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THERMAL FATIGUE OF REACTOR COMPONENTS IN OECD-NEA MEMBER COUNTRIES: A THREE FOLD PROGRAM TO ENHANCE COOPERATION

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ABSTRACT

The OECD Nuclear Energy Agency has 28 Member countries. Under the auspices of the Nuclear Safety Division are two senior committees dealing with regulatory aspects (CNRA) and technological aspects (CSNI). Under these two committees activities relevant to thermal fatigue in LWR piping are carried out under the two Working Groups (WG's): WG on Operating Experience, WG on Integrity of Components and Structures. There is also co-operation with the former task group on thermal hydraulics application. These groups make recommendations to the senior committees.

WG on Operating Experience is mainly concerned with the analysis of safety significant incidents, but it undertakes special studies as well. WG on Integrity of Components and Structures (Integrity and Ageing, IAGE) has activities in fracture mechanics, Non-Destructive Examination and material degradation, as being the three aspects of structural integrity for metal reactor components. It also has sub-groups dealing with the ageing of concrete structures and the seismic behavior of structures. In the area of thermal fatigue, it currently has a three-fold program of work approved by CSNI:

1. A questionnaire completed by Member countries with the objective to find out how widespread a problem thermal fatigue is, to learn what kind of countermeasures have been taken by countries and to obtain a detailed view of countries' actions and regulations, if any, and to identify adequate corrective actions;
2. A benchmark to establish capabilities in thermal fatigue calculation supported by specific tests performed by CEA, France;

3. An active program of information exchange between experts worldwide through a biennial Conference on Fatigue of Reactors Components in association with the EPRI and the USNRC.

This paper provides background on the Agency itself, while focusing on the thermal fatigue activities within NEA carried out mainly through the Committee on the Safety of Nuclear Installations and the groups of technical experts on operating experience, structural integrity, and thermal hydraulic. It presents recent accomplishments in each fold on the program and provides areas where efforts should be pursued.

Keywords: Thermal fatigue, questionnaire, benchmarking, conference

1 INTRODUCTION

Thermal cycling is widespread and recurring problems in nuclear power plants worldwide. Several incidents with leakage of primary water inside the containment challenged the integrity of the primary system of nuclear power plants although no release outside of containment occurred. Some complex thermal loads are not taken into account at the design stage of some operating plants (i.e. stratification, mixing). Regulatory bodies, utilities and researchers have to address them for operating plants and design of future plants. There are complex phenomena that involve and link thermal hydraulic, fracture mechanic, materials and plant operation.

In 2002, the Committee on the Safety of Nuclear Installations (CSNI) requested the working group on the integrity of reactor components and structures (IAGE WG) to prepare a program of work on thermal cycling to provide information to NEA member countries on operational experience, regulatory policies, countermeasures in place, current status of research and development, and to identify areas where research is needed both at national and international levels.

Thermal cycling is connected either to operating transients (low cycle fatigue) or to complex phenomenon like stratification, vortex and mixing (low and high cycle fatigue). The former is covered by existing rules and codes. The latter is partially addressed by national rules and constitutes the major effort needed.

The working group proposed a 3 fold program that covered:

1. Review of operating experience, regulatory framework, countermeasures and current research;
2. Benchmark to assess calculation capabilities in NEA member countries for crack initiation and propagation under a cyclic thermal loading, and ultimately to develop screening criteria to identify susceptible components; results of the benchmark is published in 2005 [1];
3. Organization with the EPRI and the USNRC of the international conference on fatigue of reactor components. This conference reviews progress in the areas and provides a forum for discussion and exchange of information between high level experts. The conference is held every other year to follow the progress and to direct research to key aspects. The last edition was held on October 3-6, 2004 [2,3,4]

In addition a large number of NEA member countries are participating in the OECD Piping Failure Data Exchange Project (OPDE) to collect field experience on piping degradation [5,6,7]

2 PART 1: REVIEW OF THE OPERATING EXPERIENCE

The current part covers the first bullet of the program. The IAGE WG prepared a questionnaire that was completed by NEA member countries in 2002-2003. This questionnaire addressed:

- Regulatory requirements and codes;
- Practical experience and incidents;
- Countermeasures related to stratification and mixing;
- Research on thermal fatigue;
- Low versus High cycle fatigue curves.

The questionnaire addressed several plant designs and is limited to pressure retaining components in safety-class systems. A synthesis of the answers is provided hereafter, and more precisely in the report [B].

2.1 Thermal cycling phenomenon

Complex thermal cycling phenomena are mainly connected to stratification, vortex penetration in tees, dead legs, or valve, mixing tees:

- Two fluids at different temperatures stratifying in a pipe cause temperature non-linearity at the interface. This non-linearity induces deformation and important bending stresses in the pipe. In addition flow conditions can create displacement of the interface that can be superposed to fluctuations of great amplitude. All are leading to thermal cycling damages.

- As opposed to the relatively low number of cycles in thermal stratification, fatigue in vortex and mixing areas is more of a high cycle fatigue nature. It occurs in pipes where flows at different temperature and different flow rate ratio mix in a turbulent manner. Local or global temperature fields resulting from this turbulent mixing lead to stresses that may cause fatigue damages.

Both problems are complex and involve expertise in the following fields which has their own specificities and limits:

- Thermal hydraulic with regard to thermal loading (turbulent mixing or stratification);
- Mechanical expertise with regard to calculation of structure response to complex thermal loading on the inner surface including fracture mechanic;
- Material science with regard to material strengths and fatigue resistance.

These thermal loads are difficult to predict and quantify at the design stage. Degradations observed in nuclear power plants are mainly elephant-skin type of damage and in few occurrences through wall cracks. Phenomena leading to the degradation are now understood. Operating condition and design changes may greatly reduce the frequency of degradation. However, in some cases changes are not possible and strategies must be in place accounting for large uncertainties in parameters controlling initiation, propagation and kinetic. Definition of screening criteria is then needed and efforts should be pursued.

2.2 Regulatory requirements and Codes

In all countries fatigue has to be considered at the design stage and during operation.

For complex thermal loads, no specific regulatory requirements at the initial design stage (before 1988) were implemented. Codes used at this time (e.g. US ASME III, Soviet PNAE codes, French RCCM, German KTA) did not specifically mention these loads.

After 1988, some countries have issued specific regulatory requirements (e.g. USNRC Bulletins 88-08 and 88-11, YVL 3.5 in Finland) and in two cases, the regulation was amended in 2001 (Japan and France) along with respective codes.

Many countries have developed their own in-service inspection codes (e.g. USA ASME section XI, France RSEM, Soviet PK-15-14, Japan JEAC4205, Canada CSA/CAN-N285.4, Sweden SKIFS1994:1)

2.3 Operating experience and incidents

An extensive and educative list of incidents along with root causes analysis is available [B] covering BWR, PWR, VVER and CANDU reactors.

The three thermal load types have affected some BWRs to different extents. The main locations concerned are: Feedwater system piping (i.e. nozzles and spargers), Control Rod Drive return nozzles, Reactor Coolant System, Residual Heat Removal System, Reactor Water Clean-up system, Auxiliary Feedwater System and Pressure Relief System.

PWRs were also affected to different extents. The main locations concerned are: Feedwater system piping, Pressurizer surge lines, Emergency Core Cooling System injection line (leaking valves), Residual Heat Removal Piping in mixing tees, Discharge line (Dead leg), Reactor Coolant System sampling line, Make-up/High Pressure Injection nozzle, Drain lines, Reactor Coolant Pump thermal barriers and Valves (inner surface).

2.4 Countermeasures

Countermeasures are obviously linked to root causes. For stratification, new design of piping system including new thermal sleeves along with modified operating conditions was implemented. In some cases potential degradation areas have been protected by a liner and/or helical shaped devices were installed (PWR Feedwater system).

For dead legs and vortex, major concern is the leak tightness of valve. Countermeasures used are either optimization of the in service valve leak test procedure or leak collection monitoring.

For mixing tees, countermeasures consist mainly in decreasing of the amplitude of temperature difference, and/or the duration at large ⊗T by changing operating procedures. A mixing device is installed in some cases. Component replacement with more fatigue resistant component (e.g. material, surface finish, thickness variation, weld locations) is performed.

In all countries, a specific in-service inspection program is implemented. Monitoring devices have also been considered and installed in few countries. Training of operators (both plant and ISI operators) is also an important aspect to increase awareness of thermal cycling issues at the plants.

2.5 Economic impact

In overall forced outages typically consume a little more than five percent of total power availability, but losses associated with forced outages can represent as much as 30 to 40 percent of annual profits. Degradations due to thermal cycling have resulted in forced outages or in extension of outage from few days to several months. Definition of the repair and repair time, root cause analysis, life evaluation of replaced components, modification and validation of operating conditions are the main contributors.

2.6 Research programs

In the past R&D projects mainly addressed low cycle thermal cycling: stratification in piping system and fatigue of components like pumps, valves or components with thickness variations. In this frame, various types of materials and geometrical configurations were analyzed either through analysis or experimentation. Number of guidelines was published to optimize operating management, flaw detection by non-destructive examination for stratification, and changes in inner surface shape of valves.

Very little work was performed on high cycle thermal cycling in mixing areas as it was supposed to mainly concern fast breeder reactors sensitive to this type of load.

Currently few works are ongoing on stratification and major programs are now devoted to thermal cycling in mixing areas and vortex in dead legs. Three major disciplines are involved in these programs:

- First discipline is the thermo hydraulic experimentation and calculation. This area is developed because of the difficulty to understand the real thermal load applied to the inner surface of the structure. Thus, number of geometrical or flow configurations are studied to try to derive generic parameters, screening values or recommendations. This work is supported by the recent models and numerical capability development (CFD calculation on large capability computers).
- The second is the thermo mechanical component testing and calculation. The objective of these studies is to reproduce, in laboratory, a load equivalent to a thermal cycling load in mixing area on analytical mock-ups. Two main difficulties are then encountered: reaching a high number of cycles (corresponding to a mixing area) and having a good knowledge of the real imposed loading (this last point has in general to be determined by finite element calculation). At the end, the final goal of these studies is to apply the fatigue evaluation procedures and criteria to validate or not applications on a configuration as close as possible to a reactor case.
- The third is the material study in which effects of temperature, surface finish, mean stresses or environment on fatigue resistance constitute the most important part of the work performed. In this field, low and high cycle fatigue is investigated, but the main difficulty is on the determination of the material endurance limit (high cycle fatigue) under applied strain.

There are basically three poles of research: USA, Europe and Japan. These programs are merged into integrated projects. As said before, this aspect is mainly due to the multi disciplinary aspect of high cycle thermal fatigue. In parallel of this R&D effort, programs are continuing to propose or improve thermal cycling management (in stratification or mixing zones) or general fatigue assessment procedures.

For the future, because stratification is correctly understood, major R&D needs for the future are mainly dealing with the mixing and vortex issues. Following main needs are mentioned by experts:

- Definition of screening values in terms of simple parameters such as the difference of fluid temperature or stresses. Theses screening values have to cover a large number of geometrical, flow velocity or temperature range to be applicable to the industrial case and constitute the first step to improve thermal cycling management. Screening criteria can be determined by thermo hydraulic experiments or CFD calculations with parametric studies. However in each case improvements are still needed in transfer from mock-up to reactor case and CFD models.
- In mechanical field, needs concern guidelines to account for complex loading like random biaxial loads, with or without mean stresses or strains. In addition, fracture mechanics thresholds need to be improved so that they could be included in fracture assessment procedures and help to predict large crack growth.

- On material aspects, fatigue curves need improvements to take into account surface finish, mean stresses, residual stresses, welds, environments, stress biaxiality, random loads… In this regard, high cycle fatigue under imposed strain is the key research topic. A major question is still under discussion: do we need to modify our fatigue curves?

On the stratification problem, expressed needs are mainly focused on thermal cycling management and more precisely on damage evaluation by measuring temperatures on piping systems or feed water nozzles.

2.7 Synthesis of the first part

The following main conclusions are resulting from the first part:

- Thermal cycling degradations have the potential to be an important safety and economical issues. It strongly affects aging management program of safety components.
- Various incidents occurred in different systems and countries. However only few leaks have been observed and there was no release outside the containment.
- Analysis carried out showed three loading modes connected to thermal cycling: (a) stratification; (b) dead legs and vortex; (c) mixing tees.
- Screening criteria and guidelines development are now proposed to review potential locations. In-service inspection programs have been modified to integrate monitoring and valve leak tests. In addition, design changes have been implemented in different systems.
- Nevertheless large uncertainties remain on quantitative damage estimation. An important R&D effort must be pursued to confirm screening criteria values and to decrease uncertainties with the objective to optimize maintenance action.

3 PART 2: BENCHMARK STUDY ON THE THERMAL FATIGUE PROBLEM

The benchmark was focused on mixing problems in which, for high flow rate and extensive discontinuities, the mixture becomes turbulent and a wide range of turbulence frequencies and thermal fluctuations are encountered. The consequence for structures is multiple or isolated cracks which, in some cases, may not be very deep but which in others can cause perforation of the structure.

A highly complicated issue is why some configurations have more capability than others to withstand thermal stresses and why multiple cracks should occur in some places and isolated cracks in others. Many test results are available and R&D programs are currently being carried out to supplement them.

CEA believes that this lack of knowledge can be attributed to the fact that the 3D aspect of thermal loading is becoming predominant for certain flow configurations. These overall thermal loads result in complex 3D mechanical loads involving the entire thickness of a component. As a general rule, very little is known about the thermo hydraulic and thermo mechanical aspects of these loads when they occur in complex structures such as mixing tees. This is why the CEA decided to launch an R&D program designed to provide further information on thermal loading. The program is intended to clarify and illustrate the problem of overall thermal loading and to suggest tools that would enable it to be taken into account at the design stage. It includes both laboratory experiments and numerical analyses involving applied loads.

However, given the complexity of the problem, it soon became clear that discussions with external partners should be required to compare know-how and points of view. Therefore a benchmark study has been launched. Preparations for the study began in 2001 under the guidance of the OECD/NEA/CSNI.

3.1 Benchmark organization

The benchmark was organized on the basis of the CEA/FAT3D experiment. However, because the test was still at a design level when it started, it was proposed to the OECD/NEA/CSNI/IAGE working group members to participate in the test definition. The proposed experimental approach was the following, divided in a two and a half year effort:

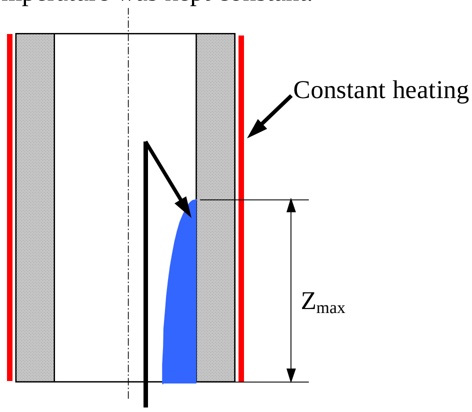
- Preliminary calculations: the aim of this stage is to determine the experimental possibilities of the test apparatus and establish the temperatures and cycle durations to be used etc. This is the first stage of the benchmark study (all participants)

- Characterization of the thermal loading: knowledge of the thermal loading imposed on the structure is a very important aspect of the problem. It is therefore determined accurately using a thermal mock-up provided with temperature measurements on the surface and through the thickness (CEA).
- Precise pre test analysis. The aim of this stage is to predict cracking of the specimen with a known thermal load. This is the second stage of the benchmark study for validating the various methods (all).
- The thermo mechanical test takes place concurrently with this calculation stage. The tests results will not be sent to the participants during the calculation stage (CEA)
- Comparison of results: the results obtained by all the participants are collected and compared with the test results and discussed at a meeting of OECD work group IAGE. The aim of the discussion will be to highlight the strong points and shortcomings of the various approaches and to broach the subject of a rule for taking the issue into account (all).

3.2 Test description: the FAT3D experiment

The first main objective of the FAT3D test was that it should be easy to carry out (without any thermo hydraulic loop) and easy to simulate with a numerical model. The second was to obtain 3D thermal loading. Thus, the choice was made to design a test on a pipe cooled locally by cyclic water injection:

- Cold water is injected into the pipe locally in cycles (Figure 1). During the first step, the cold water injection point is always the same.
- The pipe is placed inside a furnace to maintain a high temperature on the outer surface of the pipe. The air temperature was kept constant.



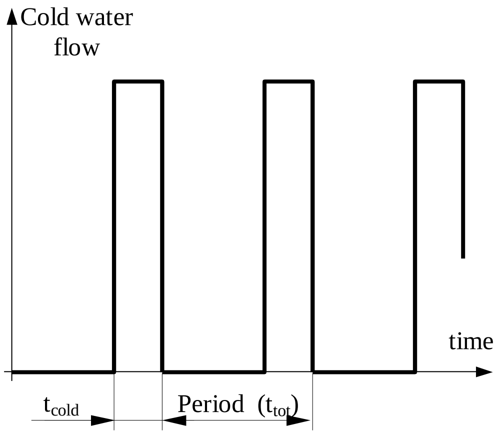


Figure 1 - Principle of the FAT3D test

This test was named FAT3D. The main advantages of this configuration are as follows:

- The chosen geometry is simple in terms of numerical interpretation of the test. The main difficulty is the description of the thermal load. But thanks to its simplicity in space and also to the possibility of measuring it accurately on the surface and through the thickness of the pipe, it seems to be possible to reproduce it by a simple numerical model.
- The thermal load is 3D. The resultant loading is a combination between a local load (which is induced by local thermal transients in the thickness) and an overall load (which is created by the overall transient from one side of the pipe to the other).
- The test is easy to carry out and seems to be reproducible. The main parameters which govern the load imposed on the pipe are as follows:
  - The high temperature imposed by the furnace.
  - The degree of local cooling, imposed by the cold temperature, the flow of cold water, the shape and angle of the water jet.
  - The frequency of the cyclic cooling and the ratio between cold time (tcold - water injection) and hot time (thot - no water injection).

The material data given for the benchmark study are taken mainly from the Appendix A3.3S and A16 of the RCC-MR [8]. More details of the material characteristics are given in the specification [9].

3.3 Thermal loading description

During the test design, a precise thermal loading qualification and optimization was performed on the following pipe geometry: Thickness of the pipe: t = 6.7 mm, External diameter: De = 166 mm, Length of the pipe : L = 360 mm. This thermal qualification was launched on a specific mock up containing thermocouples through the thickness of the pipe. The measurements performed during the thermal test concern the temperature evolution during the stabilized cycle for 19 thermocouples. All thermal data were given to the participants in [10] for the analysis

Finally, the optimized cycle was defined by:

- Water temperature : Tcold ~ 17 – 20°C
- Furnace temperature : Thot = 650°C
- Total cycle duration : ttot = tcold + thot = 190 s
- Water injection time : tcold = 15 s

Figures 2 shows an example of temperature variation with time observed were the water injection point, on the inner and outer surface of the pipe.

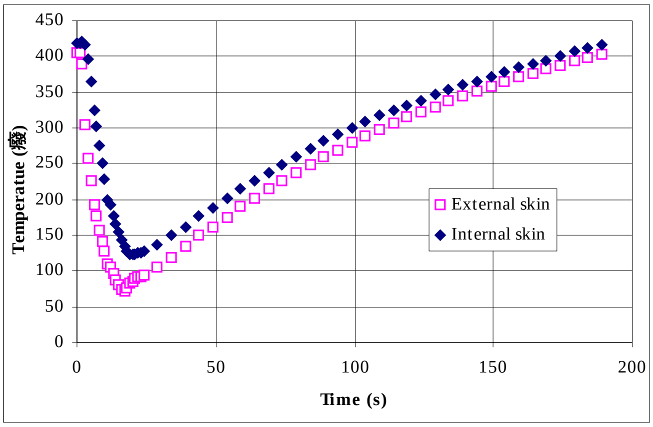


Figure 2: Temperature evolution at the water injection point

The following mechanical boundary conditions are adopted during the test:

- The section at the top of the pipe is supposed to be embedded.
- The section at the bottom of the pipe (where water goes out from the pipe) is free.

3.4 Main results and conclusions from the pre test analysis (first analysis step)

Four contributions (including the CEA one) were received for this first step, including global 3D thermo mechanical analysis and 1D analytical estimations. Participants are:

- JNC – JOYO – CRC (Japan) which propose an analytical approach called “cold spot approach” which allows taking into account structural effects in 1D thermal approach.
- Vamet (Czech Republic), DNV (Sweden) and CEA (France) which propose a complete 3D massive thermo mechanical analysis.

All contributions received concern either crack initiation and crack propagation analysis. The details of Japan, Vamet, DNV and CEA were given in [10]. Main results obtained from the analysis are the following:

- From 3D calculations and for the given thermal conditions in the first step for the pre test analysis, stress level is not important enough to reach crack initiation in a reasonable time on the inner surface.
- 1D analysis found a significantly higher loading. This is mainly due to the difficulty to take into account the strong heat transfer coefficient variation with time on the inner surface (difference between water an air exchange at different time during the cycle). However, if structural effects are not taken into account in thermal and mechanical effects, 1D approach should lead to non conservative estimations.
- With the given conditions and because of the high level of “structural stresses”, it is shown that the test is more appropriate for fatigue crack propagation than for crack initiation: time to reach 80 % of the thickness was found to be 70 days to 15 months.

- It may be interesting to reduce the thickness of the mock up to increase structural effects and then accelerate damage.
- 3D thermo mechanical F.E. calculations are time consuming and difficult to fit with experiments because of the model size and because approximately 20 complete cycles are needed to stabilize the thermal field in the pipe. As a consequence, it is difficult to optimize the thermal conditions by precise calculation and experimental optimization has to be performed before the beginning of the thermo mechanical test.

3.5 Main results and conclusions from the blind test analysis

For this second analysis step, six participants have proposed a contribution to the benchmark:

- Three from Japan: JNC, CRIEPI and INSS.
- Two from France: CEA and EdF.
- One from DNV (Sweden).

As a consequence of the conclusions of previous step, all these contributions are based on complete 3D thermo mechanical models. However, JNC proposes a 1D thermal pre analysis to limit the 3D parametric study for physical parameter determination.

First step of the work concerns calibration of thermal models. At this level, the need is to fit the physical parameter of the problem. The objective is to reproduce the temperature evolution measured during the thermal qualification of the test and sent to the participants. This step constitutes the major difficulty of the benchmark. Three different kind of parametric study are proposed. They are presented in detail in the synthesis report of the benchmark [1]

In second step of the analysis, using the fitted cyclic thermal evolution, all participants propose a stress determination by a 3D massive elastic F.E. model. In all cases, maximum stress range is observed close to water injection point, for Z = 210 mm, in the circumferential direction. Then a relevant stress level has to be proposed by the participants:

- For each contribution, the relevant stress in an equivalent stress range (Von-Mises).
- The stress ranges calculated by JNC and CEA are higher than the stress ranges proposed by CRIEPI and INSS. This observation is certainly linked to the conduction coefficient two times lower for these two calculations. This parameter has a strong influence on the through thickness thermal transient and thus on the bending stress in the pipe.
- Stress level calculated by CEA is higher than the one calculated by JNC. We think this is due to the heat exchange coefficient, higher for CEA.
- Stress level calculated by DNV is intermediate between JNC and CEA calculation. This also may be due to the higher values of Hwater and Hair employed in the calculation.

In summary, this comparison shows that both the heat exchange coefficient and the conduction coefficient are important on the stress level. Thus, a good knowledge of the temperature with time and through the thickness is needed to have a precise determination of these physical parameters.

Then, to estimate the number of cycles to crack initiation, a relevant strain range is deduced from the equivalent stress range. The number of cycle to crack initiation is then deduced from the fatigue curve ($\Delta\varepsilon$ – Nr) of the material. To determine this relevant strain range, three types of corrections are proposed:

- JNC and CRIEPI propose to deduce an elastic-plastic strain range from the elastic strain range ($\Delta\sigma_{eq}/E$) with an elastic follow up factor.
- CEA use the same kind of approach: the elastic plastic strain range is deduced from the elastic one by a codified parameter K_ν [8]. In our loading configuration, $K_\nu \approx 1.3$.
- DNV proposes a direct calculation of the equivalent strain range, assuming a plastic amplification is and incompressibility. This formulation is equivalent to the one proposed by CEA for the effective Poisson's ratio $\nu' = 0.5$ (value adopted by DNV). Plastic amplification obtained is closed to 1.25.
- INSS proposes a different approach: the relevant stress range is firstly modified in a Goodman diagram (assuming R = 0). This stress, converted in strain, is then used in the fatigue curve of the material.

For each participant, the crack appearance was predicted for the given test duration. Then, an estimation of the crack propagation is proposed. Due to the higher level of stresses in the circumferential direction, each participant estimate that multiple cracking will occur in the longitudinal direction, at the bottom of the cooling area. However, at this step for crack propagation estimation, a main question appears: what are the dimensions of the initial crack? Different assumptions where adopted to answer this question.

The number of cycles to reach penetration of the pipe thickness is ranking between 1400 and 11000 cycle, depending on the assumption on the initial crack and the calculated loading level. From these results, one can conclude that the propagation rate is important and the number of cycle to penetrate the pipe is small in comparison to the number of cycles to initiate a crack (approximately 10%) for the particular loading proposed in the benchmark.

3.6 Test observation

The test in support of the benchmark was conducted in parallel of the blind analyses. The objective was to compare, in fine, the participant predictions to the experimental results. However, due to a movement of the cooling pipe inside the mock-up the thermal loading became more severe after approximately 1000 cycles.

As a consequence, it is difficult to compare quantitatively the predictions and the experimental results. A qualitative comparison on the crack location, orientation or propagation rate can however be made because the thermal loading shape is similar.

A view to the internal and external surfaces of the mock up is shown on figure 3. It can be seen:

- An important number of cracks appear on the internal surface. They are located at the bottom of surface cooled by cold water injection.
- The most important crack, in the symmetry plane of the pipe, penetrates all the thickness of the mock up. This crack is approximately 50 mm long on the inner surface and 37 mm on the outer surface.
- The first cracking was observed on the inner surface after 12000 cycles (visual observations). The main crack penetrates after a total of 17500 cycles.
- The observation of the crack surface (figure 4) shows that the crack shape can be approximate by a semi elliptical crack front. The striation shows that the crack propagation is a pure fatigue propagation process.

Figure 3: Crack location on the mock up: internal (left) and external surfaces (right)

Figure 4: Crack surface observation

3.7 Conclusions of the benchmark

The benchmark proposed in the frame of the OECD/NEA/CSNI/IAGE working group is now at its synthesis step. Organized in three major steps, it allowed defining, realizing and analyzing an example of fatigue crack initiation and propagation under pure thermal loading in which important cracking, until penetration, was observed.

Due to a movement of the cooling pipe at the beginning of the test, the thermal loading was more severe than the loading characterized with the thermal mock-up. Thus, it is difficult to compare quantitatively the prediction of the participants with the experiment. However, a qualitative comparison shows that predictions are in good agreement with the test:

- The location and the orientation of the cracks were predicted by the participants: due to the circumferential stresses, axial cracks are dominant, at the bottom of the cooling area.
- The capability of the cracks to propagate through the thickness was predicted and, for all participants, the number of cycles to penetrate the pipe thickness is small in comparison to the number of cycles for initiation. This was observed during the test with 12000 cycles to initiate a crack and 17500 for the complete penetration.

A synthesis report with contributions from all participating organizations is to be published by the OECD/NEA working group [11]

4 PART 3: CONFERENCE ON FATIGUE OF REACTOR COMPONENTS

An active program of exchange information between experts was organized in association with EPRI and USNRC in the frame of an international conference. This conference was held in October 2004 in Sevilla (Spain)

[4] and has contained technical sessions and panel discussions. Main conclusions focused on the thermal fatigue problem are presented in this part. In complement, more detail can be found in [4].

4.1 SESSION 1: General program overview

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

- France is focused on mixing stainless steel tees on the major aspect of residual life evaluation procedure : complementary structure tests are needed, environmental effects for stainless steel 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. 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.

4.2 SESSION 2a: Load determination in thermal fatigue

Thermal load determination, in particular for the thermal mixing case, remains a key issue for future detailed evaluation. Several simulations has been presented using RANS and LES calculation process in MIT (USA), CEA (France), FRAMATOME ANP (Germany), VTT (Finland). Most of them tried to reproduce mock-up results. Form the presentations and the discussions, it appeared that:

- Boundary conditions are very important: upstream elbows or pumps…
- Low and high frequency loads have to be considered.
- To-day, only few seconds can be simulated by precise LES models, compare to 10 or 100 seconds needed.
- Heat exchange coefficient with water is 2 to 3 times the Dittus-Boelter value.

A lot of work has been done on thermal load evaluation. Nevertheless all parameters (e.g. heat exchange coefficient) are not yet fully assessed.

4.3 SESSION 2b: Laboratory experiments for thermal fatigue

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 in the case of thermal loading. From the tests presented, all are low cycle fatigue tests (only some of them reach 10^6 cycles), all are cold water jet and no information is available on water chemistry, all are constant amplitude tests (no variable amplitude test). It still remains difficult to reach high cycle fatigue with such apparatus because loading frequencies are too low.

By now, the number of available thermal fatigue data on structures is still reduced and no link with environmental effect is encountered (even if tests are performed with water).

Additionally, 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.

4.4 SESSION 4: Codes, rules and guidelines

The papers presented in this session deals with codes and guidelines in Japan, USA and Germany:

- In Japan, an important effort is made on the environmental effect and thermal fatigue problems. Two guidelines on these two subjects are under development.
- In US side, effort is made to provide guidelines for evaluation, mitigation, monitoring and non destructive examination. Major concern is on the stratification and the vortex due to a valve leakage.
- In German side, the effort is focused on the monitoring in the stratification and thermal stripping configurations. In particular, developments are performed to increase the quality of thermal stresses calculation.

4.5 SESSION 5: Engineering Consideration/Industrial applications

The session has consisted in five presentations dealing with recent fatigue events in USA, the French approach on the mixing areas and the fatigue monitoring in plan operation:

- Fatigue issues at operating plants in USA revealed an increasing trend in fatigue failure. The survey confirmed that both BWR and PWR are concerned and that fatigue due to vibration is the major cause of piping system damage.
- The French program devoted to mixing areas is following the CIVAUX 1 incident. A large program containing thermo hydraulics, component and material testing to avoid similar problems in future was detailed in the presentation.
- Fatigue monitoring presentations concern stratification in horizontal parts, thermal transient recording and stress analysis. A survey of the fatigue relevant components in Germany was presented.

4.6 PANEL DISCUSSION ON THERMAL FATIGUE

This panel discussion was organized to conclude technical sessions on the particular problem of thermal fatigue. The following conclusions were discussed:

- 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? The question is still suspended!
- 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 rooms 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 stainless steel in PWR environment, load / strain control tests, surface finish effects, mean stress and environmental 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 small 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.
- 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….
- 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.
- 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.

4.7 General consideration and synthesis of the part 3

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.

Concerning fatigue due to vortex or leaks at valves, the thermal fatigue mechanism is globally 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. The problem still remains difficult for mixing areas.

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

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

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

- 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 must be clearly documented.

5 CONCLUSIONS

The three fold program addressed the status in OECD-NEA Member countries, a benchmark to review capabilities in NEA member countries to model thermal fatigue loading with a view to improve the modeling and identified areas where more work is needed, and a cooperation with major utilities through the EPRI to complement these tasks and assess progress in research on a regular basis.

The conclusions of this program are currently used by the members of the OECD-NEA committees to better assess their facilities and focus their efforts on key issues for the safety of nuclear installations.

6 REFERENCES

[1] NEA/CSNI/R2005(2) OECD-NEA Benchmark on Thermal cycling (to be published in 2005)

[2] NEA/CSNI/R(2000)24 Proceedings of the International Conference on Fatigue of Reactor Components, August 2000, Napa, California

[3] NEA/CSNI/R(2003)2 Proceedings of the EPRI/USNRC/OECD International Conference on Fatigue of Reactor Components July 2002 Snowbird, Utah

[4] NEA/CSNI/R(2004)21 3rd International Conference on Fatigue of Reactor Components- Seville, octobre 2004 (to be published in 2005)

[5] Piping service life experience in commercial nuclear power plants: progress with the OECD pipe failure data exchange project – Proc. ASME PVP2004, July 25-29, 2004, San Diego, California, USA

[6] A Framework for International Cooperation in Piping Reliability: OECD Pipe Failure Data Exchange Project: Proc. of 25th ESReDA Seminar, Paris, France, Nov. 2003

[7] OECD pipe failure data exchange project (OPDE) – 2003 status report. Proc. ICONE-12, April 25-29, 2004, Arlington, Virginia, USA

[8] RCC-MR – Design and construction rules for mechanical components of FBR nuclear islands. Edition 2002 (AFCEN)

[9] S. Chapuliot and T. Payen: Benchmark proposal on thermal fatigue problem – final proposition. OECD/NEA/CSNI, January 2002

[10] S. Chapuliot and T. Payen: Benchmark proposal on thermal fatigue problem – second step proposal. OECD/NEA/CSNI, April 2003

[11] NEA/CSNI – Thermal Cycling in LWR components in OECD member countries (to be published in 2005)