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Thermal Fatigue Evaluation of Piping System T Connections

(THERFAT)

Editors: Klaus Metzner and Ulrich Wilke, E.ON Kernkraft (DE)

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Project coordinator

U. Wilke, E.ON Kernkraft, Germany

Project partners

1. EON	E.ON Kernkraft, Germany
2. EDF	Électricité de France, Service études, Projets thermiques/nucleaires, France
3. CEA	Commissariat à l'énergie atomique, France
4. FANP-F	Framatome France, France
5. TEC	Tecnatom, Spain
6. FHG	Fraunhofer Institut für Werkstoffmechanik, Germany
7. VTT	Technical Research Centre of Finland, Finland
8. FANP-D	Framatome Germany, Germany
9. MPA	Staatliche Materialprüfanstalt Stuttgart, Germany
10. JRC-IE	Joint Research Centre (of the EC), Institute for Energy, the Netherlands
11. FNS	Fortum Nuclear Services, Finland
12. SPG	Siempelkamp Prüf- und Gutachtergesellschaft, Germany
13. CINAR	Cinar Ltd, UK
14. VUJE	VÚJE Trnava, Slovakia
15. ENDESA	ENDESA Generación, Spain
16. JSI	Jožef Stefan Institute, Slovenia

Contents

List of abbreviations and symbols

CFD	computational fluid dynamics
FE	finite element (e.g. FE analysis)
ISI	in-service inspection
LES	large eddy simulation
NDT	non-destructive testing
NESC	network for evaluation of structures and components
NPP	nuclear power plant
PWR	pressurised-water reactor
TOFD	time-of-flight diffraction – ultrasonic technique
WP	work package

Executive summary

Thermal fatigue is one significant long-term degradation mechanism in nuclear power plants (NPPs), in particular as operating plants become older and lifetime extension activities have been initiated. In general, the common thermal fatigue issues are understood and controlled by plant instrumentation systems. However, incidents in some plants indicate that certain piping system Ts are susceptible to turbulent temperature mixing effects that cannot be adequately monitored by common thermocouple instrumentation. The THERFAT project has been initiated to advance the accuracy and reliability of thermal fatigue load determination and to outline a science-based but still practical methodology for managing thermal fatigue risks in T connections susceptible to high cyclic temperature fluctuations. The THERFAT work in the installed work packages (WP) focuses on the following technological aims:

- Screening of existing plant and R & D data (WP 1),
- Assessing the fatigue significance of turbulent thermal mixing effects in piping system T connections and identifying the fatigue-significant parameter (WP 2),
- Quantifying the existing safety margins against failure by applying standard methods and advanced fatigue and fracture mechanics analysis routes and determination of fatigue-relevant threshold values (WP 3),
- Verification of selected aspects of fatigue assessment by experimental damage tests with cyclic thermal shock loads (WP 4),
- Proposition of a road map as part of a European methodology on thermal fatigue, considering the results of current and past activities (WP 5).

Based on the compilation of existing plant experiences, a selection of various T configurations susceptible to turbulent thermal mixing effects including the identification of the critical thermal fatigue aspects was established. In experimental tests the occurring loads were quantified in terms of significant temperature differences and load cycles. In assistance numerical CFD-code analyses have been carried out as benchmark tests for the various numerical methods and to compare the numerical results with the experimental test results (WP 2). The achieved results in the experimental damage tests of WP 4 investigating the load-bearing capability of components and selected aspects of fatigue assessments confirm the predicted tendencies of higher load-bearing capability than expected by application of common code analysis procedures. The WP 2 and WP 4 output has been used as WP 3 input to verify the different integrity evaluation procedures concerning the assessment of fatigue usage, crack initiation and crack propagation issues for components or specimen sustained to cyclic thermal loads. Non-fatigue-relevant threshold values of temperature differences have been defined. In WP 5 the structure of an integrity evaluation concept has been defined as part of the “development of a European methodology” on thermal fatigue underlining the required close interaction between the different technical disciplines (load determination, stress and fatigue analyses, supporting fracture-mechanics assessments, selection of high stressed locations for NDT measures). Technical results of the project improve the understanding of thermal fatigue issues for plant operation and safety.

Due to the many (16) partners involved in the project, a strict project management structure had to be installed (“working trains”) for an appropriate information exchange between the different work packages.

The THERFAT project as a shared-cost action has been carried out by the 16 partners (utilities, plant vendors/manufacturers, consultant engineers, research institutes) as part of the Fifth

Framework Programme of the European Atomic Energy Community (Euratom). It commenced in December 2001 and had a duration of 36 months.

A Objectives and scope

Thermal fatigue as long-term degradation mechanism is an important issue in nuclear power plant (NPP) ageing management considerations. The strong linkage of the phenomenon to actual plant conditions, rather than to conservative design assumptions, is a key aspect of ongoing safety assessments. The estimation of boundary conditions for integrity evaluations (load input and calculation methods) tends to rely on approximate methods. This may lead to inaccurate results, which is not acceptable for NPP applications. Several incidents in NPPs indicate that certain piping system T connections are susceptible to fatigue arising from low- and high-cycle temperature turbulences. In-service inspections reveal that thermal fatigue cracks may occur in welds and base material of straight pipes and elbows. These effects have been attributed to thermal temperature stratification and turbulent mixing effects caused by different mass flows in "run" and "branch" of pipes merging at the T (**Figure 1**).

The high-cycle turbulence effects are not appropriately detectable by common thermocouple instrumentation. Hence, the THERFAT project addresses the present lack of verified working procedures for assessing the integrity and safety of T configurations in safety-relevant NPP systems subject to turbulent thermal mixing effects. The THERFAT work programme comprises the following tasks (see **Figure 2**):

- Collation and assessment of field experience by screening of existing plant and R & D data (**WP 1**),
- Load determination by experimental tests and computational fluid dynamic analyses to assess the turbulent thermal mixing effects in piping system T connections and to identify the fatigue-significant parameter (**WP 2**),
- Integrity evaluation to quantify the existing safety margins against failure by standard methods and advanced fatigue and fracture mechanics analysis routes and to determine non-fatigue-relevant threshold values (**WP 3**),
- Experimental damage tests with cyclic thermal shock loads to verify selected aspects of fatigue assessments (**WP 4**),
- Proposition of a road map as part of a European methodology on thermal fatigue (**WP 5**).

The THERFAT project has been carried out as part of the Fifth Framework Programme of the European Atomic Energy Community (Euratom). The THERFAT contract was signed in November 2001. The project commenced in December 2001 with a duration of 36 months, till November 2004.

THERFAT has been performed by a consortium of 16 organisations from 8 European countries (**Figure 3**), all recognised leaders in their technical fields. The THERFAT consortium combines the expertise of large utilities, plant vendors/manufacturers and several of Europe's foremost providers of structural integrity service and targeted R & D. Participation helps them to maintain and enhance their competitiveness in this field and support the continued viability of nuclear power generation. The partner JRC-IE supplies technical expertise as well as the link to the NESC and related important EC activities. Due to the large number of partners in the THERFAT project (12 original THERFAT partners, three additional partners of the originally intended ADVISE project and the NAS extension partner, JSI of Slovenia), altogether 16 partners, a strict project management has been established. The partners were assigned to the respective work packages (WP) with "horizontal" information exchange within one WP controlled by the WP leader. The appropriate “vertical” data transfer between different WPs was organised in so-called “working trains”. The THERFAT results are documented in the respective reports.

The THERFAT project processing was not limited to a scientifically orientated handling of the thermal turbulent mixing effects in piping system Ts. It focused on new useful information concerning plant operation and other measures to ensure the required long-term integrity of safety-relevant NPP components to contribute to the following benefits, e.g.:

- Improve implementation of monitoring systems and interpretation of data
- Avoid unnecessary repairs and reduce operator dose
- Exchange data and experience at European level
- Promote the introduction of new assessment procedures by industry
- Improve the expertise and competitiveness for future R & D work.

The virtual sensors developed in the project will be exploited by promoted integration of virtual sensors in existing systems for a pre-commercial application and by offering consultancy services for industry for the application of virtual sensors.

B Work programme

The project work plan comprises five major technical work packages (WP) addressing the key objectives of THERFAT and the additional work package WP 6, “Project management and co-ordination”.

B.1 WP 1: Collation and assessment of field experience

The work package WP 1 covers the identification of Ts which are sensitive to thermal turbulence and stratification effects and which are of interest to be investigated in THERFAT. The utilities involved in the project provided a selection of fatigue-susceptible T geometries and loads in their power plants. As a result, a matrix of T configurations has been compiled as input for WP 2, 3, and 4.

B.2 WP 2: Load determination

The task of WP 2 was to detect and quantify the thermal turbulence by experiments and by numerical fluid calculations. The determination of the heat transfer coefficient (fluid to wall) is considered to be one crucial point. Thermo-hydraulic tests (Plexiglas and steel T models in different configurations and with different diameters) have been performed to measure the relevant load parameters.

In addition, thermo-hydraulic analyses with computational fluid dynamics (CFD) codes have been carried out to simulate the turbulent fluid behaviour and, in particular, to determine the heat transfer coefficient (fluid to wall). The CFD approach has been validated by a benchmark calculation compared to experimental test results. Guidelines for engineering applications have been compiled from the experimental and numerical results to provide a validated basis for future CFD calculations of Ts with configurations different from those investigated in THERFAT.

As an additional sophisticated aspect, the development, training and application of virtual sensors based on neural networks and fuzzy logic tools has been included as a future option for the load determination of a selected NPP component (PWR-pressuriser surge line).

B.3 WP 3: Integrity evaluation

The objective of this central work package WP 3 was to identify the existing safety margins in the different stages of fatigue usage and of degradation starting with the crack initiation. The connection of these fundamental issues concerning degradation and failure criteria to the common integrity evaluation procedures in codes and standards (stress/fatigue analyses application, use of fatigue curves etc.) was one important task of the THERFAT project. For instance, the random surface crack occurrence known as “elephant skin” or “crazing” effect does not automatically lead to component failure. Only the development of a dominant crack in this crack field with significant crack growth will deteriorate the component integrity. Micro structural models including crystal plasticity were applied to investigate the “crazing” phenomenon.

Thus, some WP 3-partners were assigned to evaluate stresses/fatigue usage, crack initiation and crack propagation using the load input from WP 2 (“forward approach”). Other WP 3 partners performed stress/fatigue usage, crack initiation and crack propagation analyses in a “backward approach” to predict and to verify the experimental damage test results of WP 4.

B.4 WP 4: Verification damage tests

An experimental damage test pattern has been established to investigate realistic component or specimen resistance capabilities concerning specific degradation mechanisms (e.g. thermal shocks) to provide a better understanding of failure modes and the quantification of safety margins compared to the application of code procedures.

B.5 WP 5: Evaluation and development of road map

One major task in THERFAT was to improve the common understanding for the application of integrity assessments in general. A “road map” as guideline for an improved application of fatigue evaluation procedures has been developed in THERFAT explaining the conceptual outlines of an overall integrity concept as well as the relevance and the links between the various fatigue related concept elements.

B.6 WP 6: Project management and co-ordination

As the THERFAT consortium consists of 16 partners, a strict project management and co-ordination was required. The project co-ordination was focused

- on the “horizontal” information exchange within one WP controlled by the WP leader,
- the appropriate data transfer between different WPs in established “working trains”,
- the suitable documentation of achieved results and
- the controlling of general project management issues (report delivery, cost statements etc.).

C Work performed and results

The work performed and the achieved results are explained in the following sections related to the appropriate WP.

C.1 Collation and assessment of field experience

The work in WP 1 covers the identification of Ts which are sensitive to thermal turbulence and stratification effects and which are to be investigated in THERFAT. The existing field-experience has been reviewed and analysed, primarily based on the partners' experience, but available data from other sources have been included. The THERFAT utility partners E.ON, EDF and FNS provided examples of fatigue susceptible T geometries and loads from their power plants (**Figure 4 and Ref. [1], [2]**). A matrix of selected T configurations susceptible to fatigue caused by turbulent temperature mixing effects has been established. The relevant T parameters concerning the geometric configuration/position and the occurring operational loads have been identified to be investigated in detail in the following THERFAT work packages. The performed WP 1 work and the results are documented in the respective report.

Main WP 1 achievements

The WP1 compilation of field experience provides a “current state of the art” status concerning fatigue significant temperature mixing effects caused by different mass flows in “run” and “branch” pipes merging at piping system T connections. The investigation of the related phenomena is important, because these high-cycle turbulences are not obviously detectable by common thermocouple instrumentations. The investigation of the relevant damage events in the last years clarified that, in general, several different root causes were responsible for the discovered degradation effects (low fabrication quality, poor load determination, simplified integrity analysis for global and local stresses, insufficient ISI- or NDT-measures). There is no event known where the local stresses caused by temperature fluctuations at T connections are the only root cause for component failure. The local stresses usually cause only “crazing effects” (a surface crack pattern also known as “elephant skin”). Only if a dominant crack develops from this surface crack pattern, crack propagation can be expected. But, as these local through wall stresses contribute to the total amount of global and local stresses, the THERFAT investigations are useful to determine the significance of these local through wall stresses. The field experience survey leads to the following basic conclusions (**Figure 4**):

T with zero mass flow (tight valve) in branch

The “dead end” configuration (constant hot fluid mass flow in a T run, no mass flow in T branch) will lead to a “slow” warming up of the branch fluid. This configuration (absence of hot/cold mass flow mixing) is not considered fatigue significant.

T with small “cold” fluid mass flow (valve leakage) in branch

A small cold mass flow in a T branch (e.g. caused by a valve leakage) merging with a hot mass flow in the T run will cause turbulent temperature mixing effects in the branch region next to the T connection and in the pipe run downstream from the T. The thermal loads occur as “down” and “up” (or “up” and “down“) thermal shock loads, which lead to more severe temperature ranges than common operational transients (e.g. sharp temperature drop and slow heating up transient, see **Figure 4**). The location of the high stressed regions in the branch depends on the mass flow magnitude.

T with “hot” fluid mass flow in branch

A hot fluid mass flow in a horizontal branch (Civaux-event) will not immediately mix with the cold fluid mass flow in the vertical “run” pipe. The hot streak at the top of the branch will move up “around the T corner” into the pipe run. There, the hot streak starts swinging in the cold run mass flow causing fatigue significant hot/cold temperature differences in the adjacent pipe components (Civaux-example: elbow downstream from T – see **Figure 4**). The thermal loads occur as “down” and “up” thermal shock loads, which lead to more severe temperature ranges than common operational transients.

C.2 Determination of high cyclic thermal loads

The task of WP 2 is to detect and quantify the thermal turbulence occurring in the fluid by experiments and by numerical fluid calculations. The determination of the heat transfer coefficient (fluid to wall) is considered to be one crucial point. After a collation of the existing load determination experience thermo-hydraulic tests have been performed to measure the relevant load parameter. In addition, thermo-hydraulic analyses with CFD (computational fluid dynamics) codes have been carried out to simulate the turbulent fluid behaviour. Generalised guidelines for load determination have been derived from the experimental and numerical results. As an additional sophisticated aspect, the development of virtual sensors based on neural networks and fuzzy logic tools has been included to determine the temperature loads for a selected NPP-PWR component (the pressuriser surge line). The performed WP 2 work and the results are documented in the respective reports.

C.2.1 Experimental tests

The temperature differences and load cycle frequencies due to the turbulent fluid flow occurring at various mixing Ts have been simulated, illustrated and quantified by experimental approach on small-scale T test models in various positions and configurations. These tests have been performed on Plexiglas models for flow visualisation and metal mock-ups for direct measurements of temperature distributions in the fluid and through the pipe wall.

The turbulent fluid flows in different T **glass model configurations** (1:1 Ts DN 50, 1:1 T DN 100, 3:1 T 75 x 25 mm) were visualized at ambient temperature by using different specific fluid densities (**Figure 5**). Depending on the additive of salt to the water in the T branch or in the T run, fluid temperature differences up to 200 K have been simulated. Fluid temperature load spectra were determined by electrical conductivity measurements (electrical conductivity fields are analogous to temperature fields). For these conductivity measurements specific sensors were developed (**Figure 6**).

In **steel mock-ups** direct measurements of temperature distributions in the fluid and through the pipe wall were performed (**Figures 7, 8**). Specific sensors, e.g. so-called "flux meters" (**Figure 9**) had to be developed for the recording of the temperature fluctuation load spectra occurring in the transition zone between the fluid and the pipe metal wall (**Figure 10**). These recorded thermal load spectra were used as input for the WP 3 stress and fatigue analyses and for the important determination of realistic, but not too conservative, heat transfer coefficients. In most of the steel model tests a pipe wall thickness of 1 mm was selected, to be able to determine the wall temperature very close to the inner surface. These recorded temperature load spectra at the inner surface of the pipe wall provided the option to perform stress, fatigue and fracture mechanics assessments in WP 3 with any wall thickness of interest to determine the through wall stresses. The steel model test rig configurations permitted only limited temperature differences up to 90 K.

Main achievements regarding experimental tests

The occurring thermal fluctuations in T region have been determined and quantified in terms of thermal load spectra (**Figure 10**). Depending on the mass flow ratio between run and branch, in the 1:1 DN 50 experiments the significant temperature differences and load cycles occur at different T locations in different magnitude. A small mass flow in the branch (simulated valve leakage) leads to relevant temperature loads in the branch itself (80 % of the "driving temperature difference ΔT in the fluid" was registered at the inner surface of the branch pipe wall). With increasing branch mass flow the highly loaded locations are situated in the run region downstream from the T (up to 60 % of the "driving fluid temperature difference in the branch"). In the DN 80/20 T model no relevant fluid temperature alterations in the "leakage leg" were discovered; in the T run the maximum fluid temperature alteration was found at 70 % of the temperature difference of the hot and cold fluid (**Figure 11**).

The electrical conductivity measurements (conductivity analogous fluid temperature) in 1:1 DN 50 and 1:1 DN 100 Ts were of specific importance as they could be performed in cheap **glass model**s at room temperature (**Figure 12**). Depending on the additive of salt to the branch or run water, fluid temperature differences up to ΔT-values of 200 K were simulated. The turbulent load spectra in the fluid have been registered by sensors specifically developed for the THERFAT project. Local surface stress spectra can be determined by selecting an appropriate heat transfer coefficient from fluid to wall, e.g. taken from the steel model tests. As the fabrication of glass models is inexpensive, complex piping component geometries can be modelled to investigate specific temperature mixing problems with high temperature differences. But the similarity laws for the comparison of test glass models to "real steel Ts" in NPP have to be considered. The results from a 50:50 glass model T cannot be directly compared with a 50:50 steel T, because the important parameters (Reynolds and Archimedes number) vary for different materials and for different geometric T configurations.

In experimental **steel model** tests of two 1:1 DN 50 Ts (90° angle) and a 4:1 DN 80/20 T (90° angle) in various positions the temperature load spectra in the transition zone of fluid

($\Delta T = 90$ K) and inner surface of the pipe wall were recorded as data input for the WP 3 integrity evaluation. A rain flow analysis has been used to investigate the temperature time histories regarding number of cycles and temperature differences ΔT. The heat transfer coefficients α have been determined by inverse temperature analyses considering the influence of the Reynolds- and Archimedes number. The α-values determined in the steel model tests ($\alpha \leq 6000$ W/(m²K)) are lower than expected by common engineering judgement leading to less conservative through wall stresses (**Figure 11**). The thermal load spectra determined in the experiments can be extrapolated to any other temperature difference of interest and can be applied on the inside surface of any pipe wall thickness to calculate the “through wall stresses”.

C.2.2 Computational fluid dynamics (CFD) analyses

In addition to the experimental tests, numerical thermo-hydraulic calculations (CFD-analyses) have been performed for benchmark cases and for other T configurations investigated in the thermal load experiments of WP 2 and in the damage tests of WP 4. The benchmark calculations have been performed to determine the turbulent fluid distribution in a 50:50 mm T connection with different CFD-code approaches in comparison to experimental testing results (**Figures 13, 15**). The CFD-code calculations applied in THERFAT are based on different simulation approaches (Large Eddy-Simulation, Kε-approach or other code methods). The agreement between analytical predictions and experimental results is reasonable. Guidelines for an analytical load assessment that integrate velocity and temperature fields and the calibration of the heat transfer modelling between fluid and wall can be derived from the obtained results (**Figure 15**). But the CFD analyses turned out to be very time consuming, even short time history calculations of a few seconds require a tremendous amount of computer time (weeks or even months). Powerful computers are required for the execution of the CFD calculations.

Main achievements regarding CFD analyses

The agreement between analytical predictions and experimental results is reasonable. However, the thermo-hydraulic calculations conducted so far reveal the complexity of these innovative numerical analyses concerning the time consuming effect and the definition of the analysis boundary conditions. The different CFD-code applications (**Figure 16**) focus on

- common k-ε-model and
- large eddy simulation (LES).

The k-ε-model is easier to handle but requires special attention to determine the boundary conditions in fluid layers close to the wall (**Figure 15**). The LES simulation is a modern but very complex approach. The application of both methods is very time consuming. The analysis of a four second load spectrum period requires approximately six weeks of computer time.

The results obtained so far demonstrate that the engineering tools are available, the significant calculation parameters are identified and the temperature fluctuation phenomena can be qualitatively simulated. But it became obvious, that CFD analyses are still in a verification process for practical application. To provide a quantitative reliable input for practical NPP application in stress and fatigue evaluations, further validation and verification activities are required to extent the existing data base.

C.2.3 Development of virtual sensors (ref. [3])

An additional highly sophisticated aspect in the load determination field covers the development of virtual sensors based on neural network and fuzzy logic tools to simulate the dependency of thermal fluctuations on transient mass flow and temperature distributions of the surge line in the Vandellos NPP, Spain (**Figure 17**). The THERFAT-work comprises the development and training of the virtual sensors, the installation in the pilot NPP and the online data acquisition of the surge line temperature transients and the evaluation of the results.

Main achievements regarding "Development of virtual sensors"

The project results demonstrate that virtual sensors are able to determine certain power plant parameters and to detect plant transients. The neuro-fuzzy tools are suitable to design and manufacture these virtual sensors, but the cost factor has to be considered compared to the use of conventional algorithms and software. Neuro-fuzzy virtual sensors can work online and provide variable values at the same time as the real devices installed in the plant. It is possible to design virtual sensors based on neuro-fuzzy for several plants with similar technology. However, the training and validation of the virtual sensors is a plant specific task.

C.3 Integrity evaluation

The **WP 3** processing – integrity evaluation – is based on the thermal spectrum loads determined in WP 2 and WP 4. Different integrity evaluation procedures concerning the assessment of stresses, fatigue usage, crack initiation and crack propagation issues for components or specimen subjected to cyclic thermal loads have been executed. Code and standard procedures and more refined analysis models have been applied for more accurate predictions about the influence of the degradation mechanisms. The partner roles in the central WP 3 are shown in **Figure 18**. Assigned partners used the WP 2 load determination input to evaluate stresses/fatigue usage, crack initiation and crack propagation ("forward integrity evaluation approach"). Other partners already involved in WP4 (experimental damage tests) performed stress/fatigue usage, crack initiation and crack propagation analyses to predict and to verify the experimental results of WP 4 ("backward approach") – **see Figure 19**. The partner roles were fixed in so called "working trains". The performed WP 3 work and the results are documented in the respective reports.

C.3.1 Stress/fatigue analysis ("forward approach")

The work done in the Finnish **"Fortum train"** covers the analytical investigation of a T-joint mock-up from the Loviisa NPP subjected to severe thermal shock loads ($\Delta T = 280$ K). The temperature fields in the T-Joint wall have been determined based on a CFD-analysis of the fluid temperature fields and have been used as data input for a finite element stress analysis. The objective of this analysis was to identify the high stressed locations for the comparison with the experimental damage test results (see below and WP 4). Due to the required tremendous amount of computer time only a simplified T-joint could be modelled in the CFD-analysis model. The agreement of the analysis with the experimental test results regarding the location of high stresses is reasonable (**Figures 20-26**).

The **“FANP-D/F train”** (**Figure 27**) investigated a model based on the geometry and load conditions of the CEA Fatherino II experiment (temperature difference ΔT ≅ 60 K). FANP-D performed a CFD analysis of the CEA Fatherino II experiment. The results were used by FANP-F as input for a stress and crack initiation analysis applying a standard approach and a more complex load spectrum approach. The test temperature differences have been extrapolated from ΔT ≅ 60 K (experiment) to ΔT = 150 K and ΔT = 200 K to be able to calculate any fatigue degradation. To consider different geometries and weld qualities instead of stress concentration factors geometry factors have been applied taken from FANP-F research work. The stress spectra evaluated by FANP-F have been used by FANP-D for the crack propagation assessment using the Paris law. The obtained results fit into the bandwidth of results obtained by the other working trains (potential fatigue relevant degradation regarding through wall stresses are expected at temperature differences of 150 K and higher).

In parallel, the “**CEA train**” (**Figure 27**) investigated the CEA-experimental test on Fatherino II. The load determination was performed by flux-meter measurements and in parallel by CFD-calculation. The agreement between experimental test and stress/fatigue analysis results are reasonable. As result, fatigue degradation can be expected with temperature differences of approximately 160 K.

The **”SPG/FHG/TEC train**” (**Figures 28, 29**) performed stress/fatigue analyses as well as crack initiation and propagation assessments using the SPG experimental test results. At first, TEC analysed the temperature load spectrum and the heat transfer coefficients delivered by SPG with a Finite-Element (FE)-analysis using the pipe wall thickness of the SPG-test (1 mm). The experimental and numerical results show a good agreement **(Figure 30**). To simulate realistic power plant conditions, an additional FE-analysis was performed using a FE-model with 10 mm wall thickness. The load spectrum input was scaled from the temperature range of the experiment (5-95°C) in steps up to 30-275 °C. The calculated temperature fields with and through wall stresses (the stress level depends on the temperature difference between inner surface and middle of the wall) lead for a ΔT = 245 K and for assumed 32 years of full plant operation to the low fatigue usage factor of $D_{EOL} \leq 5$ % (**Figures 31, 32**). The 32-year load spectrum was extrapolated from the measurement period of 10 minutes in the experimental tests. For this analysis an averaged heat transfer coefficient derived from the experimental test results were used. This assumption –applying an averaged heat transfer coefficient- is justified because the test results demonstrate that in the fatigue significant location a non-stable turbulent temperature mixing behaviour at small mass flow (dead leg of the T) and no “fully developed pipe flow” with stable boundary layers occurs. Higher heat transfer coefficients would have to be applied only in cases with fully developed mass flows in pipes with stable boundary layers (e.g. by using the Colburn equation) leading to significant higher fatigue usage, as shown in **Figure 33** only for comparison reasons. This comparison demonstrates the importance to determine realistic heat transfer coefficients in case by case assessments. Lumped conservative assumptions may lead to wrong conclusions.

Concluding the stress/fatigue analysis results, potential fatigue degradation with the load spectra taken from WP 2 can be expected starting with a temperature difference of approximately ΔT = 150 K. This assessed threshold value depends, of course, on the geometrical T configuration and the thermal load condition (temperature difference, mass flows). Considering that other load effects may increase this through wall stress level, it was felt, that the non fatigue relevant threshold value should be limited to a ΔT-value of approximately 80 K (“attention threshold”).

To cover the crack initiation and crack propagation domain simplified analytic approaches as well as two and three dimensional FE-models were applied. The material behaviour was investigated, too, from pure elastic to complex elastic-plastic behaviour with different material laws (Chaboche, Jiang, Sester – see **Figures 34, 35 and Ref. [4]**).

C.3.2 Verification of damage tests ("backward approach")

The partners assigned to the "backward approach" performed stress/fatigue usage, crack initiation and crack propagation evaluations to investigate and verify the results of WP 4 (experimental damage tests) by common code procedures and by more sophisticated approaches.

The **"turning cylinder test"** (**Figures 36, 37**) aimed to study the fatigue behaviour of a stainless steel pipe comprising a tapered and an unflushed circumferential welded joint subjected to cyclic thermal loadings with known amplitude and frequency. The load number till the occurrence of first cracks in the test was higher than predicted by theoretical fatigue assessments.

The **"pipe/nozzle configuration"** (**Figures 21, 25, 26)** mock-up subjected to a thermal shock load of ΔT = 275 K was investigated concerning stress and fatigue issues with two different methods. The loading was chosen based on the maximal possible ΔT that could be expected in the industrial application. The maximal ΔT was selected to obtain significant thermal fatigue usage in a reasonable amount of time. The experimental heating and cooling procedure (heat induction coils) was simulated in the temperature field analysis. The stress-/fatigue analysis results based on the experimental data lead to assessed strain amplitudes "above" the ASME design curve (safe side). The cracks detected and identified by replica and dye penetrant measures and by measurement of the crack opening displacement were still in the crack initiation phase.

The **thick wall cylinder damage test** (**Figures 38, 39**) with the worst case approach (ΔT ≤ 380 K and axial tension loads) was focused on crack initiation and propagating issues. The analytic investigation of the experiment includes cyclic plasticity models and crack propagation models. The comparison of experimental and analytical results demonstrates that the typical stages seen in thermal fatigue can be simulated by the experiment (surface cracking, propagation of short cracks, formation of lead cracks). The Coffin Mason approach and the "short crack model" are able to describe the crack initiation behaviour accurately, which was measured by surface replica and with the TOFD method (time-of-flight diffraction – ultrasonic technique) in the experiment (for locating and sizing cracks). Crack propagation assessment using the Paris law are considered as appropriate. Crack arrest mechanisms were detected.
One specific feature was the investigation of the "crazing" effect (also known as "elephant skin effect") occurring due to local thermal shocks at the inner surface of the pipe wall. This random surface cracking pattern is not considered to deteriorate the component integrity significantly as long as no dominant cracks develop. An advanced method for crack initiation, a so called micro structural model has been introduced to simulate the cyclic crystal plasticity. The simulation of a few cycles was successful. The results indicate that a saturation level has been approached (**Figure 40).**

Main achievements regarding WP 3 – Integrity evaluation

The results obtained in the several "working trains" demonstrate the feasibility of the introduced integrity evaluation procedures. Code evaluation methods and other common approaches are appropriate to deal with the fatigue related issues. This applies for the stress calculation with provided thermal spectrum loads (from experimental tests and in a smaller scale from CFD-analyses in WP 2 or from damage tests in WP 4) and for the related fatigue evaluation. For the fracture mechanics assessments (crack initiation and crack propagation) common approaches based on elastic material behaviour have been confirmed as suitable. More sophisticated approaches, e.g. using elastic/plastic material laws are available for safeguarding reasons, if appropriate. As conclusion it is stated that effective simplified and more sophisticated engineering tools are available to deal with high cyclic turbulent loads.

Turbulent thermal load spectra, as investigated in THERFAT for austenitic T connections, lead to local through wall stresses in the respective location. The THERFAT results demonstrate that significant temperature differences in the mixing region are necessary to cause fatigue degradation. For a thermal load spectrum measured in the steel model tests and extrapolated to temperature difference of ΔT = 245 K, the very small "end-of-life (EOL)" fatigue usage factor of ≤ 5 % was determined for assumed 32 years of full power operation). For this fatigue analysis the applied averaged heat transfer coefficient was justified by the test results (turbulent temperature mixing behaviour at the fatigue relevant locations in the dead leg). Only in cases of velocity profiles with stable boundary layers at the pipe wall (fully developed pipe flow) higher heat transfer coefficient values have to be assumed (e.g. by using the Colburn equation).

As conclusion of the WP 3-results, thermal turbulent load spectra with temperature differences of ≥ 150 K can be considered as fatigue relevant. But as these local through wall stresses have to be added to the additional global system stresses, it was felt that as a lower bound "attention threshold" for turbulent thermal load spectra a ΔT value of 80 K should be defined for austenitic material. That means that turbulent thermal loads below this ΔT value of 80 K are not considered fatigue relevant because they do not exceed the endurance limit value of the fatigue curves. Even potential crack initiation and "crazing" effects with a surface crack pattern will not lead automatically to component failure as long as no leading crack is starting. Nevertheless, high load cycle numbers should be avoided by proactive measures as optimizing the system operation procedures or by maintenance measures, e.g. to stop potential valve leakages. If these high cyclic loads cannot be avoided in the plant or if it is uncertain whether they occur or not, THERFAT is providing engineering tools to predict the fatigue usage behaviour as well as the potential crack initiation and crack propagation for the stipulation of appropriate NDT-intervals.

The analytic investigation of the large-scale damage tests performed in WP 4 with severe thermal shock loads demonstrate that the first cracks occurred later than expected by parallel analytic assessments. This proves that the current code procedures for fatigue evaluation are appropriate and that the evaluation results of WP 3 based on the WP 2 and WP 4 experience are generally valid for all respective component types subjected to cyclic loads and are not limited to T connections.

C.4 Experimental small-scale and large-scale damage tests

In WP 4 several damage tests on small-scale specimens (investigation of fatigue behaviour and fracture mechanics parameters) and on large-scale components using realistic mock-up configurations have been carried out. The selection of the large-scale test configuration was based on a comprehensive compilation of existing thermal fatigue laboratory test data and of information about the most fatigue relevant parameter (e.g. surface finishes, mean stress effects). In most fatigue tests performed so far mechanical loads were applied, only a few thermal load tests are known. Therefore, the THERFAT large-scale damage tests were focused on (severe) thermal shock loads. Tests on small specimen with mechanical loads were performed to compare the effects of mechanical to thermal loads. The experimental damage test pattern established in THERFAT (**Figures 25, 36, 39, 41)** was supposed to investigate realistic component or specimen resistance capabilities concerning specific degradation mechanisms (e.g. thermal shocks) to provide a better understanding of failure modes and the quantification of safety margins in terms of the load/stress-fatigue-crack initiation interaction and to single out the most relevant parameter that can serve as criteria for the verification and calibration of integrity procedures. The performed WP 4 work and the results are documented in the respective reports.

Small-scale tests on specimen with thermal (mechanical) loads **(Figure 41)** were performed to identify potential differences concerning the fatigue behaviour under different loads (mechanical or thermal loads). The test results confirm known tendencies, that the number of load cycles up to crack initiation is comparable between mechanical and thermal loads. But in the further development from crack initiation to failure, the current experience shows, that cracks caused by mechanical loads tend to propagate, while initiated cracks due to thermal loads appear to come to a crack arrest.

In a "turning cylinder mock-up" (450 mm diameter austenitic steel pipe – see **Figures 36, 37)** a "moderate" thermal shock load of $\Delta T = 120$ K was applied (alternating infrared heating and cold spraying). These tests aimed to study the fatigue behaviour of the stainless steel pipe comprising a taper and an un-flushed circumferential welded joint, subjected to cyclic thermal loadings with known amplitude and frequency. First cracks occurred after more than 120 000 load cycles in the tapered base material area **(Figure 37**). The size of the defects at the surface has been measured with dye penetrant technique.

A "higher" thermal shock load of $\Delta T = 275$ K was used in the "pipe/nozzle configuration test" **(Figure 25**). In common NPP operation this temperature difference may sometimes occur during extraordinary plant operation conditions (upset, emergency, or faulted conditions). The thermal loads were generated by local induction heating and quenching in the T-junction area. The temperature was measured on some surface locations. Cracks occurred after more than 10000 load cycles. The evolution of the surface cracks has been monitored with surface replicas and crack opening displacement (video technique).

The third damage test, a thick wall cylinder subjected to axial loads and thermal shocks of $\Delta T = 380$ K **(Figure 39**) was considered a worst case example. In particular, the degradation initiation and propagation due to extreme thermal loads beyond common plant conditions were studied. The cylinder was induction- heated from the outer surface and cooled from the inside by room temperature water. First cracks on the pipe inside occurred after 20 000 load cycles (later than predicted). The surface cracking was monitored by the replica technique and the evolution of cracks (length as well as depth) is measured with a special ultrasonic technique TOFD (time-of-flight diffraction). In addition, low-cycle fatigue tests have been performed on the material to determine the cyclic behaviour of the material.

Main achievements regarding WP 4 – Damage tests

The achieved results in the experimental damage tests concerning the load bearing capacity of components and regarding selected aspects of fatigue assessments confirm the predicted tendencies of higher load bearing capabilities than expected by application of common code analysis procedures. In terms of fatigue usage, all the experimental test results showed strain rates above or in accordance with the ASME-design fatigue curve, proving the currently applied fatigue curves (ASME design curve) as appropriate (**Figure 42**). The tests confirmed known tendencies, that the number of load cycles up to crack initiation is comparable between mechanical and thermal loads. But in the further development from crack initiation to failure, the current experience shows, that cracks caused by mechanical loads tend to propagate, while initiated cracks due to thermal loads appear to come to a crack arrest.

The results of the damage tests in WP 4 with the related analytic investigation in WP 3 are generally valid for all respective components subjected to cyclic thermal loads and are not limited to T connections:

The performed experimental investigations confirm that a good strain amplitude evaluation leads to a reasonable agreement between tests and code fatigue rule predictions. E.g. elasto-plastic finite element analyses with different types of strain-stress relationships were used (Chaboche or cyclic isotropic hardening). Additional approaches based on elastic material behaviour (RCCM K_e appliction) were applied. All analytic results are in a good agreement with test results.

The fatigue usage factor assessment based on the (S, N) code curves in ASME, RCCMR, RCCM, KTA (which are identical up to 10^6 cycles) show a significant margin in term of allowable cycles. The surface finish conditions can have a significant influence on the stress/strain range (up to a factor of 2.8). But this effect is more related to surface finishes of class 2 and 3 piping systems.

In the experimental tests, small crack networks occurred, except for JRC test T3 where the crack depth is 5mm for a thickness of 14 mm after 38 000 cycles.

Different crack growth analysis models have been tested. A specific model developed in Finland covered crack sizes from 0.1 to 1 mm. For larger cracks various analyses methods were applied (elastic, elasto-plastic, 2D or 3D analysis, ΔK, ΔJ, ΔCO etc.). All these models can lead to conservative crack growth rates because the neglected crack closure effect can have a very significant influence on thermal fatigue crack growth.

C.5 Development of road map for thermal-fatigue evaluations

The THERFAT project had been initiated to provide improved thermal-fatigue evaluation approaches for managing thermal fatigue risks in T connections susceptible to high cyclic temperature fluctuations. It was intended to close a gap regarding one specific fatigue issue. Although the THERFAT project scope covered only this small-scale fatigue issue, a conceptual approach was required to frame and to condense the activity results of several technical disciplines to provide useful conclusions for practical engineering application. Furthermore, the THERFAT consortium consists of 16 partners with different technical and scientific background and objectives. Thus, a common understanding had to be developed, which parameters were fatigue significant and important compared to those of less importance. To reach this goal, a conceptual approach was required for the THERFAT project processing focused on the “small-scale” T connection investigation. In NPP, the same configuration of different technical disciplines and persons with different technical background exists. Simple guidelines are helpful how to mitigate or even avoid fatigue significant loads before they occur e.g. by optimising the system operation procedure or by ISI-measures to stop a valve leakage. Plant operation people who are usually not familiar with fatigue analyses in detail should get an idea which temperature differences may be stress and fatigue relevant. The applied THERFAT processing approach can be regarded as a small example for the application of a general integrity concept. Enlarged for general application it can be used for all kinds of integrity evaluations (e.g. “leak-before-break” assessments, or ageing-management activities). The WP 5 report explains the different elements of this overall integrity concept and how they are linked together. The approach may help to improve a harmonized understanding for the people involved and can be regarded as a first step on the road to a future European fatigue evaluation methodology. The objective is to demonstrate that an unnecessary accumulation of conservatisms in single integrity concept elements can be avoided and that a balanced interaction between the different elements can be achieved by increasing the importance level of one element compensating the reduced significance level of another element, if appropriate (**Figure 43**).

Basically, the following main subjects have to be covered:

- the current system/component integrity status, and
- to safeguard the required component quality during the future plant operation,

correlated to the relevant potential degradation mechanisms and related to the safety significance of the system/component under consideration.

Following the system classification (safety relevant) and the component ranking (high, medium, lower safety significance) the integrity evaluation starts with the assessment of the current component/system quality status because degradation mechanisms from operation so far may have had an impact on the originally designed component quality. The proactive route tries to avoid/minimize premature degradation effects. The reactive track deals with degradation effects after they have occurred and have been detected. Also, relevant changes in the “state of the art“ have to be considered.

The application of the concept leads to the following advantages:

- The actual component quality status is known.
- Safeguarding of quality by intensified proactive monitoring of root causes of degradation mechanisms (loads) and by reactive surveillance of consequences of degradation mechanisms (NDT, etc.) are considered.
- More realistic determination of stress/fatigue usage factors based on actually occurring loads from measurements instead of lump design loads leads to improved knowledge about the system under consideration.
- Based on these results, subsequent measures can be established more realistically (maximum acceptable defect sizes determined by integrity evaluations which **have to** be found by NDT, instead of minimum defect sizes which **can** be found by the respective NDT method).
- The balanced interactive handling of the different concept elements according to the respective safety relevance leads to a reduction of conservative assumptions.
- Harmonized co-operation of people dealing with the different concept elements leads to improved results.

Usually, it is not always required to perform a complete new integrity evaluation. But the results have to be bundled with respect to the specific integrity objective. In addition to the handling of the technical issues, administrative procedures have to be established for transparent documentation and delivery of results.

As a consequence, the establishing of an overall integrity concept serves as a guiding integrity related framework. Occurring questions and problems can be linked to the respective location within the framework without questioning the entire "integrity building" (**Figure 44**). This methodology is not new, of course. It is the basic philosophy of the safety related precaution measures for NPP starting with the plant design and continuing during the entire plant lifetime.

Applying this conceptual approach to the T connections investigated in THERFAT leads to the following conclusions regarding the different fatigue related integrity concept elements:

- Evaluating the "basic quality" supplied by design and fabrication of the T connection under consideration,
- Monitoring of occurring thermal load type and load cycles,
- Transforming of monitored load data into the load input for stress and fatigue analyses,
- Performing the stress and fatigue analyses,
- Arranging a long-term fatigue surveillance programme (cycle counting), if appropriate,
- Fracture mechanics assessments to determine acceptable flaw sizes,
- Establishing of safeguarding NDT measures.

The Ts investigated in THERFAT are considered to be of high safety concern. Consequently, thermal load monitoring is strongly recommended, e.g. to control valve leakages causing turbulent mixing of hot and cold water. Preferably, the "degradation root cause" should be avoided, e.g. by stopping the valve leakage with preventive maintenance measures. If no thermocouples are installed at the T, the maximum temperature difference can be determined using the plant operation parameters. If the occurring ΔT values are below the fatigue relevance threshold, no further action is required. If the estimated ΔT is significant and cannot be reduced by system operation means, a detailed stress and fatigue analysis is necessary. A selection of engineering tools to be applied is provided by THERFAT. First analysis objective is to demonstrate that the endurance limit of the respective fatigue curve is met, which means, that there are no limitations on the load cycle numbers. If the determined stresses exceed the endurance limit and the allowable load cycle numbers are limited, additional measures are required. A fracture mechanics assessment can estimate the crack initiation and propagation history based on an assumed flaw size as basis for the definition of specific NDT measures regarding the expected degradation mechanisms.

Based on this integrity evaluation approach, the THERFAT results are foreseen to provide basic guidelines for simplified assessments to be done first (e.g. determination of non fatigue relevant threshold values). If this does not lead to satisfying results, more sophisticated approaches are necessary; the various appropriate engineering tools have been tested in THERFAT as suitable.

As conclusion concerning a conceptual approach, one always has to bear in mind that the most important evaluation element is the load monitoring and the determination of loads as an input for the integrity evaluation including a realistic heat transfer coefficient assessment. A realistically determined load spectrum allows the application of simplified stress/fatigue analyses. But uncertainties of a roughly assumed load spectrum cannot be compensated by a detailed stress/fatigue analysis type because the analysis boundary conditions are already uncertain, which is not acceptable for safety relevant NPP components.

The performed WP 5 work and the results are documented in the respective report.

C.6 Project management and co-ordination

The THERFAT project management in **WP 6** comprises the co-operation between WP partners and the interaction between the different WPs. In addition, the project administration issues (e.g. checking and approval of documentation reports and cost statements as well as the appropriate information transfer to the EC scientific officer) were handled in WP 6.

Due to the large number of partners in the THERFAT project (12 original THERFAT partners, three additional partners of the originally intended "ADVISE" project and the NAS extension partner JSI of Slovenia), altogether 16 partners, a strict project management and project co-ordination was required. The project co-ordination was focused on the "horizontal" information exchange within one WP controlled by the WP leader, the appropriate data transfer between different WPs in established "working trains", the suitable documentation of achieved results and the controlling of general project management issues (report deliveries, cost statements etc.).

D Conclusions

The THERFAT project has been initiated to outline a science-based practical methodology for managing thermal fatigue risks in T connections susceptible to high cyclic thermal fatigue. THERFAT has been carried out as shared-cost action by the 16 partners (utilities, plant vendors/manufacturers, consultant engineers, and research institutes) as part of the Fifth Framework Programme of the European Atomic Energy Community (Euratom).

The THERFAT work focused on the following technological and scientific aims:

- Screening of existing plant and R & D data (WP 1),
- Assessing the fatigue significance of turbulent thermal mixing effects in piping system T connections and identifying the fatigue significant parameter (WP 2),
- Quantifying the existing safety margins against failure and determination of fatigue-relevant lower bound threshold values and evaluation of standard methods and exploration of advanced fatigue and fracture mechanics analysis routes (WP 3),
- Verification of selected aspects of fatigue assessment by critical experiments, i.e. "damage tests" with cyclic thermal shock loads (WP 4),
- Proposition of a road map as part of the "European Methodology on Thermal Fatigue" considering the results of current and past activities in a coherent way on a European level (WP 5).

The THERFAT project has been successfully accomplished. The technical results of the project improve the understanding of thermal fatigue issues for plant operation and safety and lead to the following conclusions:

Although the THERFAT work was orientated on piping system T connections subjected to high turbulent temperature mixing effects (in particular the load determination in WP 2), the project results (in particular of WP 3 and WP 4) can be of practical use for other NPP components with high cyclic temperature loads.

The compilation of existing plant experiences lead to a selection of representative T configurations susceptible to thermal fatigue degradation caused by high cyclic temperature mixing effects.

In glass model tests of various Ts at ambient temperature, fluid temperature differences up to 200 K were simulated by using different specific fluid densities (salt water). Fluid temperature load spectra were registered by electrical conductivity measurements (electrical conductivity fields are analogous to temperature fields). For these conductivity measurements specific sensors were developed. As the fabrication of glass models is inexpensive, other complex component geometries can be modelled to investigate specific temperature mixing problems with high temperature differences (up to ΔT values of 200 K). But the similarity laws for the comparison of test glass models to “real steel Ts” in power plants have to be considered.

In steel mock-ups direct measurements of temperature distributions in the fluid and through the pipe wall were performed with temperature differences up to 90 K. Specific sensors (e.g. flux meters) have been developed for the recording of the temperature fluctuation load spectra occurring in the transition zone between the fluid and the pipe metal wall. The recorded temperature load spectra at the inner surface of the pipe wall were used as input for the stress and fatigue analyses and for the important assessment of realistic, but not too conservative, heat transfer coefficients.

In addition to the experimental tests, numerical thermo-hydraulic calculations (CFD analyses) have been performed for a benchmark case and for other T configurations. The CFD-code calculations were based on different simulation approaches (large eddy simulation, Kε approach or other code methods). The agreement between analytical predictions and experimental results is reasonable. But the CFD analyses turned out to be very time consuming. Even short time history calculations (a few seconds) require a tremendous amount of computer time (weeks or even months). Powerful computers are required for the execution of the calculations. It became obvious, that CFD analyses are still in a verification process for practical application.

An additional highly sophisticated aspect in the load determination field covers the development of virtual sensors based on neural network and fuzzy logic tools to simulate the dependency of thermal fluctuations from transient mass flow and temperature distributions of the surge lines in a pilot plant. The project results demonstrate that virtual sensors are able to assess certain power plant parameters and to detect plant transients and that the neuro-fuzzy tools are suitable to design and manufacture these virtual sensors. But the cost factor has to be considered compared to the use of conventional algorithms and software.

Different integrity evaluation procedures concerning the assessment of stresses, fatigue usage, crack initiation and crack propagation issues for components or specimen subjected to cyclic thermal loads have been executed. The partners assigned to the “forward approach” used the results from experimental tests and from CFD analyses to calculate through-wall stresses, fatigue usage, crack initiation and propagation. The thermal load spectra determined in the experimental steel tests with ΔT values of up to 90 K were extrapolated in several steps to higher temperature differences up to ΔT values of 245 K, to define the “threshold values” where fatigue degradation can be expected. In the stress analysis models, realistic wall thickness values from plant experience were used (e.g. 10 mm) to calculate the thermal through-wall stresses and the related fatigue usage factors. For temperature differences of ΔT = 245 K the low fatigue usage factor of ≤ 5 % for 32 years of full plant operation was calculated applying realistic heat transfer coefficients derived from the test results. Potential fatigue degradation can be expected at a temperature difference of approximately ΔT = 150 K. These results depend, of course, on the geometrical T configuration and the thermal load condition (temperature difference, mass flows). Advanced crack initiation and propagation assessments were performed using two- and three-dimensional finite-element (FE) models. The material behaviour was investigated, too, from pure elastic to complex elastic-plastic behaviour with different material laws (Chaboche, Jiang, Sester).

The partners assigned to the “backward approach” performed integrity evaluations to verify the results of WP 4 experimental damage tests on small-scale test specimen and on large-scale components using realistic mock-up configurations. In most fatigue tests performed so far mechanical loads were applied. Only a few thermal load tests are known. Therefore, thermal shock loads were applied in the three large-scale tests in THERFAT.

In one “turning-cylinder mock-up”, a “moderate” thermal shock load of $\Delta T = 120$ K was applied to study the fatigue behaviour of the stainless-steel pipe comprising a taper and an un-flushed circumferential welded joint. The size of the defects at the surface has been measured with dye penetrant technique. The load cycle number till the occurrence of first cracks in the test was higher than predicted by theoretical fatigue assessments.

A “pipe/nozzle configuration” mock-up subjected to thermal shock loads of $\Delta T = 275$ K was investigated by FE-stress calculations with loads determined by CFD analyses and with temperature fields taken from the experimental heating and cooling process. The simplified CFD analysis was able to identify the locations of steep temperature gradients. The stress/fatigue analysis based on the experimental data lead to assessed strain amplitudes “above” the ASME design curve (safe side). The evolution of the surface cracks has been monitored with surface replicas and crack-opening displacement (video technique).

The analytic investigation of a thick wall cylinder damage test with severe loads ($\Delta T \leq 380$ K and axial tension loads) was focused on crack initiation and propagating issues. The typical degradation stages due to thermal fatigue could be simulated (surface cracking, propagation of short cracks, formation of lead cracks). The Coffin Mason approach and the short crack model are able to describe the crack initiation behaviour accurately, which was measured in the experiment by surface replica and with the TOFD method (time-of-flight diffraction ultrasonic technique). Crack propagation assessments using the Paris law are considered as appropriate. Crack arrest mechanisms were detected.

One specific feature was the investigation of the “crazing” effect (also known as “elephant-skin effect”) occurring due to local thermal shocks at the inner surface of the pipe wall based on a micro structural model, which is able to simulate the cyclic crystal plasticity. The simulation of a few cycles was successful and the results indicate that a saturation level has been approached. This random surface cracking pattern is not considered to deteriorate the component integrity significantly as long as no dominant cracks develop.

The achieved results in the experimental damage tests investigating the load-bearing capability of components and selected aspects of fatigue assessments confirm the predicted tendencies of higher load bearing capacities than expected by application of common code analysis procedures. In terms of fatigue usage, all the experimental test results showed strain rates above or in accordance with the ASME-design fatigue curve, proving the currently applied fatigue curves (ASME design curve) to be appropriate. The tests confirmed known tendencies that the number of load cycles up to crack initiation is comparable between mechanical and thermal loads. But in the further development from crack initiation to failure, the current experience shows that cracks caused by mechanical loads tend to propagate, while initiated cracks due to thermal loads appear to come to a crack arrest.

Turbulent thermal load spectra, as investigated in THERFAT for austenitic T connections, lead to local through-wall stresses in the respective location. The THERFAT results demonstrate that only significant temperature differences of ≥ 150 K in the mixing region are able to cause fatigue degradation effects. But as these local through-wall stresses have to be added to the additional global system stresses, it was felt that an "attention threshold" for turbulent thermal load spectra should be defined at a ΔT value of 80 K. It means that turbulent thermal loads below this ΔT value of 80 K are not fatigue relevant because they do not exceed the endurance limit value of the fatigue curves. Even potential crack initiation and "crazing" effects with a surface crack pattern do not lead automatically to component failure if no leading crack is starting. Nevertheless, high load cycle numbers should be avoided by proactive measures as changing the system operation procedures or by maintenance measures, e.g. by stopping potential valve leakages. If these high cyclic loads cannot be avoided in the plant or if it is uncertain whether they occur or not, engineering tools are provided by THERFAT to predict the fatigue behaviour as well as the potential crack initiation and crack propagation for the stipulation of appropriate NDT intervals.

The framework of an integrity evaluation concept has been defined as part of the development of a European methodology on thermal fatigue underlining the required close interaction between the different technical disciplines dealing with fatigue issues (load determination, stress and fatigue analyses, supporting fracture-mechanics assessments, selection of high stressed locations for NDT measures).

Condensed summary of conclusions

- The applied "integrity building approach" was useful to frame the multidisciplinary partner co-operation.
- Besides common evaluation approaches, more refined routes are available, if needed.
- Load determination from mock-ups appears to be possible.
- The ASME fatigue curve is conservative for the investigated thermal fatigue cases.
- Crack growth to leak is not expected due to turbulent temperature mixing loads.

The scope of thermal fatigue and integrity assessment is very broad and the broad background expertise of the multidisciplinary THERFAT consortium showed its value in realisation and evaluation of the THERFAT project objectives. Accordingly, one of the main conclusions was the confirmed value of integrated assessment approaches.

The results obtained in the several "working trains" and benchmarks demonstrated the feasibility of the introduced integrity evaluation procedures. It was also demonstrated that more sophisticated analysis methods provide more realistic results.

Complete "evaluation chains" were conducted starting with a turbulent temperature mixing in a small-scale laboratory test going on with experimental/analytic load determination and ending with realistic component fatigue evaluation and fracture-mechanics assessments (crack initiation and propagation). Also, the time-dependant interaction between thermal load and steel structure was investigated using a new analytic evaluation model. The result differences between these different analyses can be explained in terms of simplification in the evaluation methods used. With appropriate non-linear analyses a margin of more than 20 in life against the ASME III fatigue design curve was demonstrated for the applied thermal loads.

Various models for thermal load evaluation were compared to experimental results. The analytic results agree reasonably well with each other and with the experimental results. The assumption and the assessment of heat-transfer coefficient and thermo-hydraulic boundary conditions turned out to be a very important issue in the determination of temperature and strain ranges which are responsible for thermal fatigue degradation.

The time-dependent stress gradients through the wall thickness are complex in cyclic loading caused by thermal fluctuations. At high frequencies the thermal stress fields will have steep gradients and the driving force will effectively vanish from cracks loaded by thermal striping only.

For crack initiation and propagation, non-linear elastic-plastic 3D FE analyses led to appropriate results. In addition, a sophisticated analysis model of the "crazing" effect with a random pattern of small surface cracks was performed using a newly developed analytical model.

In general, crack growth rates were small with thermal loads up to $\Delta T = 160$ K.

Appropriate analysis tools are available to evaluate the various thermal-fatigue aspects.

Besides, common fatigue-usage evaluations, additional determination of safety margins to failure by crack initiation, and crack propagation assessments may be useful.

Glass and steel model experiments may be helpful to improve the understanding of thermal-fatigue issues.

Publications

THERFAT project issues were presented on conferences and in published papers, e.g.:

- Snowbird Conference on Thermal Fatigue in July 2002 (**see Ref. [5], [6], [7]**),
- FISA 2003 Symposium in Luxembourg in November 2003 (**Ref. [8]),**
- EC brochure – current R & D activities in FP5 (**Ref. [9]**)
- MPA Seminar 2004 in Stuttgart, Germany, in October 2004 (**Ref. [10]),**
- Seville Conference on Thermal Fatigue in October 2004 (**see Ref. [11]-[17])**,
- NED journal contribution, Volume 235, February 2005 (**Ref. [18]**),
- MPA Seminar 2006 in Stuttgart, Germany, in October 2006 (**Ref. [19]**).

Outlook for further research activities

An extended **NESC thermal fatigue project** [**20**] assessing thermal fatigue in LWR components based on the THERFAT results has been carried out, encouraging the collaboration of different technical disciplines to cope with thermal-fatigue issues. Participants were the THERFAT partners EDF (FR), E.ON (DE), VTT (FI), CEA (FR), JRC (EU), Paul Scherrer Institute (CH), and a group of Swedish utilities and regulators (DNV).

In Euratom’s Sixth Framework Programme, the NULIFE (Nuclear Plant Life Prediction) project in terms of a Network of Excellence has been initiated to provide a forum for realising harmonised technical procedures for the nuclear energy industry, national regulators, and European regulatory working groups as a service provider and a sustainable source of qualified expertise for all customers in the nuclear energy field.

Further research activities should be also focused on the development of guidelines regarding the interaction between integrity evaluation and NDT measures. The engineering tools applied in THERFAT are suitable to assess potential crack initiation and propagation as criteria for NDT threshold values in terms of flaw length and depth as well as for NDT intervals.

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