different pipe diameters. The second paper outlined the Guideline procedures with screening criteria and different levels of evaluation criteria and methods for mitigation and inspection. The screening criteria, described by the first paper, will out-screen a very large number of components. If the line can be screened out, or if evaluation can show that the cumulative fatigue factor is below 0.7, then the normal inspection intervals stipulated in ASME XI can be used. If the CUF is between 0.7 and 1.0, the inspections should be performed at each refuelling outage. In the case that CUF is above 1 the component must be replaced or modified or as an alternative a flaw tolerance methodology can be used.

The paper “Experimental Database to Evaluate Different Parameters Influencing the S/N-Curve” by E. Roos et al presented experimental data on temperature, surface finish and strain rate effects for austenitic and ferritic steels for fatigue curves under low-cycle fatigue conditions. Under these conditions, the safety factors, 2 on stress and 20 on cycles, were shown to provide conservatism for design curves. The paper “Thermal Fatigue Due to Stratification and Thermal Shock Loading of Piping” by E. Roos et al., compared three methods to evaluate thermal stresses in situations with stratification and thermal striping: i) the fully restraint biaxial stress condition $\sigma_{\text{w}} = \sigma_{\text{v}} = - \frac{a \Delta T}{1 - v} E$; ii) formulas described by the KTA standards, which combines primary, secondary and peak stresses, and ; iii) finite element computed stresses. Computed stresses were compared for idealized boundary conditions, such as clamped and simply supported ends. The restraint biaxial stress formula usually gives very high thermal stresses whereas FEM and KTA standards gave similar stress levels. The paper illustrated the importance of a sharp transition layer between hot and cold fluid for large global bending stresses.
DEVELOPMENT OF EVALUATION METHOD OF FATIGUE DAMAGE ON OPERATING PLANT COMPONENTS IN CONSIDERING ENVIRONMENTAL EFFECT OF LWR COOLANT

Makoto Higuchi, Ishikawajima-Harima Heavy Industries- JPN

The effects of LWR water environments on fatigue life reduction of LWR component materials have been evaluated quantitatively. The environmental correction factor Fen, which is determined by strain rate, temperature and dissolved oxygen content has been proposed for assessing this reduction in the case of carbon, low alloy and austenitic stainless steels. Equations to calculate Fen have been established based on fatigue data derived under constant test conditions but strain rate and temperature in actual transients are usually not constant. A method for calculating Fen under conditions of continuously changing strain rate and temperature was established in this study for use in assessing fatigue damage on actual transients, with due consideration to the effects of LWR water environments. Fatigue damage in LWR water may be found by linear summation of the products of Fen and partial fatigue usage factor in stress cycles. The method is consisted of simple and detailed methods. The evaluation of Fen must be applied for the strain range in which the strain increases continuously. The Fen by the detailed method was found much less than with the simple method under a condition of considerable temperature change.
EXPERIMENTAL DATABASE TO EVALUATE DIFFERENT PARAMETERS INFLUENCING THE FATIGUE S/N-CURVE

E. Roos, K. Maile, K.-H. Herter, X. Schuler
University of Stuttgart- GER

The design rules according to the technical codes and standards provide for explicit consideration of cyclic operation, using design fatigue curves of allowable alternating loads (allowable stress or strain amplitudes) vs. number of loading cycles (S/N-curves), specific rules for assessing the cumulative fatigue damage (fatigue life usage factor) caused by different specified or monitored load cycles. The influence of different factors like welds, environment, surface finish, temperature, mean stress and size must be taken into consideration. In the paper the parameters influencing the S/N-curves used within a fatigue analysis, like the surface finish, the temperature, the difference between unwelded and welded areas, the strain rate as well as notches are verified on the basis of experimental results obtained by specimen testing. Thus safety margins relevant for the assessment of fatigue life are shown and compared with the safety factors implemented in the different technical codes and standards.
THERMAL FATIGUE MANAGEMENT GUIDELINE

Arthur F. Deardorff
Structural Integrity Associates

John Carey
EPRI-USA

Beginning in 1999, efforts were undertaken to develop screening and evaluation methodologies for thermal fatigue in non-isolable branch lines attached to PWR reactor coolant piping. An interim guideline was issued in January 2001. With completion of testing and analytical model development, a final thermal fatigue management guideline is planned for release in 2005. This guideline supercedes the interim guideline and provides recommendations for thermal fatigue management in non-isolable sections of branch lines, including mitigation, monitoring, analytical evaluation and non-destructive examination. This paper describes the contents of the final thermal fatigue management guideline, including the differences from the earlier interim guidelines. Examples of applying the guideline to typical plant system configurations and geometries are included.
THERMAL CYCLING SCREENING AND EVALUATION METHODOLOGY AND APPLICATION TO PRESSURIZED WATER REACTOR BRANCH LINE PIPING

J. D. Keller
A. J. Bilanin
Continuum Dynamics- USA

J. Carey
EPRI- USA

In 1999, EPRI established the Fatigue Issue Task Group (ITG) to provide leadership to the U.S. nuclear industry for thermal fatigue issues. While the overall scope of the Fatigue ITG thermal fatigue program is broad, the primary objective is the development of guidelines for the management of thermal fatigue and related issues. A significant component of this program has been the development of a thermal cycling screening and evaluation methodology from an extensive test program focusing on the thermal-hydraulic mechanisms leading to thermal cycling. The methodology has been applied in a generic assessment of the industry state with regard to branch line thermal cycling susceptibility. The screening and evaluation methodology, as well as the results from the industry branch line assessment, will be included in the Thermal Fatigue Management Guidelines, under development by the EPRI Materials Reliability Program.

This paper will provide an overview of the thermal cycling application model, describing its development with respect to current and prior research in thermal stratification and cycling in dead-ended branch lines attached to primary loop piping. Selected components of the methodology will be presented, including validation against scaled test and plant monitoring data. Results from a generic assessment of the industry state with regard to thermal fatigue susceptibility will also be summarized.
THERMAL FATIGUE DUE TO STRATIFICATION AND
THERMAL SHOCK LOADING OF PIPING

E. Roos, X. Schuler, K.-H. Herter

University of Stuttgart, GER

Most of the fatigue relevant stresses in piping systems are caused by thermal loading. The difference between the density of the fluid caused by the temperature gradient from bottom to top of the pipe cross section combined with low flow rates can result in thermal stratification in the horizontal portions of a piping system. The hot and cold fluid levels of the stratified flow conditions are separated by a interface or mixing layer. On the other hand high flow rates can cause a temperature gradient in pipe longitudinal direction (jump of temperature) and result in a thermal shock loading on the inside pipe surface constant throughout the pipe cross section. These loading conditions impact the secondary stress and the fatigue usage analysis typically performed for piping components by equations in the technical codes. Thermal stratification in piping system causes a circumferentially varying temperature distribution in the pipe wall resulting in local through wall axial stresses and global bending stresses in the piping system. Maximum local thermal stress is found when a thin interface (mixing) layer occurs in the upper or lower parts of the pipe cross section. Maximum global thermal bending stress is found when a thin interface layer occurs in the middle of the pipe cross section.
CURRENT STATUS OF DEVELOPMENT ON CODES FOR FATIGUE EVALUATION IN JSME

Takao Nakamura
The Kansai Electric Power Co-JPN

This paper introduces the current status of JSME activities to establish codes on high-cycle thermal fatigue and environmental fatigue that are international issues of fatigue on nuclear power facilities.

Triggered by the leakage from regenerative heat exchanger at Tsuruga Unit2 (The Japan Atomic Power Company), the activity to establish a code to prevent high-cycle thermal fatigue of piping started in JSME. As the first edition of JSME code, they started to establish evaluation methods of thermal striping in a mixing tee with hot and cold water and thermal stratification in a branch pipe with a closed end. In November 2003, this code was published as evaluation guideline for piping design that can apply to general industrial plants, not only to nuclear power facilities.

On the other hand, MITI of those days decided to apply the evaluation of environmental fatigue, as part of confirming structural integrity of components in plant life evaluation of LWR plants operated for 30 years, and notified utilities of tentative guidelines for environmental fatigue evaluation. These guidelines provided evaluation formulas about fatigue life reduction that were obtained from the results of R&D in Japan until that time, but they did not include detailed methods for applying the evaluation formulas to actual plants. So “The Guidelines for Evaluating of Environmental Fatigue” were issued by TENPES (Thermal and Nuclear Power Engineering Society) in June 2002, as more detailed and practical guidelines. In response to these activities, JSME organized the Subgroup on Environmental Fatigue Evaluation in March 2004, and started to examine code of environmental fatigue evaluation including results of recent R&D activities as Codes for Nuclear Power Generation Facilities.
### Session V

Engineering Consideration/ Industrial applications

Dr Kilian (FRA-ANP-GER), Dr Solin (VTT-FIN)

#### Session Summary

**Abstracts:**

-A survey of current US nuclear plant fatigue issues  
A. Deardorff, USA, and al.

-Thermal Fatigue In Mixing Areas: Status And Justification Of French Assessment Method  
C. Faidy, FR

-Stratification phenomenon in the pressurizer surge line and its influence on low cycle fatigue  
I. Lopos, SK, and al.

-Fatigue analyses as aids for the in-service monitoring. Possibilities and limitations  
S. Dittmar, GER, C. Hüttner and al.

-Fatigue evaluation for the socket weld in nuclear power plants  
H.D. Chung, KR, and al. (Paper was not presented)

-Fatigue monitoring and evaluation. Programmes and results for several German NPPs  
W. Kohlpaintner, GER

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#### Session Summary:

The session consisted of five presentations, a review on recent fatigue concerns in operating plants in USA, Summary of French approaches for high cycle thermal fatigue and three papers dealing with fatigue monitoring in plant operation:

- ✓ A survey of current US nuclear plant fatigue issues (A. Deardorff, USA, et al.)
- ✓ Thermal fatigue in mixing areas. Status and justification of French assessment method (C. Faidy, FR)
- ✓ Stratification phenomenon in the pressurizer surge line and its influence on low cycle fatigue (I. Lopos, SK, et al.)
- ✓ Fatigue analyses as aids for the monitoring. Possibilities and limitations (S. Dittmar, GER, C. Hüttner et al.)
- ✓ **Cancelled:** Fatigue evaluation for the socket weld in nuclear power plants (H.D. Chung, KR, et al.)
- ✓ Fatigue monitoring and evaluation. Programmes and results for several German NPPs (W. Kohlpaintner, GER)

"A survey of current US nuclear plant fatigue issues" by Arthur F. Deardorff, Karen K. Fujikawa (Structural Integrity Associates) and John Carey (EPRI), USA.

The paper provided a summary of a survey aiming to determine current fatigue issues at operating plants in USA by summer 2004. The survey revealed an increasing trend in fatigue failures during a couple last years. Both BWR’s and PWR’s have experienced several fatigue failures since 2002. The survey confirmed that fatigue due to vibration is the major cause of piping system fatigue-related damage, especially for plants undergoing power upgrades. Mechanical vibration is currently the most common and flow induced vibration is the second fatigue issue at operating plants in USA. Fatigue of small bore piping is a typical
problem, but there are many components subjected to fatigue. The speaker addressed that the combined effects of adverse loadings and environmental effects might lead to more cracking than has been observed in the past. Furthermore, increased flow rates due to BWR upgrades might become a concern for reactor internals and component supports.

“Thermal fatigue in mixing areas. Status and justification of French assessment method” by Claude Faidy (EDF), France.

The major root cause of CIVAUX 1 incident of a leak in reactor heat removal system (RHRS) was identified as high cycle thermal fatigue in a mixing T-joint and a large program was launched to avoid similar problems in future. A large amount of analysis and experimental work has been performed. Aims and results of the parallel R&D programs were presented also in sessions 1 (general), 2a (thermohydraulics), 2b (component testing) and 3 (material testing). Fatigue curves and fatigue reduction factors for high cycle fatigue are being re-considered, but more importantly, full scale tests are used to assess behaviour of real components and a step by step procedure to screen and analyse T-joints with long duration at high ΔT between the mixed fluids has been developed. The paper introduced the procedure, the background of the methodology and summarised the R&D work that support this procedure. Essential features of the procedure are screening criteria for allowable ΔT, estimation of the usage factor and detailed analyses of usage factor and crack growth rate based on specific operating transients. The speaker addressed that assessments need to be based on realistic experiments and comprehensive procedures. International co-operation is needed to share expenses and experiences on R&D related to these generic problems.

“Stratification phenomenon in the pressurizer surge line and its influence on low cycle fatigue” by Ivan Lopoš, Miloslav Hrázský and Milan Mikuš (VUJE Inc.), Slovak Republic

The paper presented a practical case on monitoring and mitigation of thermal stratification in horizontal parts of a pressurizer surge line in Bohunice NPP. Vuje has developed procedures and software tools for periodic life-time monitoring to identify existing degradation potentials and to provide service life predictions for individual components and structures. Performed analyses led to replacing of a critical elbow section of the surge line and justification for the action was confirmed through metallurgical evaluation and fatigue tests for the replaced material. The speaker addressed the importance of monitoring temperature and other operational parameters, because the archived operation history can be used for decision making in future, and because loading due to stratification is impossible to predict quantitatively. Furthermore, experiments revealed strong influence of unit operation modification on stratification events appearing mainly during start-up and shut-down of unit.

“Fatigue analyses as aids for the monitoring, possibilities and limitations” by Christian Hüttner, (TUV München) and Siegfried Ditmar, (TUV Hamburg)

-Abstract- In the German federal republic in all LWR more or less extensive monitoring systems were installed. These allow recording occurring transients based on in service monitoring of measuring datas (pressure, temperature, mass flow) under inclusion of certain local temperature measurements at the surface of components and compare them with the transients based in the load catalogues and in the fatigue manuals used for the fatigue analyses. The accuracy of the fatigue usage factor of the checked component derived from these measured values depend considerably on the accuracy of the measurement, the consideration of factors influencing the fatigue behaviour (fluid, surface state, component size ...) and the accuracy of the stress analysis. The contribution aims at a critical valuation too to the point of view that frequently in fact occurred fatigue damages can not be verified by a
recalculation. For this purpose the effect of the consideration or non-consideration of different influencing factors and the effect of the scatter band of the material values used at the fatigue analyses, will be showed exemplarily. As consequences from these considerations possible measures are discussed.

„Fatigue Monitoring and Evaluation – Programmes and Results for Several German NPPs“ by Willi Kohlpaintner (E.ON Kernkraft, GER)

Abstract- Monitoring of stress/fatigue-relevant temperature loadings is a key issue in lifetime management of NPP-components. Consequently, normal plant instrumentation in German NPPs was extended with additional measurements at locations where relevant temperature loadings were expected. In order to show the field experience with thermal fatigue in German NPPs a survey of fatigue relevant components is given and the currently existing monitoring programmes for these components are presented. Programme results show that fatigue increments are well below one percent per year. As a main feature fatigue evaluation and monitoring based on operational loads, considering transient thermal stratification is demonstrated for a PWR surge line and a main feed water nozzle. The examples show that the programmes are working well and even components exerted to transient thermal stratification loads can be successfully monitored. Damages as a consequence of thermal fatigue were not observed.
A SURVEY OF CURRENT US NUCLEAR PLANT FATIGUE ISSUES

Arthur F. Deardorff/Karen K. Fujikawa
Structural Integrity Associates

John Carey
EPRI-USA

Efforts under the EPRI/Materials Reliability Project to date have concentrated mainly on thermal fatigue in non-isolable sections of piping attached to reactor coolant system piping. To gain a broader understanding of the complete range of fatigue issues in operating plants, a survey was conducted relative to all fatigue issues that are currently occurring. From this survey, it was confirmed that fatigue due to vibration is the major cause of piping system fatigue-related damage, especially for plants undergoing power uprate. In many cases, it has been very difficult to determine the source of the loadings that had led to vibration. This paper provides a summary of the results of the survey and provides an assessment of where additional research is needed.
THERMAL FATIGUE IN MIXING AREAS: STATUS AND JUSTIFICATION
OF FRENCH ASSESSMENT METHOD

Claude FAIDY – EDF-FR

Following the CIVAUX 1 incident of a leak on RHR system, EDF has developed a step by step
procedure to screen and analyse similar locations: mixing tees with long duration at high $\Delta T$
between the 2 fluids.
The paper present the status of the procedure, the background of the methodology and few R&D
work that support this procedure.
The procedure is based on:
- screening criteria on maximum $\Delta T$ and minimum duration
- screening criteria without any duration consideration, only $\Delta T$ and material
- a simplified and conservative estimation of a usage factor
- a detailed analysis of usage factor and crack growth rate, based on specific data collection of
  operating transients
Around that procedure, EDF launched an R&D program on fatigue curves and different fatigue
reduction factors; thermal fatigue test on structures and review the agreement of predictions with
French RHR system field experience.
The major results are included in the last edition of the French code RCC-M for future design.
The existing codes like ASME or KTA are not totally in agreement with our results from the
field.
All these points will be discussed in the paper.
STRATIFICATION PHENOMENON IN THE PRESSURIZER SURGE LINE AND ITS INFLUENCE ON LOW-CYCLE FATIGUE.

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The effect of thermal stratification was monitored in the horizontal portions of pressurizer surge line of the NPP Jaslovske Bohunice V2 for unit 3. Continual temperature measurements were aimed at obtaining quantitative assessment of influence the stratification phenomenon. Outputs from monitoring system were analysed and processed by means of the algorithm of the special developed program STRATIF. Results of this program represented characteristic inputs for computational analysis of assessment impact on remaining lifetime of surge line components due to stratification. Computational analysis was performed by means of computer code using numerical methods (FEM). Outputs from thermo-elastic calculation were used for performing fatigue analysis and results revealed areas the most subjected to fatigue - critical spots of pressurizer surge line. The maximum fatigue damage cumulation appeared in elbow 6. Due to calculated critical values of fatigue damage cumulation was realized stress-strain measurement. Realized analyses led to the suggestion to replace this critical section of surge line. Metallurgical assessments and fatigue test programs were performed on specimens from replaced elbow to assess remaining service life of existing structures. Based on the results of these analyses were carried out several experiments during transient and steady state operation of the unit. These experiments were aimed at modification of operation conditions responsible for stratification occurrence. The results from these experiments revealed influence of modification operation unit regimes on stratification events appeared during start-up and shut-down of unit.
FATIGUE ANALYSES AS AIDS FOR THE IN-SERVICE MONITORING. POSSIBILITIES AND LIMITATIONS

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In the Germany federal republic in all LWR more or less extensive monitoring systems were installed. These allow to record the occurring transients based on in service monitoring of measuring dates (pressure, temperature, mass flow) under inclusion of certain local temperature measurements at the surface of components and compare them with the transients based in the load catalogues and in the fatigue manuals used for the fatigue analyses. The accuracy of the fatigue usage factor of the checked component derived from these measured values depend considerably on the accuracy of the measurement, the consideration of factors influencing the fatigue behaviour (fluid, surface state, component size ...) and the accuracy of the stress analysis. The contribution aims at a critical valuation too to the point of view that frequently in fact occured fatigue damages can not be verified by a recalculation. For this purpose the effect of the consideration or non-consideration of different influencing factors and the effect of the scatter band of the material values used at the fatigue analyses, will be showed exemplarily. As consequences from these considerations possible measures are discussed.
FATIGUE EVALUATION FOR THE SOCKET WELD IN NUCLEAR POWER PLANTS

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The operating experience showed that the fatigue is one of the major piping failure mechanisms in nuclear power plants (NPPs). The pressure and/or temperature loading transients, the vibration, and the mechanical cyclic loading during the plant operation may induce the fatigue failure in the nuclear piping. Recently, many fatigue piping failure occurred at the socket weld area have been widely reported. Many failure cases showed that the gap requirement between the pipe and fitting in the socket weld was not satisfied though the ASME Code Sec. III requires 1/16 inch gap in the socket weld. The ASME Code OM also limits the vibration level of the piping system, but some failure cases showed the limitation was not satisfied during the plant operation. In this paper, the fatigue behavior of the socket weld in the nuclear piping was estimated by using the three dimensional finite element method. The results are as follows. (1) The socket weld is susceptible to the vibration if the vibration levels exceed the requirement in the ASME Code OM. (2) The effect of the pressure or temperature transient load on the socket weld in NPPs is not significant because of the very low frequency of the transient during the plant lifetime operation. (3) ‘No gap’ is very risky to the socket weld integrity for the specific systems having the vibration condition to exceed the requirement in the ASME OM Code and/or the transient loading condition. (4) The reduction of the weld leg size from 1.09*t₁ to 0.75*t₁ can affect severely on the socket weld integrity.
FATIGUE MONITORING AND EVALUATION, PROGRAMMES AND RESULTS FOR SEVERAL GERMAN NPPs

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Monitoring of stress/fatigue-relevant temperature loadings is a key issue in lifetime management of NPP-components. Consequently, normal plant instrumentation in German NPPs' was extended with additional measurements at locations where relevant temperature loadings were expected. In order to show the field experience with thermal fatigue in German NPPs' a survey of fatigue relevant components is given and the currently existing monitoring programmes for these components are presented. As a main feature fatigue evaluation and monitoring based on operational loads, considering transient thermal stratification is demonstrated for a PWR surge line and a main feedwater nozzle. The examples show that the programmes are working well and even components exerted to transient thermal stratification loads can be successfully monitored. Damages as a consequence of thermal fatigue were not observed.
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