Modelling of Thermal-hydraulic Loads and Mechanical Stresses on Reactor Pressure Vessels

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1 Introduction

For the assessment of the integrity of reactor pressure vessels (RPVs), various tasks of different technical fields have to be involved to achieve a general statement. The thermal-hydraulic loads and the consequential structure-mechanical stresses, occurring as a result of postulated incidents, have to be analysed. The material conditions at the respective time up to the scheduled end of operation has to be estimated. Further, possible defects from manufacture and operation, or defects to be postulated due to the limits of the non-destructive testing technology, have to be determined. To simplify the process of proof, the nuclear rules and regulations include standards regarding defect sizes to be postulated, load conditions to be considered and on the trend of the material toughness curve, which then have to be adapted to the respective plant-specific conditions. A plant-specific consideration is necessary for an appropriate safety-related assessment.

In the recent years, remarkable progress has been made regarding the development of analysis methods for the assessment of the thermal loads as well as the structure-mechanical stresses on reactor pressure vessels. Uncertainty bands in connection with the determination of the loads and stresses could have been reduced considerably, so that conservative assumptions to cover uncertainties can largely be replaced by "best-estimate" analyses, nowadays.

This success can be attributed, to a major part, to the extended data base established within the framework of large-scale experiments. In this regard, the UPTF- and HDR-experiments have to be mentioned on the thermal-hydraulic side, and the thermal-shock experiments at MPA-Stuttgart, at HDR as well as abroad at AEA-Technology (UK), ORNL (USA) and Prometey (Russia) on the structure-mechanical side.

For the other part, the progress made is based on an in-depth methodology which resulted, in the course of further upgradings, in reliable analysis tools for the determination of critical load conditions and crack loadings. Considering the interdisciplinary aspects both the thermal-hydraulic conditions in the RPV and the stresses in the RPV-wall directly resulting from them are determined.

International comparative studies showed that regarding the methodology a largely uniform view has been formed on how to proceed for the determination of thermal loads and their impact on the RPV-integrity. However, they also showed that, in part, there are considerable differences among the developers regarding the model assumptions applied. [SIE 94], [SIE 96], [SIE 99], [IAE 99].

This report presents the state of the methods for the determination of thermal loads (see Chapter 2) and their structure-mechanical impact (see Chapter 3). In addition, comments are also made on the potential of development concepts, as they are currently being pursued.

The R&D work of GRS mentioned here, was performed within the framework of research projects sponsored by the German Federal Minister for Education and Research (*Bundesminister für Bildung und Forschung - BMBF*).

2 Methods for the determination of thermal loads

Especially in case of hot-leg loss-of-coolant accidents (LOCAs) in the cooling system of a pressurised water reactor, the coolant recirculation may be interrupted, depending on the leak size and the availability of the emergency core cooling (ECC) system. A cold-leg emergency core cooling into stagnant warm primary coolant then leads to a formation of cold-water layers in the cold leg and to cold-water stratification in the downcomer during transition into the downcomer.

If this fluid-temperature distribution in the downcomer acts on the RPV-wall for a longer period, it leads to thermal stresses in the material which are partly considerable.

The thermal-hydraulic analysis has the task to determine accident sequences where the temperature differences in adjacent parts of the RPV-wall are large and last for a longer period of time. A catalogue on all relevant load conditions having the potential to cause such temperature differences has to be drawn up for each reactor plant individually, since each plant is characterised by system-specific equipment features. Such a catalogue normally includes transients during start-up and shut-down, transients such as the inadvertent opening of a main steam by-pass system (at zero load hot), faulty excitation of the high-pressure injection during shut-down and leak transients with different leak cross-sections in the hot leg.

Under the conditions described above, a high degree of detailing is required from a thermal-hydraulic analysis. Usually, the downcomer is being subdivided in thermal-hydraulic analyses into one or several vertically arranged flow areas, the so-called parallel channels. With regard to the accuracy required for a detailed brittle fracture analysis, this subdivision is not sufficient. This becomes obvious when considering the cooling mechanisms which have been observed in the corresponding test facilities.

2.1 The cooling mechanisms plume and stripe cooling

Two different cooling mechanisms, the plume and stripe cooling, are considered in connection with the determination of thermal loads. Stripe cooling occurs when the cold-leg emergency core cooling takes place at a time when the water level in the downcomer has fallen below the opening of the cold-leg nozzle. Here, those loss-of-coolant accidents are taken into consideration which either show a sufficiently large leak cross section or where the emergency core cooling has limited availability.

The stripe cooling causes the biggest thermal load by far, because an only moderately heated cold water stripe of relatively small width cools down the RPV-wall with a large temperature difference to its surrounding area.

However, the significance of cold water stripes for the determination of thermal loads is restricted, since corresponding experimental analyses show that cold water stripes already become detached from the RPV-wall with a relatively low mass flow rate.

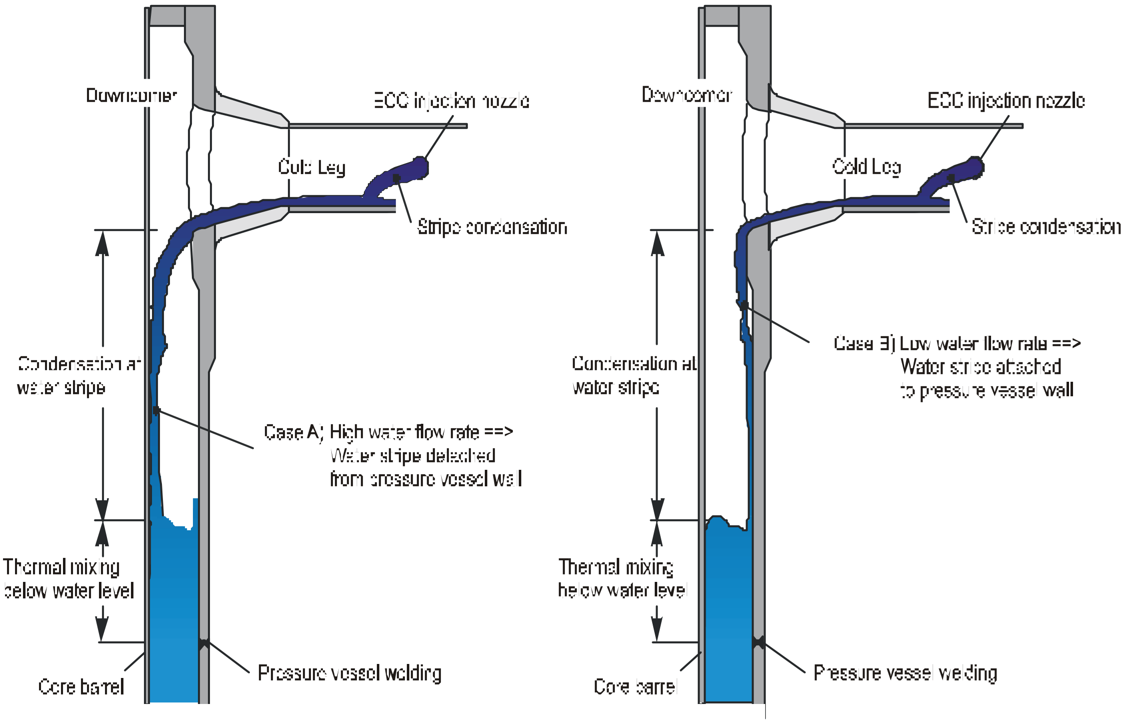

Fig. 1: Water stripes in the downcomer with large and small mass flow rate – Mechanisms for the heating of the emergency core cooling water

Depending on the constructive layout of the cold-leg nozzle, 10 kg/s are for example sufficient to detach a water stripe from the vessel surface (see Fig. 1). Compared to it, the injection rate for a high-pressure emergency core cooling system with 80 kg/s is high. Therefore, the stripe cooling is most significant for the area of the cold-leg nozzle.

The width of the cold water stripe depends on the flow velocity of the draining cold water stripe. Experimental investigations show that this velocity is determined by the flow phenomenon "critical flow«. Dependent on the mass flow of the emergency cooling water, a water level in the cold-leg appears at which the flow velocity exactly corresponds to the critical flow velocity. It turns out that for the relevant mass flows stripe widths of about 10 to 30 cm are to be expected in the cold-leg nozzle. Within this width, the nozzle is cooled down locally.

Cold water plumes are formed if the cold-leg emergency coolant is injected into a downcomer filled with water. Such a situation arises, e.g., from loss-of-coolant accidents with a smaller leak cross section in the hot leg.

In a perspex model, established in 1983 by IVO (Finland) in its flow laboratory, one half of the downcomer with connected cold legs of a WWER-440 type reactor was modelled on a scale of 1 : 2.56. The flow distribution was made visible by adding red pigments. Fig. 2 shows a situation in the downcomer where cold water (red) is injected via a cold leg for 50 s. A clearly separated, meandering plume is formed in the scaled downcomer model.

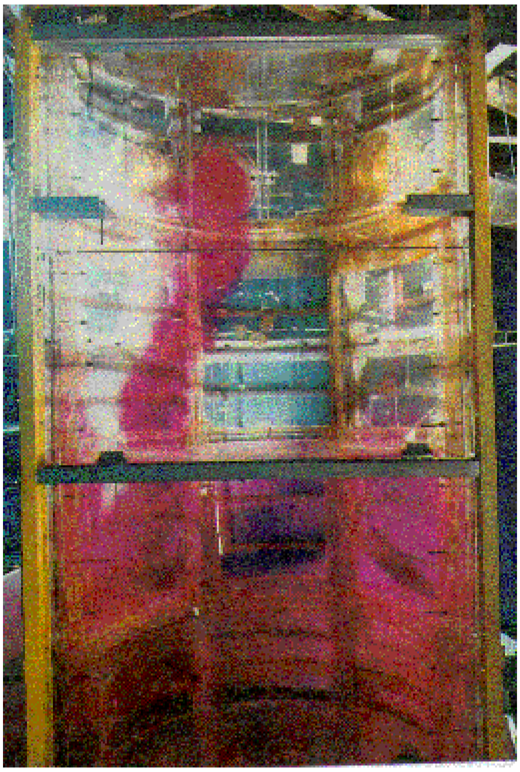

Fig. 2: Formation of a cold plume in one half of the downcomer [TUO 86]

Moreover, plumes coming from neighbouring cold legs can merge and can intensify the cooling effect on the RPV-wall.

Fig. 3 schematically shows the merging of plumes, as it approximately can be interpreted from the experimental data of the UPTF-TRAM experiment C1.

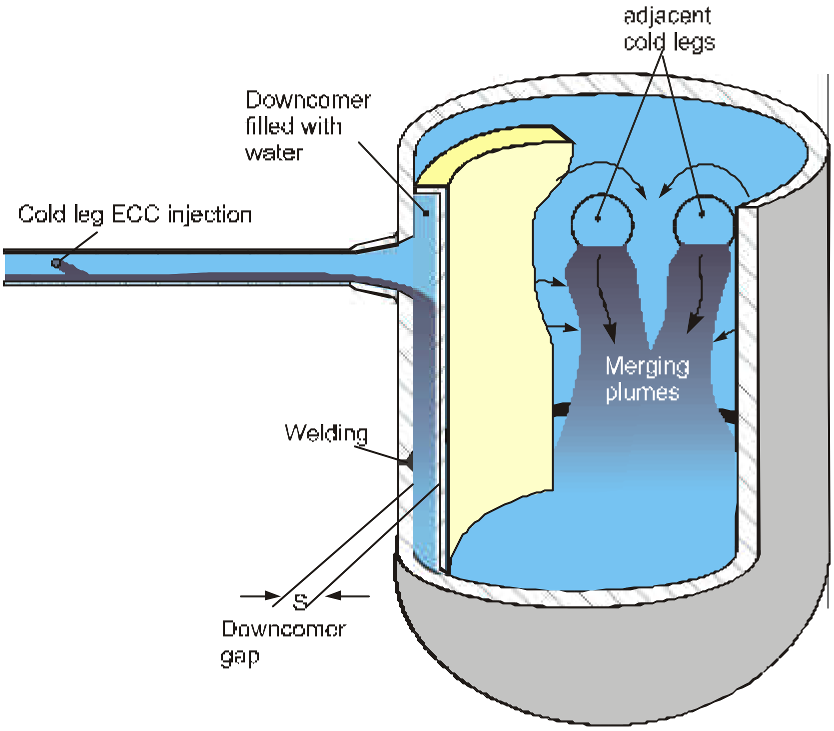

Fig. 3: Merging of plumes during injection into neighbouring cold legs

Since these plumes stay for a longer period until final mixing, i.e. about one to two hours, the temperature differences can act on the RPV-wall correspondingly long. In contrast to the stripe cooling, the concentration of cold emergency coolant here is lower. By admixture with the water surrounding the plume, there is a permanent exchange. The plume width is dependent on the injected mass flow and the exchange with its environment.

Requirements for predictive models can already be derived from these experimental findings.

2.2 Methods for the determination of local fluid-temperatures and local heat transfer coefficients

By means of the so-called parallel-channel technique, thermal-hydraulic computer codes, such as RELAP5, TRAC-P or ATHLET, can basically fulfil the requirements stated above regarding the degree of detailing. However, the international discussions within the framework of the RPV PTS ICAS standard problem [SIE 99] show that the uncertainties related with it are considerable in the thermal load and that detailed temperature distributions are necessary if an in-depth fracture-mechanical analysis is required. As a result, too much emphasis is laid on the mixing processes in the majority of cases solved by the parallel-channel technique and plume temperatures differ to a smaller degree from the environmental temperatures.

The so-called CFD computer codes (CFD: Computational Fluid Dynamics) are codes which solve the Navier-Stokes equations optionally two- or three-dimensionally, having the potential to reach the necessary degree of detailing. However, the application of these computer codes is limited at present because of the determination of adequate turbulence parameters which have a considerable influence on the calculation results.

Therefore, such analysis results are used for plausibility considerations, since they predict flows in geometrically complex structures qualitatively well, whereas quantitative statements are still connected with considerable uncertainties.

At present, the most important approach to determine local temperature differences is delivered by so-called engineering models. By means of these models, as far as they refer to a qualified experimental data base, the local thermal load can be determined relatively exactly with a relative small number of calculations.

2.2.1 Coarse-grid and parallel-channel technique

Thermal-hydraulic computer codes generally offer the possibility to subdivide the downcomer azimuthally in separate parallel subsections, i.e. the parallel channels. These parallel channels admit a lateral exchange. Here, the downcomer is seldom subdivided into more than four channels.

The parallel-channel computer codes have the advantage that, besides the one-phase flow processes, such as the mixture of cold and warm water, the two-phase flow processes, such as condensation of steam at subcooled water, can also be simulated.

The TRAC-P code, which is to be regarded as coarse-grid technique within the framework of the application up to now, offers, like the parallel-channel technique, the possibility of a more refined azimuthal discretisation of the downcomer. Within the framework of the international standard problem RPV PTS ICAS, a downcomer model for a 4-loop plant was developed by the participants for the TRAC-P code. In this model, the downcomer was subdivided into 16 azimuthal zones of the same width, which is equivalent to a parallel-channel representation with 16 channels.

The participant himself criticised that the resulting plume width depends on the chosen azimuthal discretisation to a large extent. This means that the calculated plume mostly is congruent with the widths of the discrete model zones. However, it can be stated that a description of the merging plumes is recognised correctly by this approach. But the predicted merging does not take place between the cold legs with injection, although symmetrical injection into the four cold legs is specified. The calculated merging preferably shifts below one of the two injected cold legs (Fig. 4). This result does not correspond to the observations made in UPTF, where a merging of plumes took place between the injected cold legs.

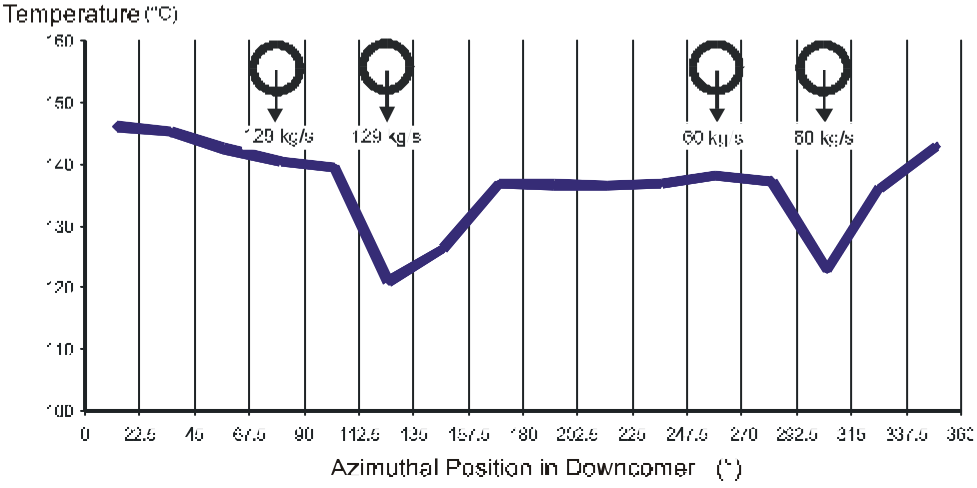

Fig. 4: Azimuthal temperature distribution in the downcomer 2 m below injection nozzles from a TRAC-P analysis on plume formation (time 900 s)

It can be concluded that coarse-grid- and thus the parallel-channel technique are not yet sufficient for this specific requirement. The achievable results are plausible with regard to the discretisation, but they are not helpful for the quantitative determination of local temperatures and heat transfer coefficients, as they are required for a subsequent stress analysis. At present, it cannot be assessed definitely, whether a further refinement of the discretisation is helpful. However, it seems to be plausible that this approach shows a potential for further development to reach the required accuracy in future.

2.2.2 CFD computer codes

CFD computer codes solve the mass-, impulse- and energy conservation equations (Navier-Stokes equations) in their two- or three-dimensional form. Initially, they were developed for one-phase flows, but they are also increasingly applied for the calculation of two-phase flows. Velocity-, pressure- and temperature fields can be determined with a high degree of accuracy. The discretisation aspect in CFD codes is less sensitive than in coarse-grid methods. Thus, a higher degree of universal validity can be expected.

The application limits of CFD codes are to be found in the large effort required for a calculation, on the one hand, and the accuracy of the turbulence- and phase-interactions modelling, on the other hand.

With respect to the integrity assessment of pressure vessels, a large number of load cases is to be calculated ranging from normal operation with start-up and shut-down over faulty excitation of the emergency core cooling systems up to loss-of-coolant accidents with different leak sizes. Here, the CFD codes can only be applied for selected tasks for financial reasons.

The exact prediction of one-phase cooling mechanisms, such as the stripe cooling, also represent a challenge for the CFD codes. The flows within the cold leg and the downcomer are driven by small density differences between cold emergency cooling water and the residual hot water inventory in the vessel. In the cold leg and in the downcomer, regions of stagnation and of relatively low velocities occur. Therefore, a transition from turbulent to laminar flows takes place at the borders of these regions.

This means for CFD codes and the implemented turbulence models that both buoyancy effects and effects of small Reynolds numbers have to be modelled adequately. This can be done either by the application and calibration of two-equation turbulence models with empirical corrections or «Second Moment Closure Turbulence Models« requiring more time and efforts, corresponding to a modelling of fluctuations. Up to now, the laminar-turbulent transition is not reliably predicted with the turbulence models used so far.

In Germany, the CFD-program ANSYS/FLOWTRAN has been applied for the assessment of thermal load assumptions. In the first line, this CFD-analysis [STÄ 97] serves to gain phenomenological understanding of the process of plume merging. Moreover, the local temperature- and velocity profiles were determined which are, e.g., the basis for the calculation of heat transfer values for plume-free areas.

The users of the CFD-programs emphasise that prior to such analyses, a verification by means of task-related experiments is necessary. However, the number of tests to be performed is significant lower compared to the derivation of correlations for methods with coarse-grid and parallel-channel technique due to the broader general applicability of CFD-methods.

To intensify the application of CFD-methods in the field of nuclear technology, the calculation time has to be reduced considerably, e.g. by the use of parallel computers. Furthermore, the existing turbulence models, as briefly addressed to here, have to be refined. In this respect, it is a challenging task to make models available for the description of multi-phase flows as well as for the description of the interactions between multi-phase flows and turbulence. Only with this extended basis, a CFD-analysis may be made available also to the load cases with the cooling mechanism "stripe cooling".

2.2.3 Engineering models

Engineering models can be described as a conglomeration of correlations and equations having the potential to determine the heating process of the emergency cooling water from the injection location to the position aimed at in the downcomer. Here, all conditions, as they are expected, e.g. during a transient, are to be treated by these models. This means that both condensation processes and mixture processes are to be quantified by these engineering models.

This definition is also applicable to computer programs such as REMIX, «physically based zonal approach«, KWU-MIX and the engineering model GRS-MIX.

These engineering models cannot be applied to other geometrical conditions than those specified without essential modifications. A model for "thermal mixture during injection into the pump bend", e.g., is not suitable if the experimental base of the model is limited to analyses where the injection takes place between pump and downcomer and not in the pump bend.

Moreover, these models can only be applied with valid results as far as they have been validated by corresponding model verification on an experimental base. If, however, all these prerequisites are fulfilled, these engineering models yield the requested data with a very high quality.

In 1995, the experimental data base was established for nuclear installations of the KWU type by means of the UPTF-TRAM experiments (test series C1 and C2). The great importance of the experiments is attached to the full-scale representation of the thermal hydraulic phenomena which might occur in a KWU pressurised water reactor plant. However, it has to be noted that the pressure vessel walls of the UPTF-test facility are considerably thinner than in a real reactor plant.

From these experiments, the heating of the emergency cooling water can be observed from the point of injection in the cold leg to the position aimed at in the downcomer. In this connection, experiments have been carried out both with water-filled downcomer and with a water level below the cold leg nozzle. This means, both the heating by thermal mixture and the heating by steam condensation can be quantified by means of these experiments.

Within the framework of its phenomenological analysis from data of UPTF-TRAM experiments, GRS has determined flow regimes, developed corresponding correlations for each flow regime, and implemented them in the engineering model GRS-MIX. This modelling also considers, besides data from the UPTF-TRAM experiments, experimental data from scaled test plants in order to include the scale effect in these correlations. Thus, a model is available by which the heating effects of the emergency coolant resulting from condensation and resulting from thermal mixing can be predicted with a high degree of accuracy.

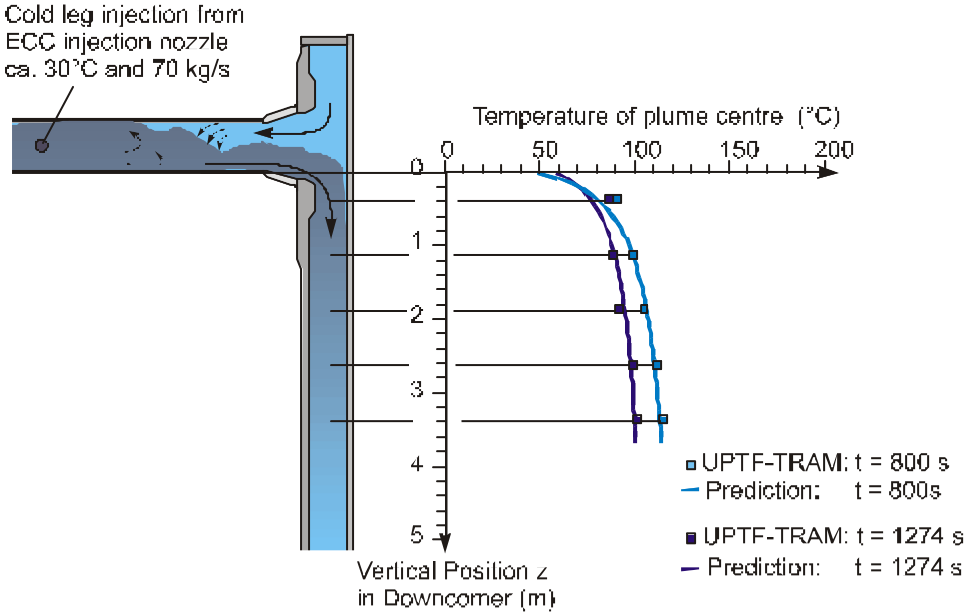

Fig. 5: Post-test prediction with engineering model GRS-MIX of test run C1, run3b1 of the UPTF-TRAM-test programme

Fig. 5 exemplary shows the post-test prediction of the UPTF-TRAM test run C1 with the engineering model GRS-MIX. The calculated temperature in the plume centre results from the thermal mixing in the cold leg and mixing in the downcomer. The accuracy achievable by this model is very high with ±3K, and thus fulfils the requirements aimed at within the framework of integrity assessments.

2.3 Assessment of the methods for the determination of thermal loads

The international benchmark RPV PTS ICAS, based on the geometrical conditions of the test facility of the UPTF-experiments, but with wall thicknesses of a reactor plant, allows the comparison of different models and methods, respectively, for the prediction of temperatures in the centres of plumes (see Fig. 6).

It turned out, that the participants achieve different results, even if the heating of the emergency cooling water, as shown schematically in Fig. 5, is only due to mixing. On the other hand, the same comparison shows a good agreement for the participating models c) KWU-MIX and b) GRS-MIX.

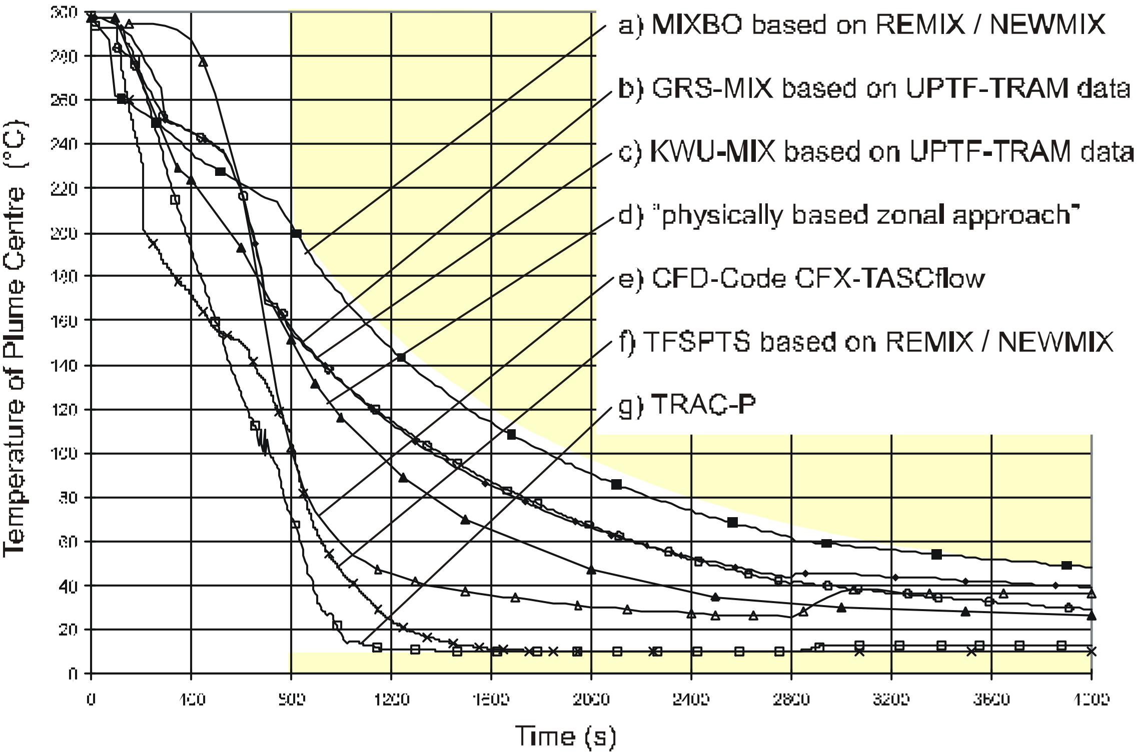

Fig. 6: Temperature in the plume centre 2 m below the cold leg nozzle in the downcomer

The remarkable agreement between the two engineering models shows that, among other things, data from the UPTF-experiments have been referred to for the modelling. These experimental data have not been available to the other participants for modelling. In this respect, the plume-centre temperatures determined by the participants c) and b) may be regarded as reference solution for the benchmark task respectively.

The comparison of the different approaches clearly shows that the choice of the method, e.g. CFD-model or engineering model, does not necessarily allow a prediction of the quality of the results.

It further shows that the parallel-channel technique (TRAC-P) is still far away from realistic conditions. In the estimation of the authors it cannot be expected from this technique that corresponding modelling improvements will be sufficient to perform integrity assessments in the foreseeable future.

The CFD-program CFX-TASCflow applied here does not yield satisfactory results in this first trial, either. An improvement in the turbulence modelling by using relevant experimental data (UPTF, HDR, etc.) is still required before it can be applied in connection with integrity assessments.

The other engineering models (MIXBO based on REMIX/NEWMIX, «physically based zonal approach», TFSPTS based on REMIX/NEWMIX) deliver very different analyses results. When using these models, the experimental data base, used for the modelling, should be valuated with regard to compatibility with the geometry to be analysed.

In general, engineering models should only be applied if the application can be related to a relevant verification, i.e. that there are no large deviations in geometry. An extrapolation according to an application to a deviating geometry not covered by the corresponding experimental data base is regarded as problematic, since large-scaled convective flows, such as mixing of flows with different temperatures in the downcomer, depend on the geometrical situation to a great extent. A modelling of these flow processes on a reduced scale normally shows other phenomena or phenomena with other intensities. This results in a correspondingly limited modelling so that the applicability of the model remains limited, too.

Altogether, the comparative study RPV PTS ICAS shows, that until today experimental studies on a relevant scale cannot be replaced by computer codes, regardless what kind of code is used. Presently, the engineering models of SIEMENS and GRS are of outstanding importance, since they are based on the best data base available. Already today, they fulfil the requirements to be put for a thermal-hydraulic analysis in the course of a detailed integrity assessment.

3 Methods for the determination of structure-mechanical response

With regard to the great importance of the integrity of the reactor pressure vessel for the observance of the protection goals in the defence-in-depth concept, special importance is placed on the scientific qualification of the methods, procedures and examinations applied for the integrity assessment. Accordingly, a great number of projects for the development of methods to describe load bearing characteristics, including crack loadings and the performance of large-scale experiments, have been promoted in the past within the framework of reactor safety research. Further, the accuracy of the results of the applied analysis methods was examined within the framework of parametrical analyses. As supplementation, a systematic analysis was carried out which delivers a classification system for uncertainties of the total calculation chain and the input data.

In the following, analyses methods are presented, by means of which structure-mechanical issues in connection with the integrity of reactor pressure vessels under thermal-mechanical transient loads can be treated.

3.1 Methods for the calculation of structure-mechanical parameters with the finite-element method (FEM)

As analyses tools for structure-mechanical issues, Finite-Element (FE) computer program systems, such as ADINA [ADN 97] and suitable pre- and postprocessors, are used for the effective preparation and evaluation of calculations, in addition to programs based on simplified methods. Fig. 7 shows the structure-mechanical analysis chain of GRS.

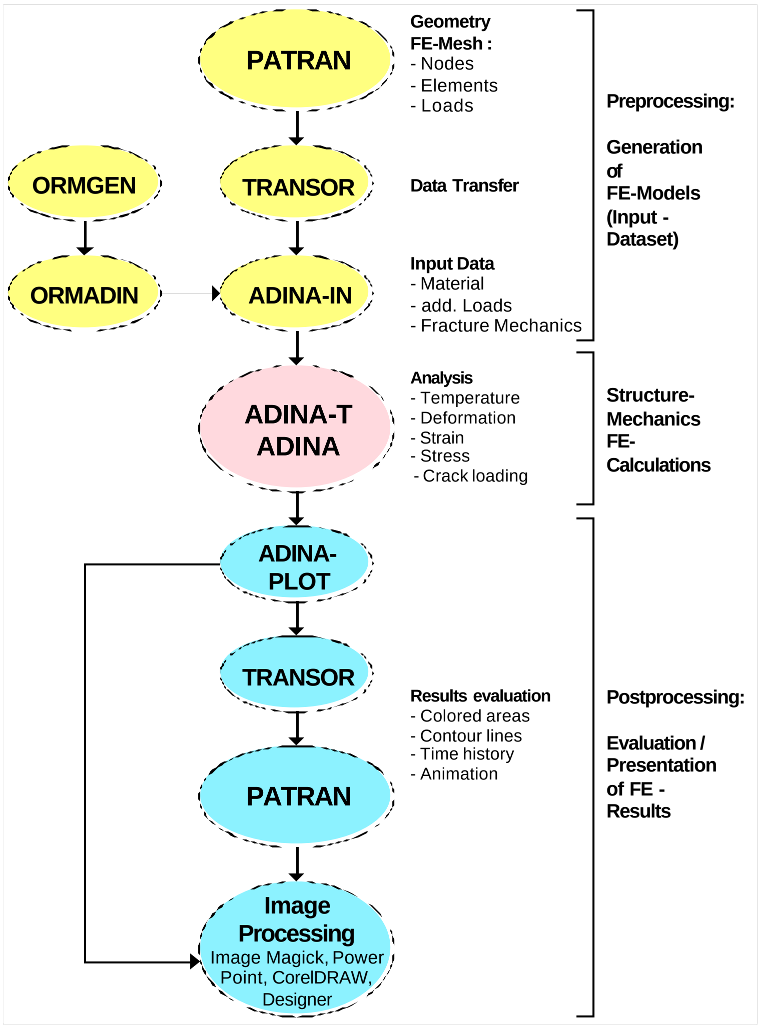

Fig. 7: Program chain for structure-mechanical analyses at GRS

When developing complex models, e.g. crack models, where transitions between the regions with coarse- and fine-meshing have to be modelled, the application of totally interactive processors, e.g. PATRAN [MSC 96], is worth wile. The connection to ADINAIN is established with an interface program, where the analysis preparation is completed with the determination of the material data and the transient loads.

The analysis results are evaluated with ADINAPLOT or PATRAN. With the different postprocessors, suitable graphical illustrations, as e.g. coloured areas, isolines, deformed structure, time histories can be generated by selection from the data variety.

The loading of a crack in a component, e.g. a RPV or a test specimen, under thermal-mechanical load can be described by the J-integral [LOR 85].

The validity of the common J-integral formulation used for the description of the crack loading is limited to load conditions which can be described with a non-linear elastic material model. For states with load reduction after plastification, extensions of the J-integral formulation were examined [SCH 99].

3.2 Fracture-mechanical assessment scheme (KT-diagram)

For the calculation of the crack loadings in a fracture-mechanical test specimen or a test vessel, or of a postulated crack in the RPV-wall accordingly, simplified methods and procedures on the basis of the FE-method are generally available. When using the FE-method, the crack loadings are determined locally by the J-integral along the crack front, e.g. according to the method of the virtual crack extension [LOR 85]. For the fracture-mechanical assessment it is recommended to determine the stress intensity factor K_I from the J-integral. For the elastic area or in case of small-scale yielding, the following relation exists between K_I and J:

$$K_I = [\,J \;\; E'\,]^{1/2}$$

with $E' = E$ for states near the plane-stress condition
with $E' = E/(1-n^2)$ for states near the plane-strain condition

For thermal-mechanical transient loads, the fracture-mechanical assessment of the crack loadings is performed as function of the time or function of the crack tip temperature (load path curve) respectively, by comparison with the crack resistance curves J_R or the temperature-dependent fracture toughness K_{IC}.

The proceeding for demonstrating the integrity is presented schematically in Fig. 8.

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Fig. 8: Fracture-mechanical assessment of cracks under thermal-mechanical loads (schematic representation)

In the increasing part of the load path curves $K_I(T)$ determined according to the thermal-mechanical load and the crack size and crossed from the right to the left, a point of intersection with the fracture toughness curve K_{IC}, connected with the crack initiation values K_{IJ}, which are derived from the fracture resistance curves, indicates crack initiation.

For intersections in the area of decreasing crack loadings, i.e. after the maximum of the load path curve, experiments show additional safety margins. No crack initiation takes place in the area of timely decreasing crack loadings (partial aspect of the "warm prestress effect"). This aspect has been verified by comprehensive experiments at small-scale specimen [ROO 97b] and can be explained with local plastification processes at the crack tip.

Further, with the KT-diagram stable crack growth can be quantified with corresponding values deviated from crack resistance curves. The methodology described proved to be valuable within the framework of post- and pre-calculations of numerous large-scale thermal-shock experiments for the determination of brittle and ductile crack initiation and of stable crack growth (see Chapter 3.3).

The previously described fracture-mechanical assessment method, by means of which the calculated crack loadings are compared with the values for fracture toughness and crack resistance, respectively, determined with the subsize specimen, in the KT diagram, is based on the assumption that the behaviour of the cracks in the small-scale specimen can be transferred to the behaviour in large-scale specimen and components, respectively (see Fig. 9).

Experimental studies of MPA Stuttgart [ROO 97a] show that the temperature-dependent curve for the physical crack initiation (see Fig. 8) is geometry-independent, and thus transferability is given from small-scale specimen to large-scale specimen and components.

However, additional experimental studies on fracture mechanics specimen show that both the crack resistance [CLA 89, KOR 87] and the brittle fracture initiation are geometry-dependent, as far as they occur in connection with considerable plastification. These circumstances are also indicated in Fig. 8. Therefore, additional parameters are being evaluated with regard to the transferability to components, to describe the stress triaxiality on the crack ligament. In this respect, it is the aim to extend the one-parameter concept, based on the J-integral, to a two-parameter concept, to find specimen during application, the crack behaviour of which can be transferred.

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Fig. 9: Transferability of the crack behaviour of small-scale specimen to large-scale specimen and components

For the evaluation of the crack behaviour in the component, the crack resistance of those specimen should be taken, the stress triaxiality of which approximate the ones of the components optimally. Since the stress triaxiality in the component changes with time due to thermal-mechanical transient loads, one representative crack resistance should be selected for each relevant load condition.

3.3 Level of verification of the fracture-mechanical analysis methods

The crack behaviour under thermal-shock load, partially combined with mechanical load (pressurised thermal shock-PTS), has been investigated in numerous experiments, among others at MPA Stuttgart at the large-scale test facility HDR in Kahl, in the ORNL (USA), at AEA-T (UK) and Prometey (Russia), especially at cylindrical specimen with cracks. Here, it was aspired that the test specimen correspond to the wall thickness of real pressure vessels.

With regard to the stiffness conditions and potential load symmetry tolerances, however, the experiments show considerable deviations in comparison with real pressure vessels. Regarding the realised loads, the specimen surfaces were frequently exposed to shock-like and axisymmetric temperature differences. In contrast to it, the realistic emergency core cooling transients show essentially lower gradients in the time history of fluid temperatures and asymmetries in the heat transfer.

The crack behaviour of the tested material in the transition area can be described satisfactorily with regard to the crack initiation within the framework of the K_{IC}-concept in connection with the K_{IJ}-curves derived from crack resistance curves. In this respect, the crack behaviour during assessment on the basis of measured K_{IC}-values or on the basis of K_{IC}-procedure curves, respectively, is approximated optimally with measured reference temperatures (RT_{NDT}).

In some experiments (AEA-T, Prometey), the crack was initiated later in connection with considerable plastification and with considerably higher stress intensities, compared to the K_{IC}-curve. This effect is attributed to differences in the stress triaxiality (constraint) between the fracture-mechanics specimen and the test cylinders [SIE 97b].

Since the load sequences for the reactor pressure vessels in case of incidents may be rather different, the verification of the methods developed can only be realised by means of a comprehensive verification matrix to cover different time histories of the loads, different types of defects (surface cracks and sub-clad cracks) and different material conditions.

All experiments refer to the issues crack initiation and limited stable and unstable crack growth during coupled thermal-mechanical load. The thermal-shock experiment carried out at the HDR test facility was stopped before completion due to an erroneous prognosis of non-destructive tests. Consequentially, no crack initiation took place.

For the major part of the experiments, comparative calculations were carried out by different institutions within the framework of the FALSIRE project [SIE 94], [SIE 96]. For 13 large-scale experiments, a database was established with the experimental results and the results of 84 analyses performed by 29 organisations from 13 countries. Methods based on the FE-method, as well as simplified methods were applied by the participants.

In summary, it can be concluded from the extensive analyses on thermal-shock experiments that the fracture-mechanical assessment method on the basis of the J-integral has a high verification level for the determination of the crack initiation (brittle or ductile) and the quantification of stable crack growth. Therefore, this method is recommendable for the demonstration of the RPV-integrity. In this respect, the results of the analyses on crack loadings should be assessed by means of measured curves for fracture toughness and crack resistance.

3.4 Experiences from the application of the methods for the integrity assessment of reactor pressure vessels

Issues related to the integrity of reactor pressure vessels can be analysed with the finite-element method by elasto-plastic stress calculations, and the loading of postulated cracks can be determined with the method of virtual crack extension in a realistic way. Here, different materials, such as cladding, base material and weld material, with temperature-dependent material characteristics can be considered as multi-linear approximation.

In the area between cladding and weld material or base material, respectively, strong stress gradients, a large plastification in the cladding and a limited plastic zone may occur in front of the crack front. On the basis of an analytically determined elastic stress distribution or an elastic or elasto-plastic stress distribution calculated with an FE-model without crack, stress intensity factors or the J-integral as load parameter for postulated cracks can be determined with analytical approximation procedures.

In an RPV safety analysis, the temperature distribution and the stresses in the RPV-wall, as well as the loadings of postulated cracks in the near-core wall area are to be calculated in subsequent work steps. The fracture-mechanical analyses on reactor pressure vessels under thermal and mechanical transient load can be carried out in a RPV-model with crack or in two steps with a global model without crack and a detail model with crack.

In the two-step approach, the structure-mechanical load of the RPV is calculated time-dependent in the global model without crack and transferred at the contact surfaces between global and detail models to the detail model with crack in form of time histories of deformation and temperature. A comprehensive, complex global model has the advantage that the effect of idealising deformation boundary conditions on relevant results can be minimised.

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Fig. 10: RPV-1, 3D-360°-FE-model with three cooling stripes

For German reactor pressure vessels of the older generation (4-loop and 2-loop), axisymmetric and 3D-360°-finite-element models have been developed with sufficient degree of detailing as global models without crack and as detail models with crack in the near-core weld as well as in the region of the nozzle corner edge (see Fig. 10).

The structure-mechanical response on transient loading due to ECC injection was calculated within the framework of elasto-plastic FE-analyses, first in the global model and transferred to the detail model in form of time histories of deformation and temperature functions at the contact surfaces between global and detail models. After that, elasto-plastic FE-analyses were performed with the detail models.

This approach is particularly effective in connection with parameter studies regarding the crack geometry, since only one global model analysis is required. In the 360°-global models, the geometric asymmetries and the possible asymmetries due to loadings have been considered. The cladding is considered with a thickness of 7 mm in all models, and the near-core circumferential weld is determined at an average axial width of 50 mm.

In the detail models, circumferential cracks have been analysed, since these are more critical than axial cracks during plume or stripe cooling due to increased axial stresses, if the percentage of crack loadings due to internal pressure is considerably smaller than the thermal percentage.

The results of the analyses as well as interdisciplinary aspects of the analysis methodology are summarised in [SHU 96]. Studies on the influence of the parameters cooling stripe width and number, FE-model height, deformation boundary conditions, plasticity and crack form on the RPV were performed, among other things, at RPV of the WWER-440 and -1000 type, respectively. These results are summarised in [SIE 97a].

Regarding the task matrix of the international comparative study RPV PTS ICAS [SIE 99], elasto-plastic calculations were performed with the previously described analysis method based on the FE-method and the J-integral as parameter for crack loadings. In this respect, the influence of the parameters crack geometry, cladding thickness, load transient including cooling assumptions on the analytically determined maximum allowable nil-ductility transition temperature $RT_{NDT}^{allowable}$ have been analysed.

In this respect, basically different assessment criteria can be applied (see Fig. 11).

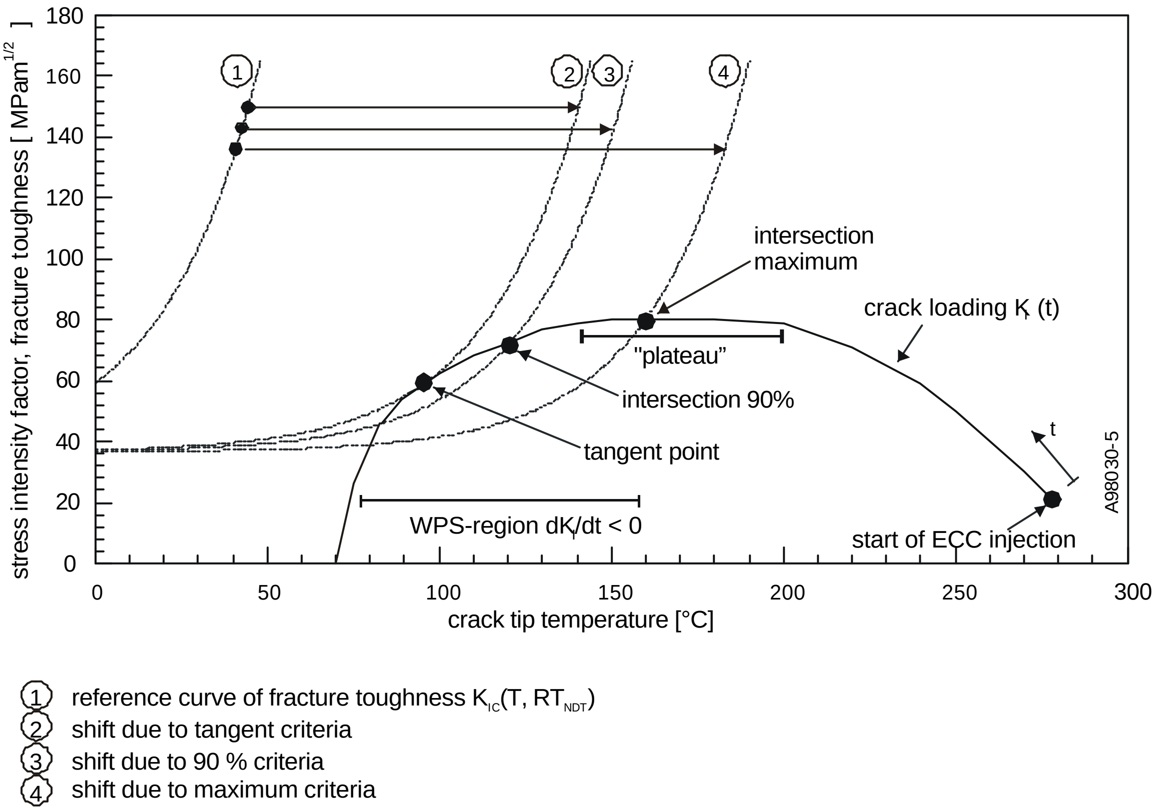

Fig. 11: Schematic representation of criteria for fracture-mechanical assessment of crack loadings during emergency cooling transients, determination of the maximum allowable nil-ductility temperature $RT_{NDT}^{allowable}$

For many transients considering mixing effects, crack loading curves are flattened in plateau form in the area of their maximum. Due to the low loading level, and partially also due to the increased yield strength by irradiation embrittlement, there is nearly no plastification in the weld material or the base material, respectively. A numeric uncertainty regarding the determination of the maximum may have a strong influence on the location of the maximum in this case.

Therefore, GRS made the proposal, within the framework of the discussions on the safety assessments of brittle fracture resistance of older German RPVs, to use a point of intersection 10% below the maximum. By this approach, numerical analysis uncertainties shall be covered sufficiently. The approach has also been included in the IAEA-guidelines on the performance of integrity assessments for WWER-type reactor pressure vessels [IAE 97].

For the axisymmetric transient T1 (20 cm^2 leak) from the ICAS-task matrix, a circumferential crack of 360° (C1 with a crack depth of 16 mm), a half-elliptical surface crack (C2 with a crack depth of 16 mm and half crack length of 48 mm) and a half-elliptical sub-clad crack (C4 with a crack depth of 10 mm and half crack length of 30 mm) have been analysed. As expected, the highest loads occur at the 360° circumferential crack, followed by the surface crack. The sub-clad crack has a considerably lower loading level (see Fig. 12).

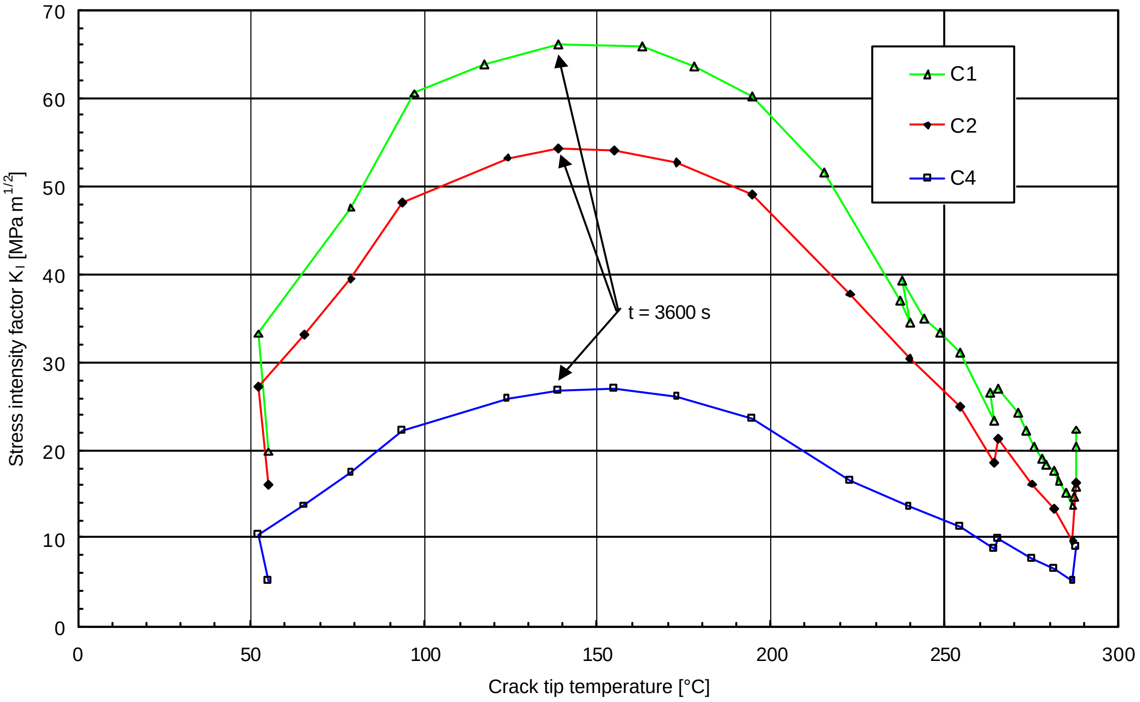

Fig. 12 Stress intensity factor as function of the crack tip temperature for the cracks C1, C2 and C4 under transient T1

Further, the stress intensity factors for the surface crack C2 have been compared to all three transients of the ICAS-task matrix. In the transients, the downcomer cools down faster with increasing leak size (20, 50, 200 cm^2) due to the increasing injection rate. By this, the largest crack loadings are reached for the 200 cm^2 leak (transient T3) but at lower temperatures compared with the transients T1 and T2 (see Fig. 13).

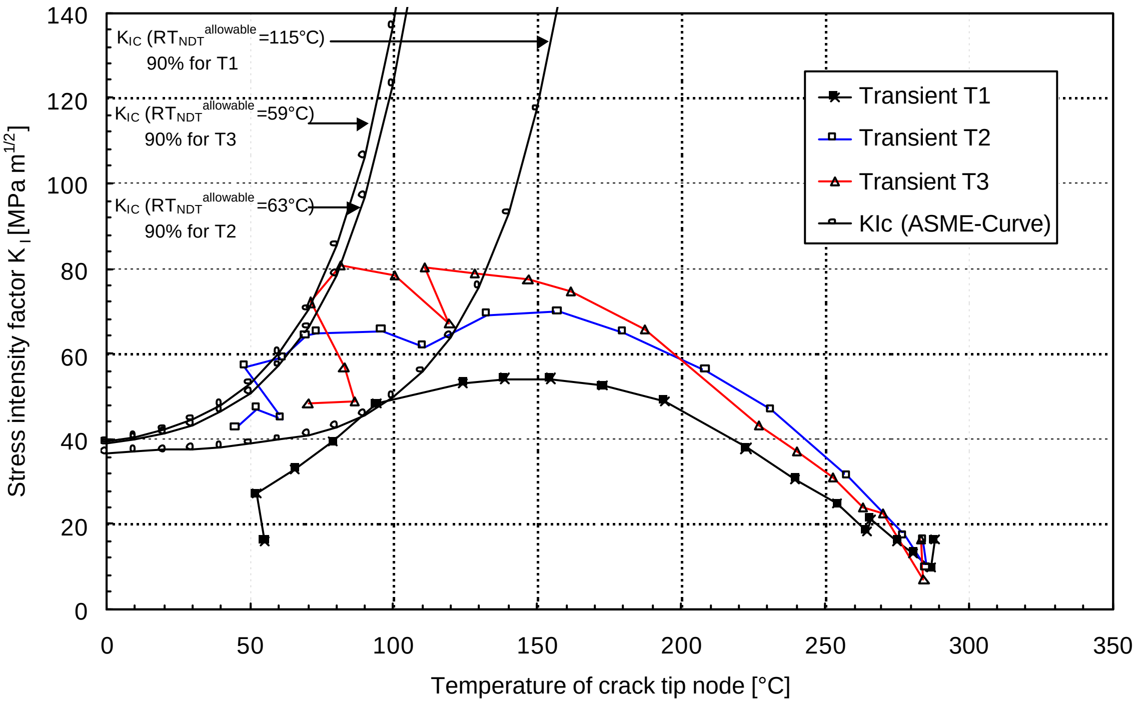

Fig. 13 Fracture-mechanical assessment at the deepest crack front point of the surface crack C2 for the three transients T1, T2 and T3.

An evaluation of the maximum allowable nil-ductility temperature at the deepest crack front point shows a band width of 59°C to 115°C for the three transients. The assessment criterion was the respective intersection between ASME curve and the crack loading, which reaches on the decreasing load path branch 90% of the maximum crack loading of the last load path maximum in time.

An assessment on the basis of the maximum stress intensity factor would result in a band width of the $RT_{NDT}^{allowable}$ values of 63°C to 146°C for the cases analysed here.

Considering transient T2 alone, there is a difference of 83°C in the $RT_{NDT}^{allowable}$, depending on whether the assessment is based on the 90% value at the decreasing branch of the last load path maximum in the K(T)-diagram or on the maximum.

Safety factors have not been taken into consideration in the fracture-mechanical assessments summarised here.

4

5 Conclusions

In the past years, the development of the analysis methods for the determination of the thermal-hydraulic loads and the structure-mechanical stresses on reactor pressure vessels has been concentrated especially on the consideration of multi-dimensional load and stress conditions, as well as on complex material conditions. Uncertainty bands in the determination of the loads and stresses have been reduced considerably so that today, conservative assumptions to cover uncertainties or simplified analyses, respectively, can largely be replaced by "best estimate" analyses.

In this respect, the progress made in the estimation of thermal loads is primarily founded on the accessibility of experimental data from the UPTF-TRAM test programme, from which the multi-dimensional flow conditions in the cold leg and the downcomer of pressurised water reactors of the KWU-1300 type can be read on a scale of 1:1.

The international standard problem RPV PTS ICAS was defined considering the geometry of the UPTF-test facility, and therefore allows to assess different model approaches which are applied world-wide in connection with the determination of thermal loads.

Basically, there are three different concepts being pursued internationally for the spatial dissolution of the three-dimensional flow in the cold leg and downcomer:

a) Coarse-grid and parallel-channel technique,
b) CFD-programs, and
c) engineering models.

It shows that a priori reliable three-dimensional flow calculations are to be expected from none of the model approaches mentioned. At present, each of the model approaches is only as valid as the experimental data base on which it is based.

Therefore, it becomes obvious from the international benchmark that the engineering models of SIEMENS and GRS are currently clearly in the lead compared to other approaches due to the access to the data of the UPTF-TRAM-experiments. They are the only model approaches not differing in their predictions.

The authors expect that the use of engineering models is not the last development in connection with analyses on structure loads, since they are always limited to a geometrically clearly defined field of application. Therefore, it is expected from future improvements within the framework of a model development regarding CFD-programs that the deficiencies existing today can be compensated and that application limits induced by geometry can be lifted.

The structure-mechanical analyses show that fracture-mechanical assessment methods are available allowing to give, in a basic approach, a consistent picture for the description of brittle and ductile crack extensions. The testing of the methodology in connection with experiments has made considerable progress. It can be derived from the comprehensive analyses on thermal-shock tests that the fracture-mechanical assessment method on the basis of the J-integral has a high verification level for both the determination of crack initiation (brittle or ductile) and the quantification of a stable crack growth. Thus, it is recommendable for the assessment of RPV-integrity. In this respect, the analyses results for the crack loadings should be assessed by means of measured curves of fracture toughness and crack resistance, respectively.

Regarding safety-related assessments, it is possible to carry out detailed analyses on the respective task with a very limited amount of time required by means of the analyses tools available today. The existing uncertainties both in the thermal-hydraulic flow analysis and in the fracture-mechanical analysis can be quantified with little additional efforts in form of parametric studies, and can be considered in the assessment.

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