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Activities of the OECD Nuclear Energy Agency in the Area of RPV PTS Fracture Mechanics

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ABSTRACT

There has been a series of PTS analysis round robins under PWG3, organised jointly by GRS and ORNL. They have had a large international participation. The first such exercise was FALSIRE (Fracture Analysis of Large Scale International Reference Experiments), in the period 1988-1992. This considered 6 tests on RPV steels under PTS conditions. There was subsequently a second phase of FALSIRE in the period 1993-1996. This studied 7 reference fracture experiments, under cleavage fracture conditions. The current phase, RPV PTS International Comparative Assessment Study (ICAS), is a purely numerical benchmark of relatively shallow cracks postulated in the near core weld of a RPV under PTS loading. In this phase there are also probabilistic fracture mechanics tasks and thermal hydraulics tasks addressing mixing.

INTRODUCTION

The Safety Division of the OECD Nuclear Energy Agency provides the secretariat for the Committee on the Safety of Nuclear Installations (CSNI), which deals with technological aspects, and for the Committee for Nuclear Regulatory Activities (CNRA) dealing with regulatory aspects. Under these committees, activities are carried out through five Principal Working Groups (PWGs). The relevant group for integrity aspects of Pressurised Thermal Shock (PTS) is PWG-3 on the integrity of structures and components, and for thermal hydraulic aspects, PWG-2 on coolant system behaviour. CSNI carries out its work by preparing reports and organising round robins, Specialists Meetings and Workshops.

FALSIRE I

Description

The Project for Fracture Analysis of Large-Scale International Reference Experiments (Project FALSIRE) was created under PWG3. The motivation for the project was the fact that inconsistencies were being revealed in predictive capabilities of a variety of fracture assessment methods, especially in ductile fracture applications. Hence PWG3 decided to evaluate fracture prediction capabilities currently used in safety assessments of nuclear components through interpretative analyses of selected large-scale fracture experiments. Participants were from laboratories and research organisations in Western Europe, Japan, and the United States of America (USA). The US Nuclear Regulatory Commission's (NRC's) Heavy-Section Steel Technology (HSST) Program at the Oak Ridge National Laboratory (ORNL) and the Gesellschaft fur Anlagen- und Reaktorsicherheit (GRS), Köln, Federal Republic of Germany (FRG) had responsibility for organisation arrangements related to Project FALSIRE. The project is described in reference 1.

Priority was given to thermal-shock experiments including combinations of mechanical and thermal loads. The reference experiments selected were: NKS-3&4 (MPA), PTSE-2A&B (ORNL), SC-I& II (AEA), and Step B PTS (JAPEIC). The experiments used were designed to examine various aspects of crack growth in RPV steels under PTS loading conditions. These conditions were achieved in three of the experiments by internally pressurising a heated cylindrical vessel containing a sharp crack and thermally shocking it with a coolant on the inner (NKS-3, 4) or outer (PTSE-2) surface. In the series of spinning cylinder (SC) experiments, a thick cylinder with a deep crack on the inner surface was thermally shocked with a water spray while simultaneously spinning the cylinder about its axis in a specially constructed rig. The Japanese Step B test used a large surface-cracked plate subjected to combined mechanical loading of tension and bending, co-ordinated with a thermal shock of the cracked surface. The analyses concentrated on the phase of ductile crack growth.

37 participants representing 19 organisations performed a total of 39 analyses of the experiments. The analysis techniques employed by the participants included engineering methods (e.g. R6) and FE methods. These techniques were combined with applications of JR methodology and the French local approach. Analysis results provided estimates of variables including crack growth, CMOD, temperatures, strains, stresses, and applied J and K values. Conditions of crack stability and instability were identified in the experiments. Where possible, computed values were compared with measured data. Details are given in ref. 1.

Conclusions

Generally, these experiments were designed to evaluate fracture methodologies under prototypical combinations of geometry, constraint, and loading conditions. The complexities of the experiments do not permit a clear separation of the effects of the many variables involved. Discrepancies can be interpreted by parametric studies. Modelling requirements for the experiments incorporate history-dependent mechanical, thermal, and body force loadings; temperature-dependent material and fracture-toughness properties; specially designed materials; residual stress states; and 3-D effects. Interactions of both cleavage and ductile modes of fracture must be modelled for certain loadings. Hence, comparisons of analysis predictions with test results would give significant variations.

The structural mechanics behaviour of the test specimens could be approximated well in case of the NKS experiments, but not in PTSE-2, with the largest differences in PTSE-2A. In the SC tests, structural mechanics results could not be compared with experimental measurements. The restrictions in some FE codes to input stress-strain curves only by bilinear approximations produced large scatterbands for CMOD and J-integral. All the analyses assumed temperature independent material properties as no data were available. These factors may have contributed to the large underestimation of the measured CMOD in the experiment. These analysis results highlight the importance of obtaining high-quality material properties and structural response data (CMOD, strains, etc.) from the experiments to model structural behaviour of the specimen before performing fracture mechanics evaluations.

In applications of JR methodology based on small specimen data, all analyses (estimation scheme and FE) correctly distinguished between stable crack extension and ductile instability conditions for each experiment. However, as a technique to predict crack extension, JR methodology was partially successful in some cases (NKS experiments) but not in others (PTSE-2 and SC experiments). Fracture assessments based on CT specimens overestimated stable crack growth in the case of NKS-4, SC-I and -II, and Step B PTS because the crack resistance in the large-scale test specimens is greater than predicted by small specimens (e.g., CT-25). SC-I and -II fracture results show that crack extension can be described quite well with the J-integral and the JR-curves of the large-scale test specimen. In PTSE-2A, the first phase of stable crack extension is underestimated because the crack loading also represented in CMOD is underestimated. Furthermore, differences between pretest characterisation data and post-test in situ data for material and fracture toughness properties gave rise to questions concerning whether JR curves from CT specimens were representative of the flawed region of the vessel. None of these temperature-dependent JR curves were consistent with all phases of ductile tearing observed in PTSE-2. It should be pointed out that the PTSE-2A transient included load-history (i.e., warm-prestressing) effects that were not incorporated into the JR methodology. The substantial differences between fracture toughness curves generated from the SCs and from CT specimens focused attention on other factors. These included the possibility that crack-tip behaviour in the SC is not characterised by a single parameter fracture mechanics in terms of J. Other measures considered in dealing with the transfer of small specimen data to large structures include constraint and stress triaxiality parameters.

FALSIRE II

Description

It was proposed that the follow-on FALSIRE II project should emphasise experiments that focus on behaviour of relatively shallow cracks subjected to combined thermal and mechanical loading in the transition temperature region. If possible, experiments for cracks showing two stages of extension (e.g., stable crack extension followed by unstable extension) should be included. Investigations of crack initiation and extension in connection with clad surfaces were also proposed. In 1993, these criteria were utilised to select a new set of experiments for the FALSIRE II project. The project is described in ref. 2.

The experiments utilised examined various aspects of the cleavage fracture process in RPV steels for a wide range of material crack geometries, and constraint and loading conditions. PTS loading conditions were applied in three of the experiments by internally pressurising a heated vessel containing a sharp crack and thermally shocking it with a coolant on the inner surface (NKS-5 and 6, from MPA) or outer surface (PTS-I/6, from CRISM Prometey, Russia). In the spinning cylinder experiment (SC-4, from AEAT), a thick cylinder with two deep cracks on the inner surface was thermally shocked with a water spray while simultaneously spinning the cylinder about its axis in a specially constructed rig. Clad beams (DD2 and DSR3, from EDF) subjected to uniform temperature and uniaxial four-point bending were used to investigate initiation of shallow underclad cracks in the base material. The influence of out of-plane biaxial loading on cleavage fracture toughness of shallow cracks in the transition temperature region was studied using a biaxially loaded cruciform beam (BB-4, from ORNL). Data provided for these experiments included pretest material characterisation, geometric parameters, loading histories, instrumentation, and measured results for temperatures, strains, CMODs, and crack extension histories.

More than 30 participants representing 22 organisations from 12 countries performed a total of 45 analyses of the 7 reference fracture experiments in FALSIRE II. Analysis techniques employed by the participants focused primarily on FE methods, combined with single- or dual-parameter constraint methodologies for FM assessments. Participants provided analytical results for the parameters that characterise the thermal/structural behaviour of the test specimens and the fracture behaviour of the cracks. For each of the experiments, these parameters included temperature, CMOD, strains, stresses, crack loading in terms of J-integral and stress intensity factor, as well as various constraint parameters. Also, conditions of crack initiation were identified in the experiments, and where possible, computed values of parameters were compared with measured data.

Conclusions

- The temperature distributions in the specimens loaded by thermal shock generally were approximated with high accuracy and small scatter bands. Discrepancies appeared only for limited time periods during the transients and could be traced to different assumptions concerning the heat transfer coefficients.
- Structural response (CMOD, strains, etc.) of the test specimens was predicted reasonably well from best estimate analyses. This outcome represents a significant change compared with some of the results achieved in FALSIRE I. In part, the change reflects a more widespread recognition that the assumptions adopted to ensure failure avoidance in safety assessments are inappropriate when attempting to predict final failure.
- Discrepancies that appeared in the structural calculations could usually be traced to the material models and to approximations of material properties (i.e., stress-strain data).
- Calculations of fracture parameters such as J or K_I and the parameter CMOD generally showed small scatter bands. Discrepancies could be traced to the differences between elastic and elastoplastic approaches or assumptions concerning material properties.
- The K_I vs temperature diagram combined with material data curves describing fracture toughness vs temperature were determined to be useful for fracture assessments of crack behaviour. Crack initiation could be predicted from a single fracture parameter (K, J, etc.) reasonably well where constraint effects were not significant.
- When constraint effects become significant, a single parameter is not sufficient to characterise crack-tip conditions, and a second parameter should be introduced into the fracture model. Candidate constraint parameters employed by the participating analysts include Q-stress, stress triaxiality h, local approach of cleavage fracture, and a strain based function of the plastic-zone width in the crack plane. In the SC-4 experiment, constraint effects were quantified using the Q-stress and, to a more limited degree, the triaxiality parameter h. In PTS-I/6 and NKS-5, the parameter h showed indications of loss-of-constraint, while the Q-stress was not evaluated. In BB-4, a shallow crack effect was demonstrated by the computed Q-stress, which indicated a loss-of constraint due to the departure of in-plane stresses from reference small-scale yielding conditions.
- The Q-stress and other stress-based constraint methodologies have been applied successfully to correlate constraint conditions for in-plane (or uniaxial) loading conditions. However, prior studies have determined that stress-based constraint

methodologies (such as the Q-stress) are not sensitive to changes in constraint conditions due to changes in out-of-plane biaxial loading. The plastic zone width was employed successfully to correlate changes in constraint conditions for shallow cracks subjected to changes in out-of-plane biaxial loading ratios. Further investigations are necessary to clarify whether a single constraint parameter is adequate.

- Additional toughness data measured in the transition temperature region using a range of specimen geometries and constraint conditions are required to validate the predictive capabilities of cleavage fracture methodologies that incorporate constraint effects
- Simulations of crack growth and crack arrest events (e.g., in NKS-6) showed large uncertainties among the applied fracture methods.
- Additional data concerning the HAZ fracture toughness are necessary for further refinement of analyses of shallow subclad flaws.
- Almost all participants elected to use the finite-element method in addressing the problems of FALSIRE II. This represents a marked change from FALSIRE I, which included applications of a number of different estimation schemes. The detailed information that participants were asked to provide from the analyses in FALSIRE II encouraged the use of finite-element methods over estimation schemes. It should not be inferred from the outcome of FALSIRE II that detailed finite-element analyses are always the preferred or necessary technique for structural integrity assessments.

Regarding the original objective of the PWG3 to evaluate the predictive capabilities of fracture assessment methods for nuclear components it has been shown in the frame of the FALSIRE project that crack initiation and ductile crack growth as well as cleavage fracture in large scale experiments can be predicted by fracture methods based on the stress intensity factor calculated by the J-integral within tolerable scatterbands. In some cases which are characterised by strong differences in stress triaxiality between the large scale test specimen and the small scale fracture test specimens used to measure fracture toughness or fracture resistance the methods predict crack initiation at smaller loads or earlier in time. Improvement can be achieved if constraint parameters are included in the methodology of fracture assessment. The attempts to predict crack arrest resulted in large scatterbands which indicate that more effort has to be put on this subject.

INTERNATIONAL COMPARATIVE ASSESSMENT STUDY (RPV PTS ICAS)

Description

The ICAS Project grew out of a strong interest expressed by participants in the previous FALSIRE II Project to proceed with further evaluations of analysis methods used in RPV integrity assessment. It was again organised by GRS and ORNL. Thermal hydraulic aspects were also included, with the co-operation of PWG-2 (Coolant System Behaviour). The study is described in reference 3.

The Problem Statement defined a Western type 4-loop RPV with cladding on the inner surface. The RPVs proposed in the Problem Statement incorporate country-specific concerns. Special emphasis was placed on the interdisciplinary aspects of determining RPV loading conditions due to loss-of-coolant accidents. The calculations of fluid temperature and heat transfer to the structure using thermal-hydraulic analysis techniques was studied, with consideration given to models of fluid-fluid mixing and steam condensation. There were three tasks: Deterministic Fracture Mechanics (DFM), Probabilistic Fracture Mechanics (PFM), and Thermal-Hydraulic Mixing (THM).

In the DFM task the postulated loading transients refer to small-break loss-of-coolant accidents (LOCA) due to leaks of different sizes. One transient is appropriate for US nuclear plants, and two other transients are appropriate for German plants. A RPV was utilised that is typical of German design (Type 1300MW). The cladding thickness was proposed to vary in the range of designs used in the US, France, Germany and Russia. Three different transients were specified: axisymmetric small break LOCA, and 2 asymmetric (plume cooling) loading conditions due to hot leg breaks of 50 and 200cm^2. There were 5 postulated circumferential and axial surface and subclad cracks. Additional parametric studies were defined for various aspects of the problem, including the influence of clad thickness, clad and weld yield stresses, and crack aspect ratio. Furthermore different residual stress distributions due to the cladding and the welding process were provided to allow participants to investigate the influence of these stresses on crack loading. Participants were asked to calculate the temperature and stress distribution through the wall and the crack loading of the postulated cracks along the crack fronts. Fracture assessment of the postulated cracks was for crack initiation to determine the maximum allowable transition temperature (RTNDT) according to three different criteria: the maximum -, the tangent - and the 90% criteria. In the framework of the fracture assessment the fracture toughness curve from the ASME Code, Section XI, Appendix A, was assumed for all cases.

Objectives of the PFM task were to compute the conditional probability of crack initiation and the probability of RPV failure for four tasks by PFM methodology. The probability is conditional in the sense that the transient is assumed to occur. Failure means propagation of the flaw through the thickness of the RPV wall. A RPV was proposed which is typical of US construction. The four tasks investigated conditional probabilities of crack initiation and vessel failure for circumferential and axial welds under 2 different transients, with a range of inside surface fluences, and a parametric study of the crack aspect ratio.

The objective of the THM task was to compare analytical models that estimate the effects of thermal mixing and steam condensation for the emergency cooling water in the cold leg and the RPV downcomer. The assumed plant type was a 1300MW four-loop PWR. The internal measurements of the fictitious RPV and the cold legs corresponded to those of the Upper Plenum Test Facility in Mannheim, Germany. The assumed transient was due to a 200 cm^2 leak in a hot leg at time t = 0 s. Two parametric studies were proposed: the influence of variations of the water level in the downcomer; and influence of variations in the emergency cooling water injection rate per cold leg.

Conclusions

Final analysis results were provided by 25 organisations in 13 countries. The analysis results of the participants were compiled in a database and about 145 comparative plots were generated as a basis for discussions about the predictive capabilities of the analysis methods applied by the participants to the different tasks. Details are presented in reference 3.

In the DFM task 21 organisations from 13 countries participated. According to the task matrix 104 analyses were performed for the main tasks and 26 parametric studies. Some organisations used various methods. Therefore, in some tasks up to 22 sets of analysis results could be compared. DFM analysis results exhibited large scatter even for the relatively simple transient. The consideration of plasticity effects versus pure elastic approaches resulted in discrepancies between the analysis results. This conclusion can be linked to the experience of the FALSIRE project. Additional parametric studies showed that the scatter in the elastic and in the plastic DFM results could be traced mainly to a misinterpretation of the thermal expansion coefficients given in the problem statements. These values were given as usual according to the reference temperature 20°C. Most of the codes which use the mean value as input need a conversion of the data if the stress free temperature is different from 20°C. This was not done in many cases. Furthermore it was noted that differences in some of the analysis results could be a quality assurance problem related to approximation of the loading data given in the Problem Statement and input to the analysis codes.

In the PFM task 7 organisations from 4 countries performed 25 analyses and 3 parametric studies. The calculated conditional probabilities of crack initiation especially for small values of RTNDT have the largest scatter, of a factor of about 100. For the conditional probability of vessel failure this factor ranges from about 20 to 50. The conditional probabilities of elastic solutions are about a factor 2 – 4 larger than the values of plastic solutions. Some solutions which were produced with the same code showed differences which were apparently due to selection of different input parameters for simulating the margin term in the calculation of RTNDT (i.e., standard deviations for initial value of RTNDT as well as for Ni and Cu content).

In the THM task 8 organisations from 5 countries performed 7 analyses and 14 parametric studies. The methods used can be grouped into correlation based approaches, system codes and CFD codes. In the main task the expected plumes / stripes under the cold legs are simulated in some correlation based models. In these analyses the temperature difference between the centre line of the plumes under CL 2/3 reaches about 30°C. Large scatter in the results can be observed early in the transient when the water level is below the lower nozzle edge of the cold legs and the simulation of the condensation effects play an important role. Some of the models used to simulate the condensation effects (especially in system codes) show a weakness in the recognition of the flow-regime at the water stripe discharge in the downcomer. This effect is more pronounced at heights closer to the lower nozzle edge. The solutions with the lowest temperatures seem to underestimate the condensation effects in the cold legs. At times when the water level in the downcomer increases again due to low-pressure injection the results of the correlation based models are close together. The comparison of the heat transfer coefficient (HTC) results of the analyses shows an enormous scatter inside the plumes / stripes with values in the range between zero and about 10000 W/m^2K which is relevant for structure mechanics analyses. The differences between the HTC-values inside and outside the plumes affect thermal stresses and consequently an increase of the stress intensity factors for postulated cracks. Altogether, the participants determined lower HTC-values for the region outside the plumes but again with enormous scatter. Therefore a more accurate representation of the HTC especially in the range of about 1000 to 8000 W/m^2K is needed from thermal-hydraulic researchers for input to the thermal / structural / fracture analyses. For the task without condensation effects the results of the correlation based methods show a consistent trend with differences in the fluid temperature of less than 50°C and in the HTC values of up to 5000 W/m^2K. The concept of symmetric plumes under the cold legs is not supported by the three-dimensional CFD solution.

CONCLUSIONS

A series of PTS analysis round robins under OECD-NEA-CSNI PWG3, organised jointly by GRS and ORNL has been described, with the conclusions from each exercise. In the first FALSIRE exercise a lot of different estimation schemes and FE codes were applied. The main reasons for the large scatter in the analysis results were the differences in the approaches concerning consideration of plasticity effects, some simplified assumptions, lack of temperature dependent material properties, and limitations concerning their approximation in some codes. In FALSIRE II the fraction of participants which used finite element techniques increased to 75%. Together with lessons learnt from the first exercise the scatter in FALSIRE II analysis results was reduced significantly.

RPV PTS ICAS was an interdisciplinary exercise with deterministic and probabilistic fracture mechanics tasks as well as thermal hydraulic tasks. Many different estimation schemes (55% of the participants) and FE techniques were used in the deterministic fracture mechanics tasks. The main reasons for the big scatter observed for some quantities were again the differences in the approaches to consideration of plasticity effects and the required input of the thermal expansion coefficients. Besides the differences in the methods used in the probabilistic fracture mechanics tasks, sensitivity of the conditional probability for crack initiation and failure to certain input variables was identified. In the thermal hydraulic tasks the main reasons for the large scatter in the analysis results were the differences in the approaches used by the participants which were correlation based engineering methods, system codes and three-dimensional CFD codes. Some of the models especially in the applied system codes show weakness in the simulation of the condensation effects concerning recognition of the flow-regime at the water stripe discharge in the downcomer.

In summary the activities show that a best-estimate methodology on RPV integrity assessment needs a reduction of the uncertainties in each phase. A proposal for future work on the ICAS database is the selection of a set of consensus reference solutions from this exercise. This should include both estimation schemes and detailed analysis methods. Recommendations concerning how to use the reference solutions should be prepared. The resulting product could be a valuable tool for the qualification of new analysts on the subject of RPV integrity assessment.

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