Failure Assessment Methodologies for Components under Severe Accident Loading

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Abstract:
During postulated high pressure core melt accident scenarios temperature values of more than 800°C can be reached in the reactor coolant line and the surge line of a pressurised water reactor (PWR), before the bottom of the reactor pressure vessel experiences a significant temperature increase due to core melting. For the assessment of components of the primary cooling circuit, especially concerning the question which component fails first, analysis methods of different complexity have been used.
Furthermore, the behaviour of a steel containment loaded by peak-like pressure and temperature which may occur during beyond design accident scenarios with hydrogen combustion has been investigated.

1 INTRODUCTION

In face of severe accident scenarios with melted core material which occurred recently at Fukushima Daiichi and in 1979 at Three Mile Island-2 (TMI-2) the integrity assessment of primary circuit components as well as containment structures require a special concern. Exemplary best estimate calculations concerning integrity of pressure retaining components and a steel containment structure under severe accident loading scenarios are presented in the paper. Concerning pressure retaining components especially the question which component fails first is of interest. Further an efficient method for integrity assessment of piping which has been developed to be used in framework of thermo-hydraulic analysis with system codes will be described.

2 DETAILED THERMO-HYDRAULIC AND STRUCTURE MECHANIC CALCULATION OF A SEVERE ACCIDENT SCENARIO

As an example the integrity of components in the primary circuit of a PWR loaded by a core-melt scenario with remaining high pressure in the primary cooling circuit has been investigated with a complex analysis model. Thermo-hydraulic evaluations for this case show that the reactor pressure vessel (RPV) bottom, the main coolant lines (MCL) and the surge line can reach temperatures above 800°C. A main aim of the study was to clarify whether the pipe lines will fail earlier than the RPV bottom or vice versa.
To estimate the failure temperatures and times structure mechanic calculations with the FE-code ADINA [1] were performed with load assumptions concerning internal pressure and component temperatures which are gained by thermo-hydraulic calculations.

2.1 Essential Results of Thermo-hydraulic Calculations

For the thermo-hydraulic calculation of the assumed accident scenario the program MELCOR [2] was used. The complete primary circuit of a PWR was simulated. Some essential results of temperature and pressure distributions are presented in the Figs. 1 and 2.

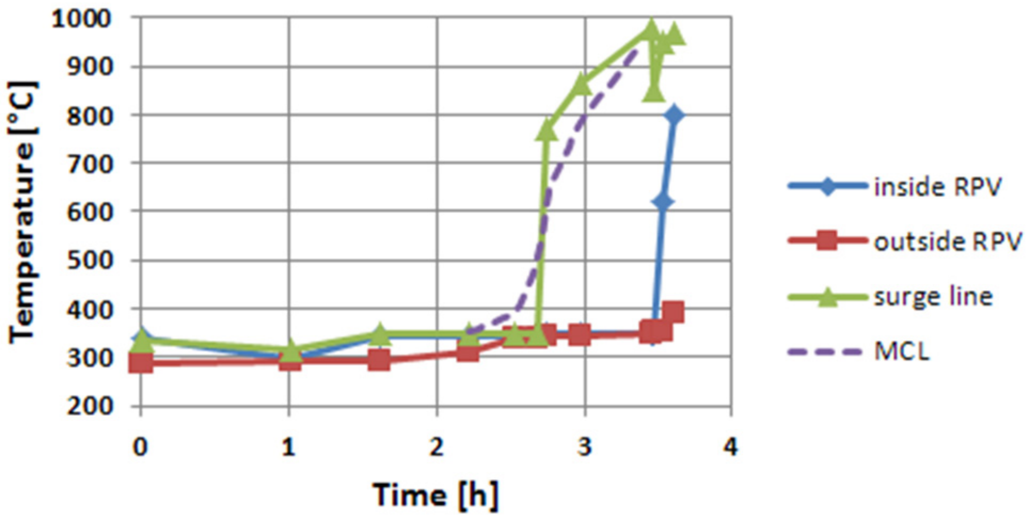

Fig. 1: Temperatures versus transient time for different positions

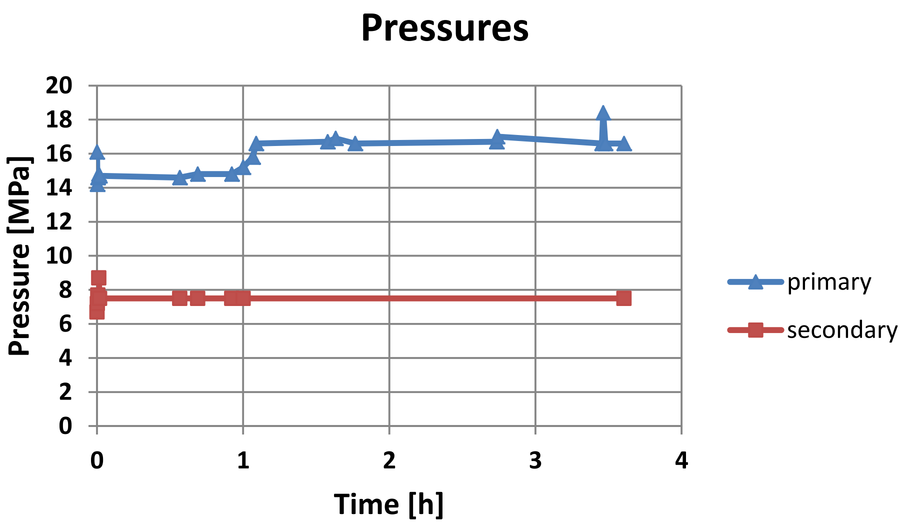

Fig. 2: Pressures versus transient time for primary and secondary circuit positions

2.2 FE-model for Structure Mechanic Calculations

For the FE-calculations with ADINA [1] a model of the surge-line loop of a PWR was used. The model shown in Fig. 3 was build up during research projects at GRS, see e.g. [3]. It also contains feedwater and steam line from steam generator to the containment penetration.

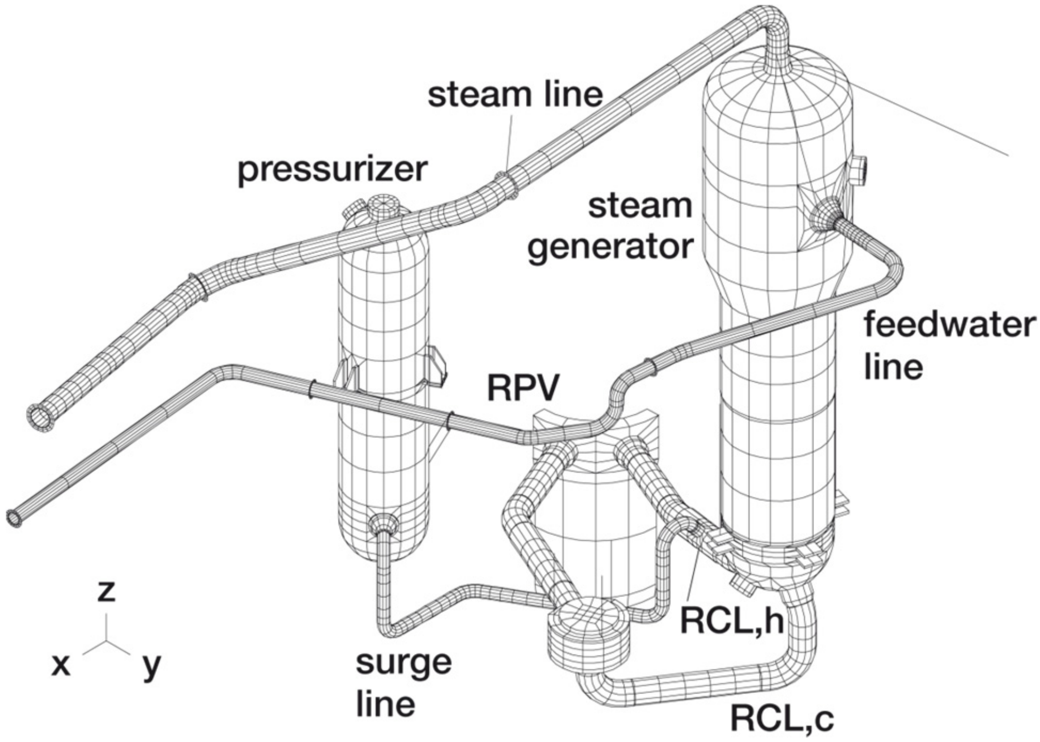

Fig. 3: FE-model of the coolant loop including surge line and pressurizer

As the model is loaded by temperatures up to nearly 1000°C corresponding high temperature material data have to be used. For the ferritic parts the stress-strain curves shown in Fig. 9 are used. Similar data are provided for the austenitic part of the model (surge line).

As mentioned already the load functions for the FE-model concerning the wall temperatures of the components and the internal pressure are delivered by results of MELCOR calculations (accident scenario „total station blackout“). At 35 positions of the FE loop model the temperature at inside and outside of the wall was evaluated. The temperature values between these positions are gained by interpolation. Also the temperature values in the middle of the wall were found by interpolation.

2.3 Estimation of Time of Failure

For the integrity assessment of pressure retaining components a strain based approach is used. Besides the calculated accumulated plastic strain and the triaxiality factor characterising constraint effects the temperature dependent uniform elongation (see Fig. 9) is used as a material parameter. According to the approach integrity of a pressure retaining component is assured if

$$e_p < \frac{e_g}{TF}$$

with the plastic strain e_p, the uniform elongation e_g and the triaxiality factor TF (see chapter 3.2).

If the calculated accumulated effective plastic strain exceeds the strain limit locally in a significant region of the component’s wall the failure of the component is assumed in the sense of a safety related assessment. Furthermore, assessments concerning failure as a matter of fact can be performed with suitable assumptions.

2.4 Selected Results of the Structure Mechanics Calculation

To show how the estimation of failure time is carried out two selected evaluations are shown in Figs. 4 and 5. The first one is for a typical integration point in the main coolant line (hot leg) between RPV and steam generator, the second one is an integration point in the surge line.

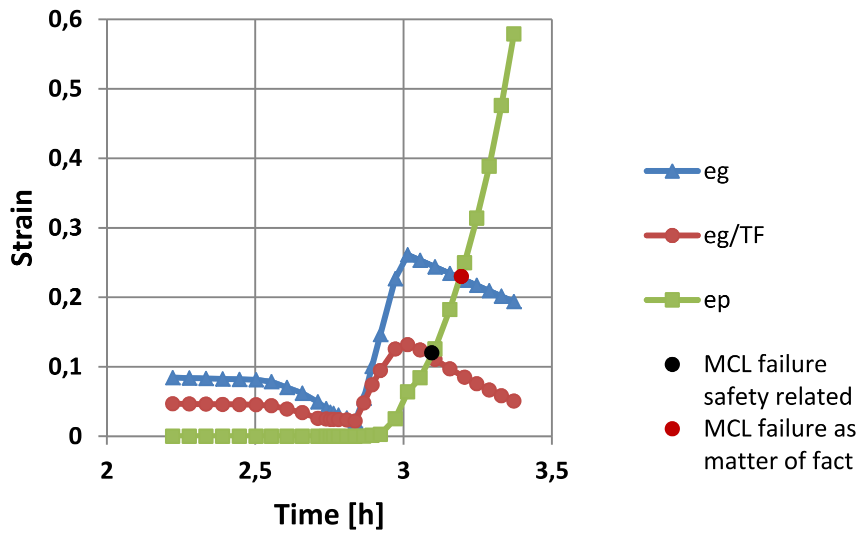

Fig. 4: Integrity assessment for a typical integration point in the MCL

The intersection points of eg/TF and ep deliver the failure times of a safety related assessment. For the MCL this gives a failure time of about 3.1 h of the transient time. An assessment of the MCL with TF=1, i.e. failure as a matter of fact, gives a failure time of about 3.2 h. For the surge line a failure time of about 3.35 h is found based on a safety related assessment.

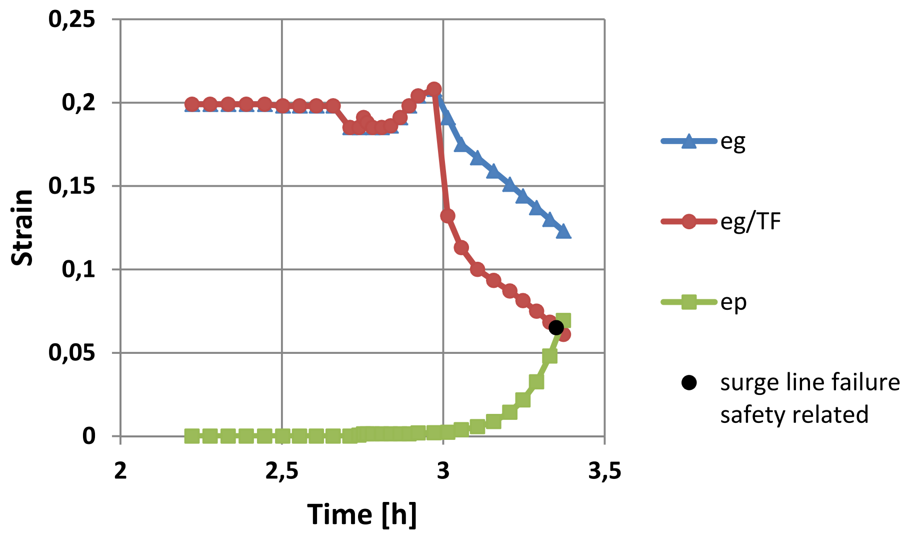

Fig. 5: Integrity assessment for a typical integration point in the surge line

Additionally Fig. 6 presents times and temperature values at failure for MCL and surge line together with the transient temperatures calculated by MELCOR.

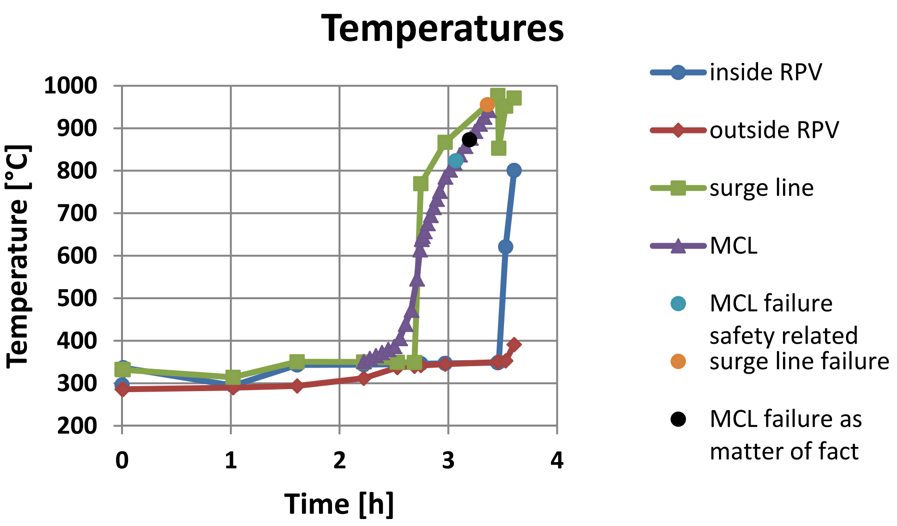

Fig. 6: Temperatures versus transient time for different positions together with times and temperatures of failure for MCL and surge line

The steep increase of the RPV temperature starts at about 3.5 h transient time. It may be concluded that failure of the MCL is expected about 0.3 h before the temperature increase of the RPV starts. Creep effects have not been considered in this analysis but they would contribute to an increase of the time difference mentioned before.

3 METHOD ASTOR

The method ASTOR is an easy applicable tool for fast estimation of failure times. Furthermore the reduced complexity enables the integration into thermo-hydraulic codes and may help to find results of structure mechanical properties which are required for coupled calculation of mechanical and thermo-hydraulic structure characteristics of primary circuit devices. Moreover the method ASTOR helps to determine the degree of structural damage after a history of load at the actual point of time. Therefore it is possible to determine the remaining durability of components under the assumption that the actual loads will continue at a constant level. The method ASTOR can be employed for failure time calculation without time intensive non-linear structure-mechanical analysis. The analysis requires a suitable failure time surface. The method ASTOR published already in [4] has been developed further to have more accurate results. In the following the method and the further development will be displayed. During a high pressure core melt accident a transient temperature and pressure load will occur on the inner surface of a pipe (see Fig. 7). The load can be characterized by a range of temperature and pressure.

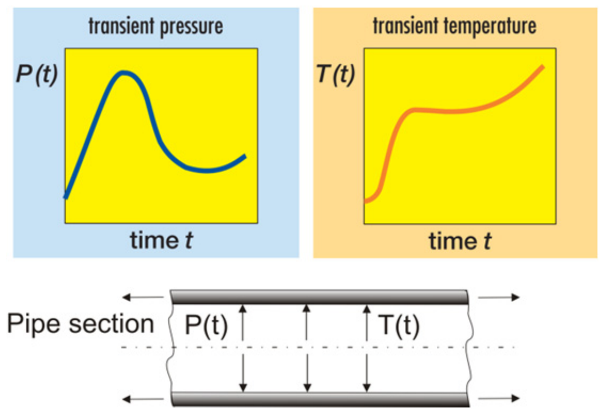

Fig. 7: Transient loads on pipe

Within the defined ranges cascaded pressure steps and temperature steps are defined. Failure times of the pipe structure under combinations of pressure steps and temperature steps are determined by finite element analysis with the FE-program ADINA [1].

Performing several numerical analyses of this kind to cover the ranges of temperatures and pressures to be expected in an accident yields a series of structural failure times which can be regarded as discrete pivots of a continuous failure time surface in the failure time-temperature-pressure space (see Fig. 8). In the next step of the procedure the failure time surface is used in connection with some damage accumulation hypothesis to predict the time to failure of the structure when subjected to loads which are varying in time. In these cases the characterizing parameters, i. e. inner surface temperature and internal pressure, do change in the course of time. For each point of time which is characterized by a temperature and a pressure value a damage increment can be calculated. The result of the summation of damage increments is a damage value *D(t)*. The failure can be assumed when the damage value *D(t)* reaches a value of 1 or a smaller value if safety factors are included.

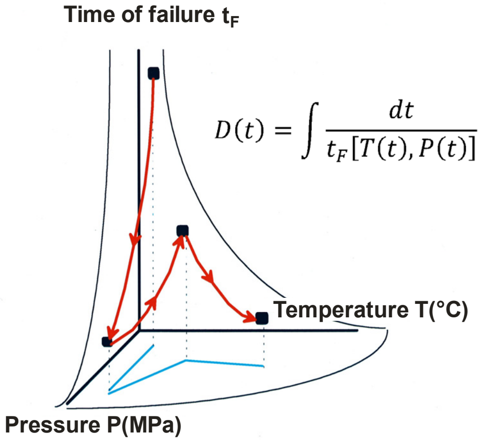

Fig. 8: Linear damage accumulation hypothesis in ASTOR

In the framework of further development a time-consuming method for the determination of failure surfaces has been developed. The chain of software modules consists of three modules. The first module provides a file structure and builds up the framework for forthcoming FE-analysis and failure assessment. The module requires input data about FE-geometry, material data, data about failure assessment and information about the number of nodes of the failure surface. After each simulation run a failure assessment is accomplished by a software module. Failure criteria for plastification and creep failure are used for failure assessment. After all simulation runs and failure assessments are accomplished a final software module collects all available output and failure data for compilation of the input file for analysis by ASTOR.

3.1 Material Data and Approximation of Creep Curves

Basis for the temperature dependent stress-strain-relations of the piping material steel 20 MnMoNi 5 5 used in German NPPs are data measured by the testing facility “Materialprüfungsanstalt (MPA)” of the University of Stuttgart [5], [6]. Temperature dependent stress-strain-curves were derived for the temperatures up to 1200°C (Fig. 9) to build up the basis for the material model of the FE-Program ADINA [1].

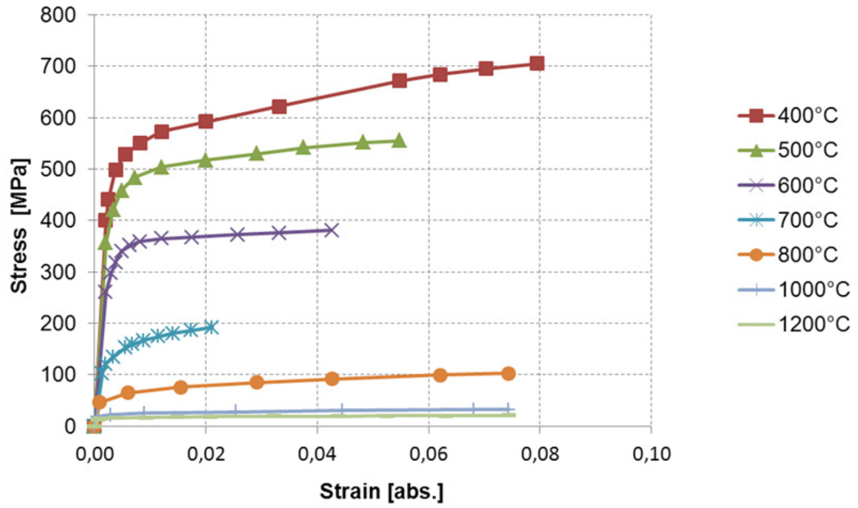

Fig. 9: Steel 20 MnMoNi 5 5: true stress-strain curves up to uniform elongation (400°C – 1200°C) derived from measured data

For the simulation of creep behaviour of components the FE-codes usually include material models which describe the time dependence of creep strain with parameters stress and temperature. On the other hand the material characterisation is usually determined by load controlled creep curves. Exemplary in Fig. 10 the approximation of load controlled creep curves for a temperature level of 1000°C is displayed.

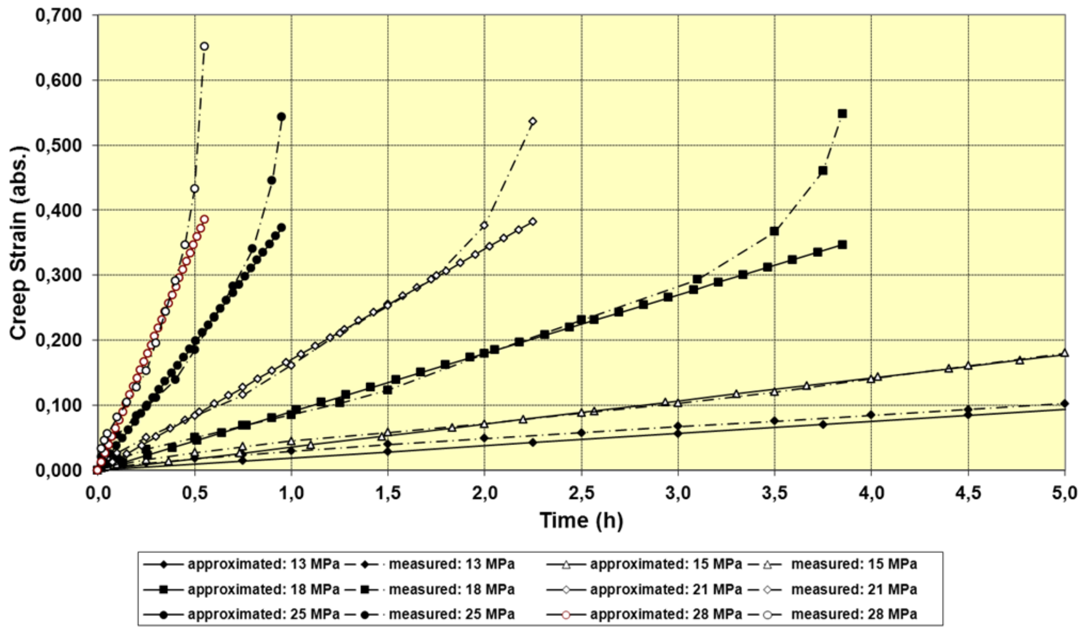

Fig. 10: Linear approximation of measured creep curves (load controlled) of steel 20 MnMoNi 55 at 1000°C

For modeling of creep properties of the steel 20 MnMoNi 5 5 a "Creep Law" of the FE-Program ADINA [1] was employed:

$^{t}\overline{e}^{C} = a_0 \; ^{t}\sigma^{a_1} \, t^{a_2}$, with temperature and stress dependent parameters a_0, a_1 and a_2.

The steel 20 MnMoNi 5 5 does not show a pronounced primary creep phase. Therefore, the secondary phase, which is important for the progress of creep, can be approximated by a straight line determined by the stress and temperature dependent parameter a_0 for the slope, a_1 = 0 and a_2 = 1. The tertiary creep phases of the load controlled creep curves are not considered because in that phase the stress level increases. According to this method the approximated creep curves of the steel 20 MnMoNi 5 5 were computed based on a spreadsheet analysis with MS Excel.

3.2 Failure Criteria

Both failure due to plastification and due to creep are employed as failure criteria for an integrity assessment based on FE-analysis. Due to the higher level of stresses and strains failure at the inside of the pipe structure is considered. To predict the time to failure of a piping based on a FE-analysis it is necessary to define criteria for failure. The analysis results are assessed concerning failure on basis of a strain criterion. An ADINA material model is employed which considers plastic strains as well as creep strains. The value of strain is determined by the temperature dependent strength and the temperature/stress dependent creep characteristic of the relevant material. As the uniaxial strain limit for plastification the uniform elongation is considered. Based on calculations of large-scale creep experiments the limit of uniaxial creep strain is determined by 60% of the creep failure strain of the uniaxial creep tests for a safety related assessment [7]. Especially for the question which component of a primary circuit fails first additionally an assessment concerning failure as a matter of fact is necessary. This kind of assessment employs a limit of uniaxial creep strain determined by 100% of the creep failure strain of the uniaxial creep tests. The Fig. 11 shows the temperature dependency of the uniaxial limit of creep strain for the 60%- and the 100%-criterion.

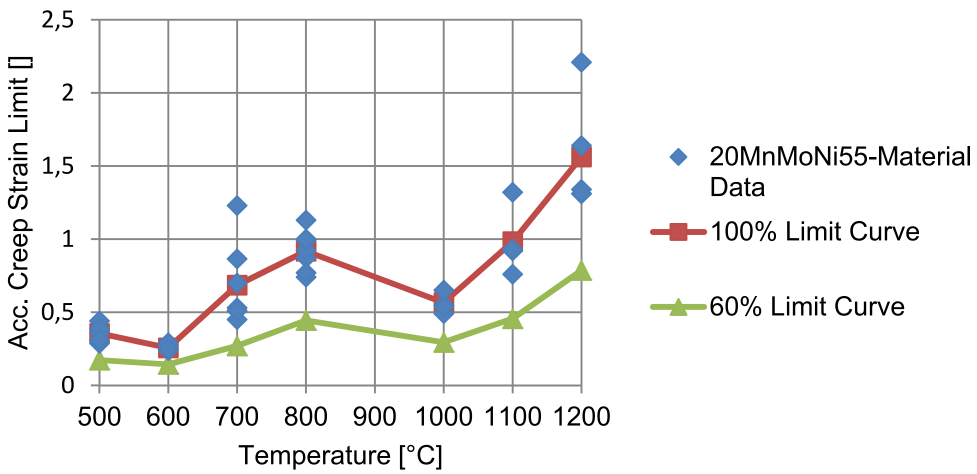

Fig. 11: Steel 20 MnMoNi 55 – Approach for definition of uniaxial creep limit

For consideration of multi-axial stress and strain states it is common practice to reduce the strain limits by division with a triaxial-factor TF which appears in the following form [8]:

$$TF = \frac{|\sigma_1 + \sigma_2 + \sigma_3|}{\sigma_{effective}}$$

The stresses σ_1, σ_2 and σ_3 represent the principal stresses and $\sigma_{effective}$ the von-Mises effective stress. The triaxial factor may reduce the strain limits for safety related assessments significantly.

3.3 Simplified Finite Element Model of a Pipe Structure

The abstraction from the pipe structure to the analysis model is displayed in Fig. 12. The rotational symmetry of the pipe can be used for a reduction of the model into a 2D-representation of the geometry. This helps to reduce computation times significantly which is obligatory in case of a high number of required computations.

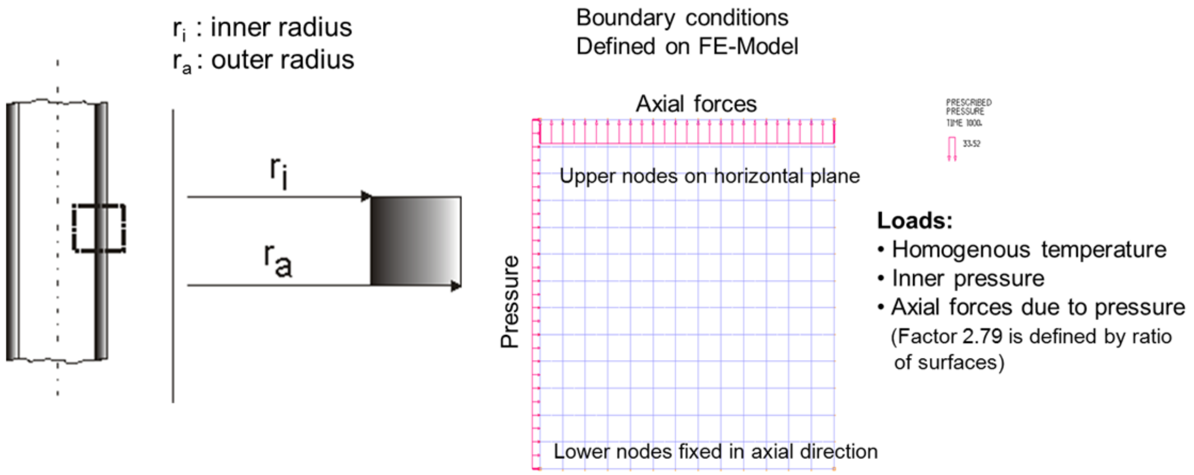

Fig. 12: 2D-Representation of pipe structure, dimensions, loads and boundary conditions

Loads (forces and temperature) as well as boundary conditions are defined. Because of the rotational symmetry it is possible to define loads and boundaries on lines. The temperature is defined as a homogenous temperature load on all elements.

3.4 Failure Surface

In the following a failure surface of a PWR reactor coolant line (RCL) with the geometry inner diameter 750 mm and wall thickness 62 mm is considered. In the Fig. 13 the calculated times of failure due to different constant temperature/pressure loads are summarized. A total of 740 FE-computations and failure assessments of a pipe structure were performed. There are 10 pressure steps from 0.5 MPa up to 18 MPa. The temperature progression covers temperatures from 100°C up to 1300°C. The correlation between increase of failure time by decrease of pressure and temperature is obvious. Failure times above a time limit of 40000 s are not considered. Exemplary the load steps of 0.5, 2, 6, 10, 14 and 18 MPa are displayed. The failure time surface is considered as the surface which is spanned by the peaks of the columns.

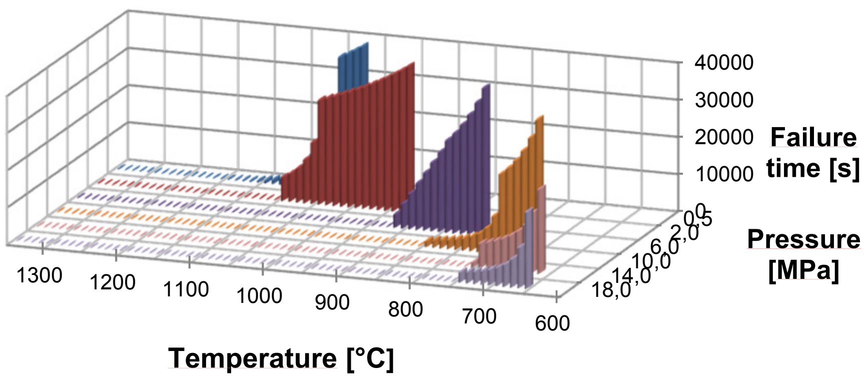

Fig. 13: Failure time diagram for a RCL of 20 MnMoNi 5 5

4 COMPONENT TEST AND SIMULATION

For validation of the employed FE-Simulation and the failure assessment procedure test data of a component test [13] are employed. The question of the short-term creep behavior at high temperatures was in the focus of this experimental investigation. The endurance and the fracture opening behavior of the reactor coolant piping were determined. For verification of the results from small specimen tests a component test on a section of piping was carried out. The reactor steel 20 MnMoNi 5 5 was used as the test material. The conduct of this test was to simulate specific accident conditions; under a constant internal pressure of about 16.6 MPa using air as the pressurizing medium the vessel was heated from outside to about 730°C to determine the time to failure (see Fig. 14). The component test was conducted on a pipe of about 8 m total length closed at its ends by dished heads. The actual test pipe section which was welded into the center had a length of 2700 mm, an internal diameter of 700 mm and a wall thickness of 47 mm. The whole test assembly was freely suspended by means of welded-on lugs. Pronounced plastic deformation commenced about 780 s before failure, i.e. about 320 s after begin of the holding phase at a temperature of about 720°C. Failure occurred by the appearance of a longitudinal crack which after reaching the circumferential weld seam of one of the two extension pipes was deflected into the circumferential direction. A thermal FE-analysis by ADINA [1] is accomplished to obtain the temperature distribution of the structure. The output of thermal FE-Analysis is used as temperature input data for the following implicit FE-analysis. A simulation model with the geometrical properties of the test pipe was employed for a FE-simulation with ADINA. The reduced 2D-model revealed in Fig. 6 was employed with modified dimensions. The test pipe has an inner diameter of D_i=700 mm and a thickness t=47 mm. A failure criterion which employs the 60% of the creep failure strain of the uniaxial creep tests reduced by the calculated stress triaxiality factor was used for a safety related assessment (see Fig. 15). The used criterion predicts a failure at 12470 s which is very close to the failure time of the test (12469 s). The results of the component test simulation have been presented on SMiRT 21 [9].

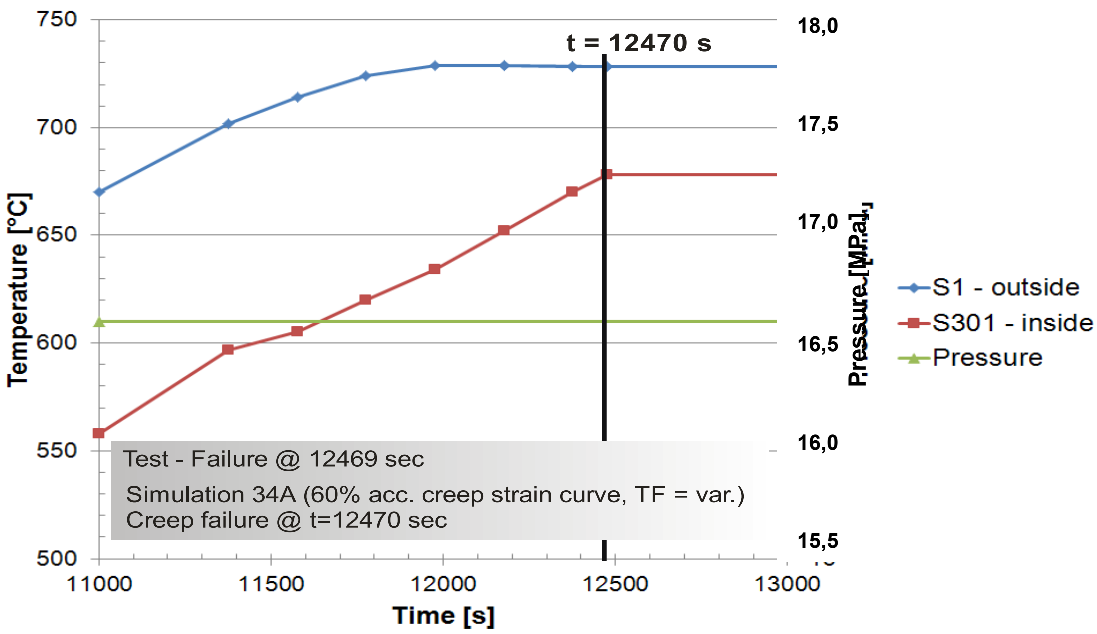

Fig. 14: Loading conditions in the test pipe

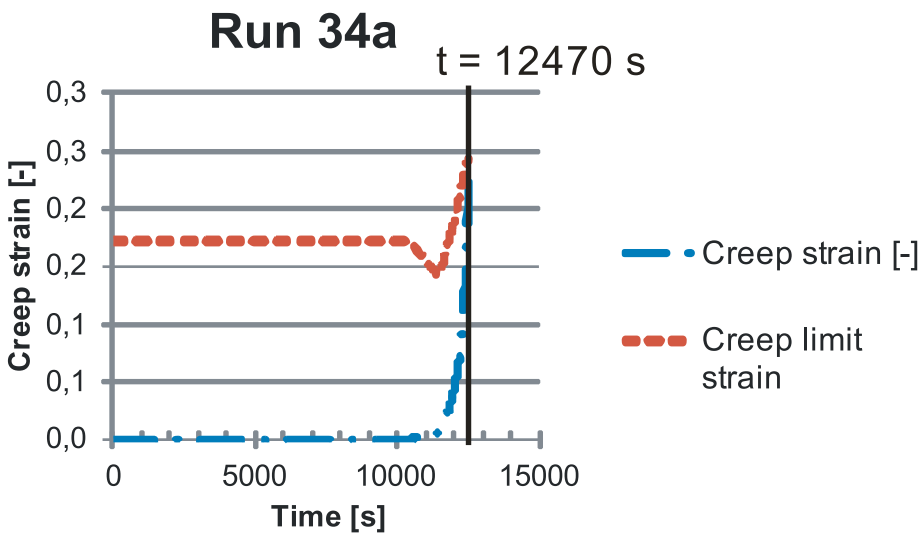

Fig. 15: Accumulated creep strain and strain limit curve (failure at 12470 s)

5 SIMULATION OF A SEVERE ACCIDENT SCENARIO

In the following section the results of a FE-based failure assessment and an ASTOR failure analysis for a RCL loaded during a severe accident scenario are compared. Due to an assumed station blackout scenario of a PWR molten core material in the reactor pressure vessel – Lower Head (RPV-LH) may cause catastrophic consequences. The time of failure of the RCL is of special concern because a failure before the RPV-LH's failure may enable a significant pressure decrease. In the following a reactor coolant line, as considered in chapter FAILURE SURFACE is assessed under high pressure and temperature conditions. The Tab. 1 gives an overview of the relevant simulation runs and the employed failure assessment criteria.

Run #	Creep failure assessment	Plastic failure assessment
A	60% limit curve (see Fig. 5) with variable TF	Uniform elongation / variable TF
B	100% limit curve (see Fig. 5) with constant TF = 1	Uniform elongation / constant TF

Tab. 1: Failure assessment criteria

The Fig. 16 reveals the temperature and pressure progression of the RCL calculated with MELCOR [2]. The temperatures reach a maximum of 969°C at 66280 s. The pressure oscillates at 12 MPa with an amplitude of 0.8 MPa. For simplification purposes up to a time of 40,000 s the maximum value of the amplitude is assumed as input data for ADINA. This simplification is only applied at low temperature levels (<500°C), where no significant failure progression is expected.

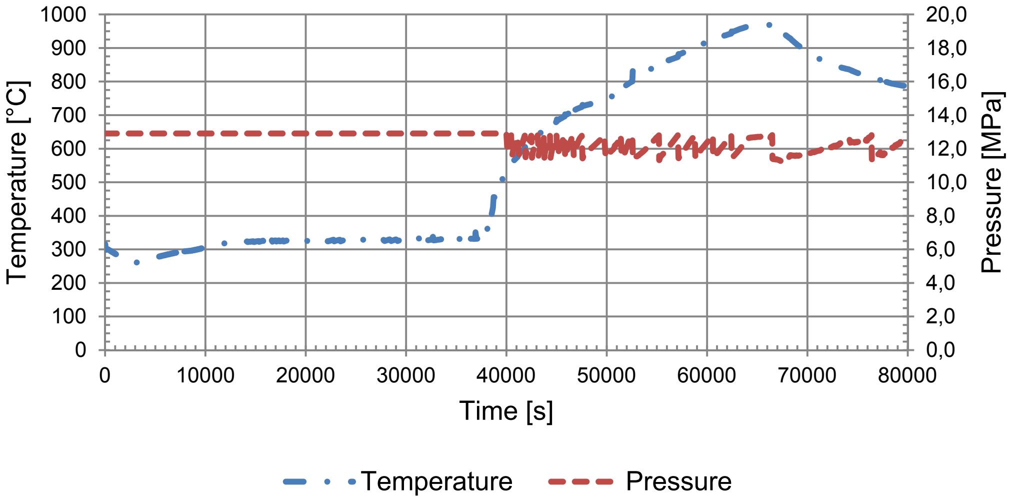

Fig. 16: Temperature and pressure progression

In Run A the creep strains meet the limit strain prior to the plastic strains based on the safety related failure criterion with consideration of the triaxial stress factor after about 47471 s (see Fig. 17). From safety related point of view failure due to creep can not be excluded after that time.

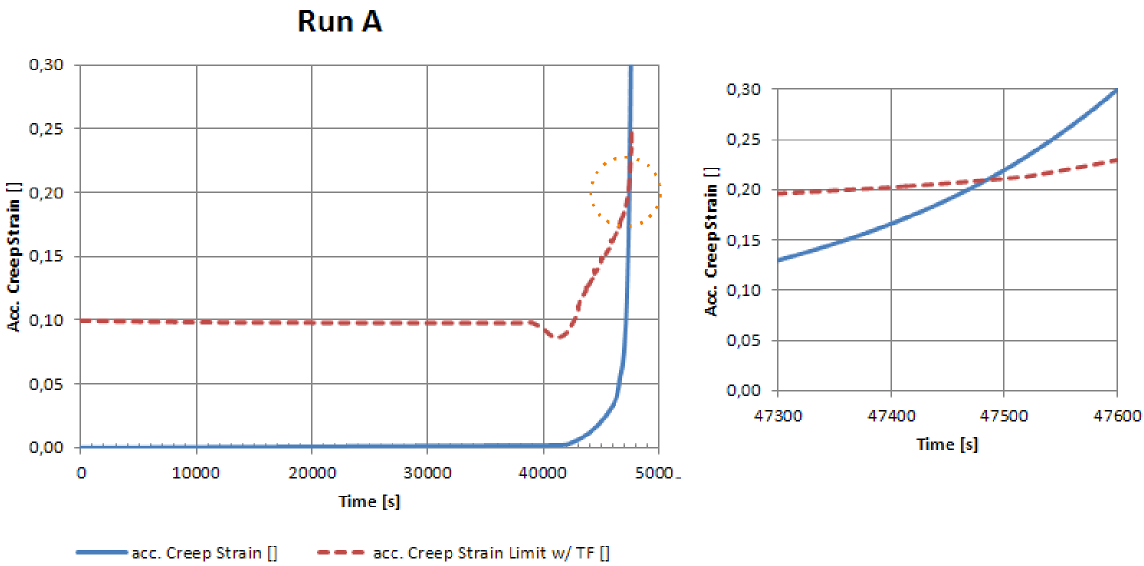

Fig. 17: Accumulated creep strain and strain limit curve (failure at 47471 s), overview and detail view

In Run B after about 47500 s a strong increase of the plastic strains can be observed. The calculated plastic strains meet the criterion for failure as a matter of fact after about 47656 s. The Fig. 18 displays the summation of damage increments within a calculation with ASTOR. For failure assessment different damage values are considered. An accumulated damage D=1.0 is fulfilled at a time of 49118 s, D=0.5 is reached at 47750 s and D=0.4 at 46760 s.

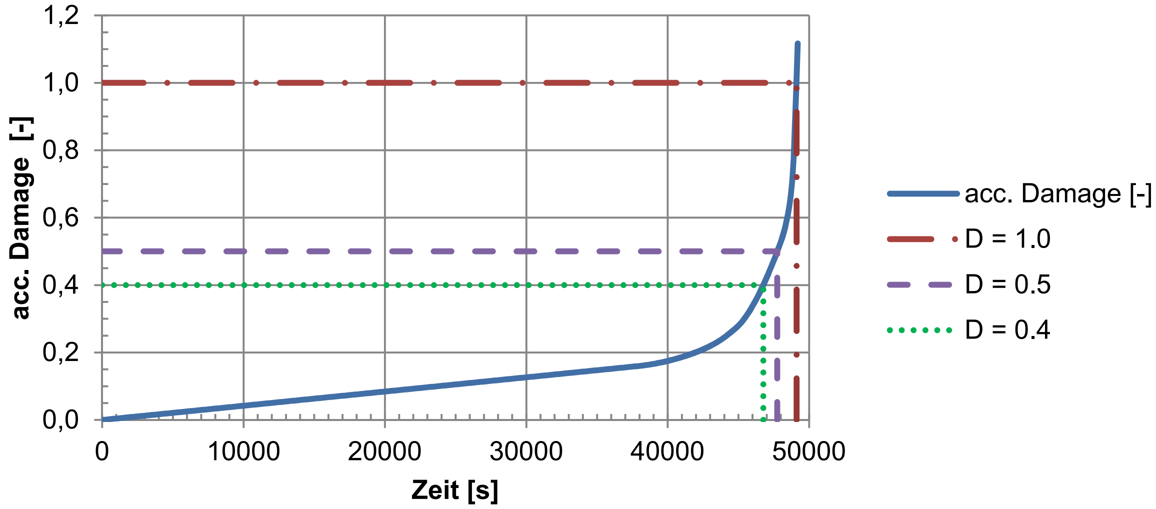

Fig. 18: Summation of damage increments (ASTOR)

The Fig. 19 summarizes the failure times of all failure assessments. As one can see the time gap between the safety related assessment and the failure as a matter of fact assessment based on FE-Analysis can be estimated by about 185 s. The failure times determined by ASTOR vary from 46760 s (D = 0.4) to 49118 s (D = 1.0). The investigation shows that ASTOR results for damage values of about 0.4 - 0.5 are close to the FE results. Further work with different loading scenarios should be performed to confirm this conclusion. The results of the severe accident simulation have been presented on SMiRT 21 [9].

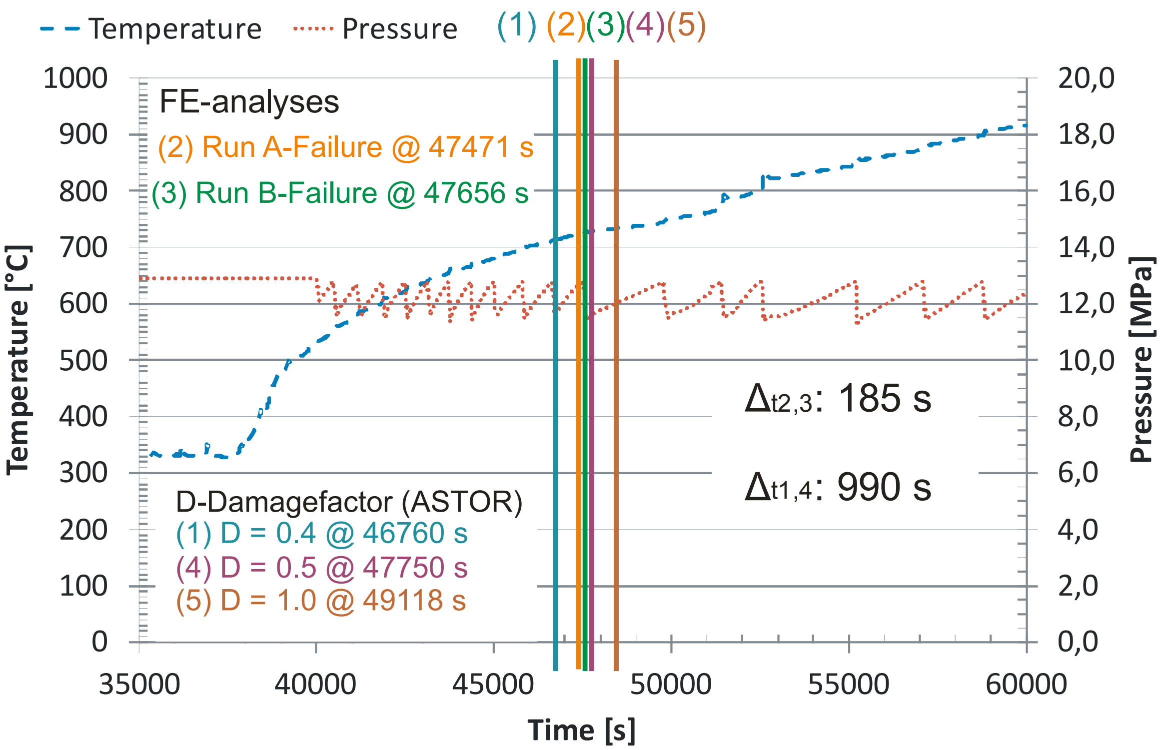

Fig. 19: Failure times and load progression

6 INTEGRITY ASSESSMENT OF A STEEL CONTAINMENT UNDER PEAK-LIKE PRESSURE AND TEMPERATURE SEQUENCES

In German PWR plants of Konvoi-type a steel containment with sphere shape has to ensure that even in the case of accidents no radioactive particles leave the reactor building to environment. To assess the integrity of the steel containment even for increased pressure and temperature loads caused by accidents the limit load bearing capacity of the containment under such loads has to be evaluated.
For the assessment of the structure dynamical behaviour of a steel containment at postulated loads due to hydrogen combustions respectively detonations, structure dynamical elastoplastic calculations have been conducted with the Finite Element computer code ADINA [1] within the frame of a recently finished project [10]. The work is a contribution for the assessment of the effectiveness of hydrogen countermeasures with possible challenges concerning the containment integrity in case of beyond design accidents.

6.1 Influence of Hydrogen Deflagration and Detonation

Characteristic loading assumptions were determined as peak-like pressure and temperature sequences from available test results and investigations on TMI-2 [11]. Furthermore, assumptions on the surface part of the containment loaded by pressure and temperature were derived from thermo-hydraulic calculations of hydrogen concentrations, conducted by GRS within the framework of the above mentioned project [12]. The peak-loads used in the studies presented here show maximum pressure values of up to 2 MPa combined with temperature increases up to 1200 °C. Depending on the postulated hydrogen behaviour the duration of the peaks is either in the region of about 20 to 40 ms or in the range of some hundred ms. Typical examples of short and longer temperature and pressure peaks are shown in Fig. 20.

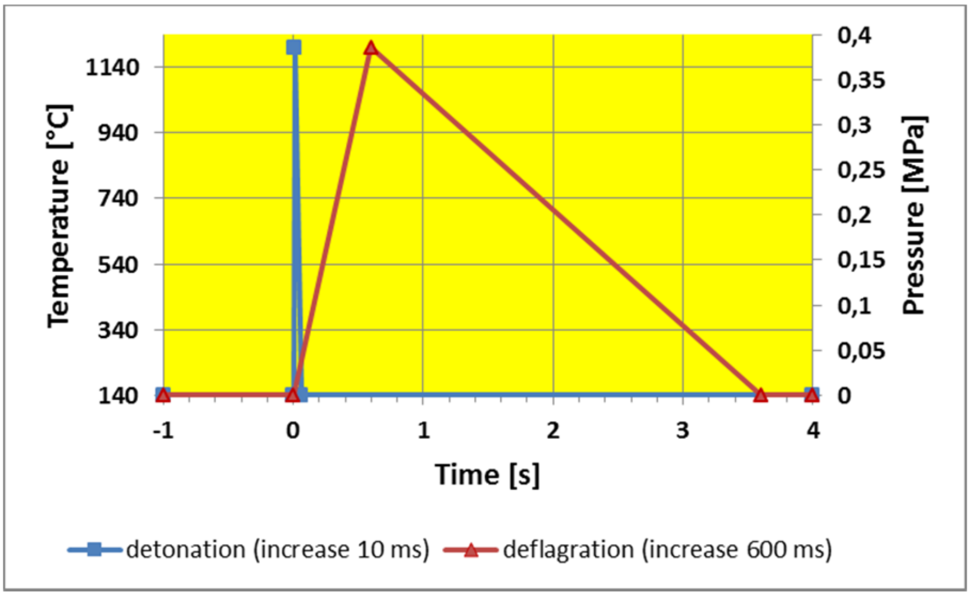

Fig. 20: Postulated temperature and pressure peaks

Furthermore, peaks with equal increase and decrease times were used especially for parameter studies.

6.2 Complex Model of the Steel Containment

The degree of complexity of the finite element models used for the calculations depends on three main questions. Firstly if a circular loading surface located at the very top of the sphere is considered and the simulation of the penetrations is omitted then an axisymmetric 2D model is sufficient. Secondly, if the middle of the load area deviates from the vertical axis a full circumference 3D model is necessary. As a priori the influence of the penetrations on the limit load is not really clear as third point the development of a 3D model with penetrations might be reasonable.

To clarify the last point a 3D finite element model of the steel containment with the most important penetrations has been developed. Fig. 21 shows some views of the model. Besides the materials lock personal and additional locks are simulated as well as feedwater and steam line penetrations. Furthermore an inclined position of the load surface (marked red in the Fig. 21) is assumed. Due to the geometry the finite element mesh is build up with tetraeder elements.

The containment is made using the ferritic steel 15 MnNi 6 3. Elastic plastic material data also for higher temperature regions are provided as described in [11]. For the heat conduction calculations temperature independent values of thermal conductivity (40 W/(Km)) and specific thermal capacity ($4.1 \cdot 10^6$ N/(m^2 K)) were used.

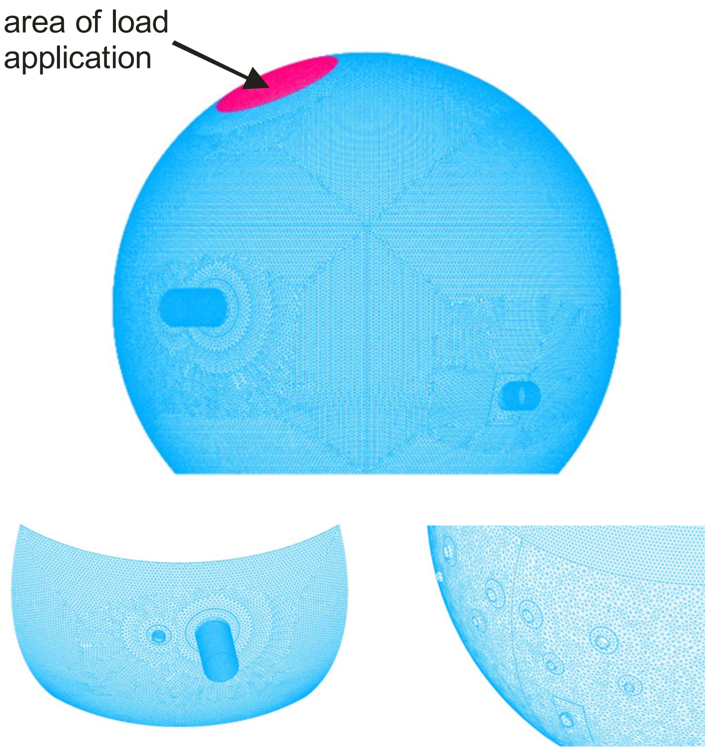

Fig. 21: Finite Element model of the steel containment with penetrations, complete model and parts

6.3 Selected Analysis Results in Cases with Pressure Peaks

Selected results of a calculation with the model with penetrations using a pressure load as shown in Fig. 22 with a maximum of 1 MPa and a duration of 32 ms are shown. Temperature effects are not considered in this case.

Fig. 22 presents the distribution of equivalent stresses at a solution time of 24 ms.

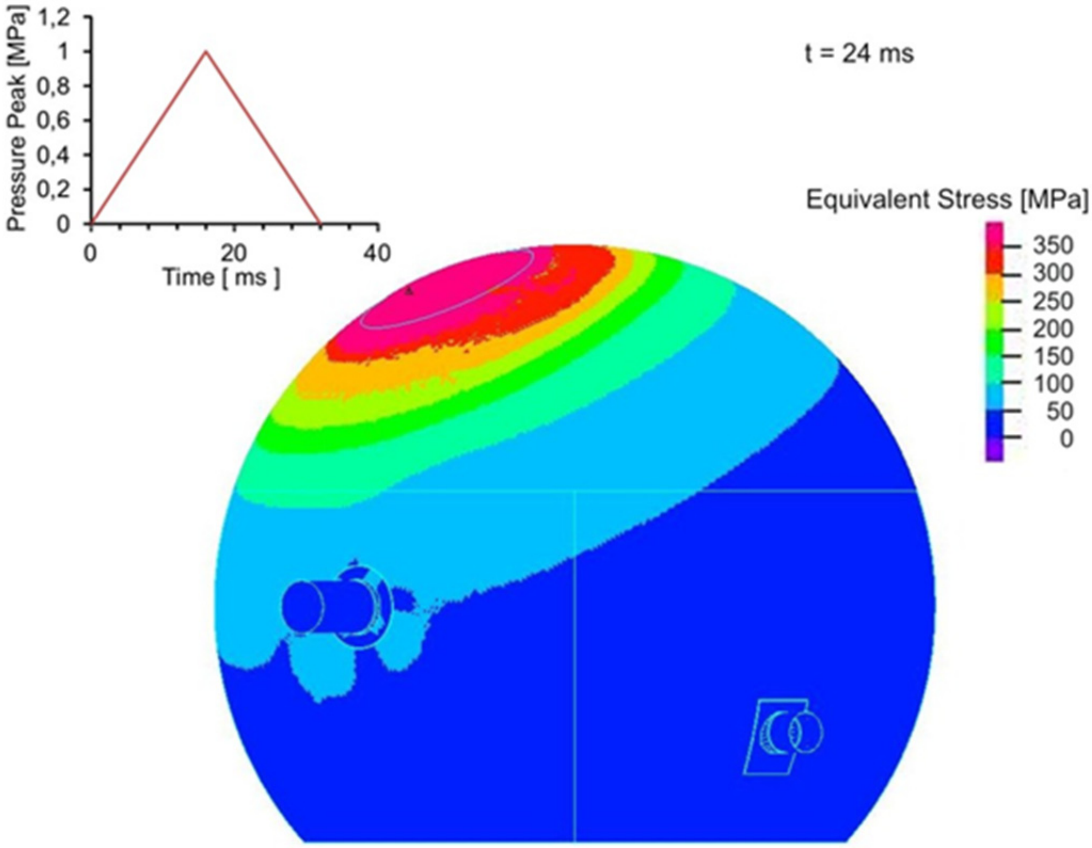

Fig. 22: Distribution of equivalent stresses at t=24 ms

The time dependence of the equivalent stress in the integration point where the maximum value is found is presented in Fig. 23.

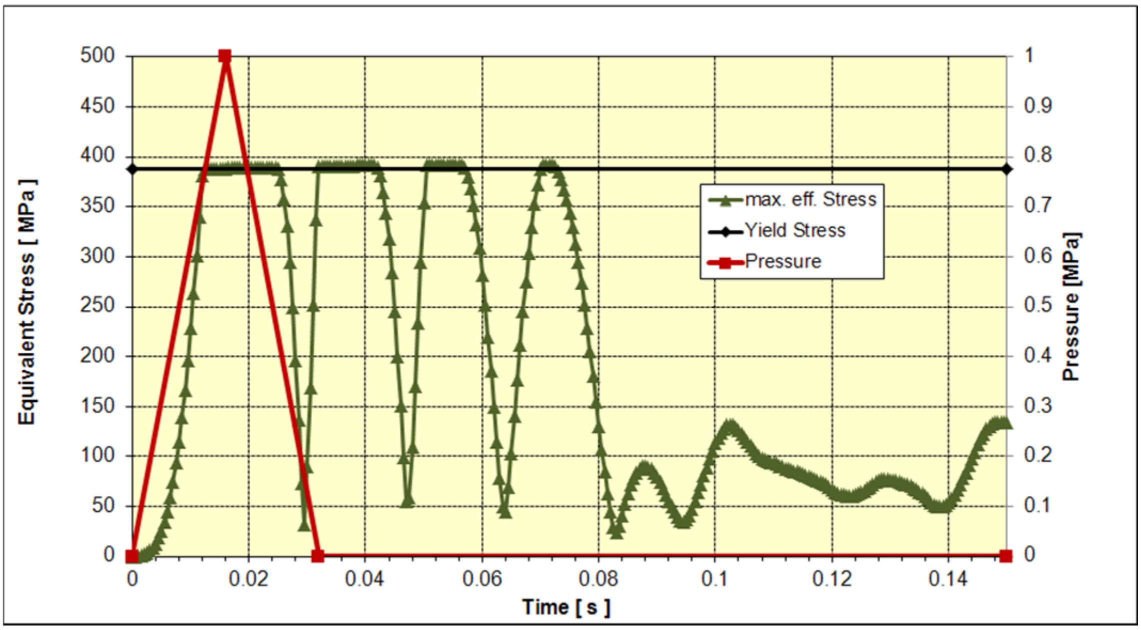

Fig. 23: Time dependency of equivalent stress for the point with the maximum value in comparison to yield stress

The figures show that the maximum stress values are found in the region of the load application and the yield stress is just reached in some parts of the transient. Furthermore, the area of load application oscillates with a period which can be correlated to the peak duration dependent on the degree of plastification. The influence of the penetrations on the global behaviour of the containment structure is small, the local effects have to be evaluated in detail.

Fig. 24 shows selected results of calculations with a 3D model without penetrations assuming peak loading in an area of 187 m² central in the dome. For the variation of peak duration and height the maximum calculated values of the accumulated effective plastic strain are presented.

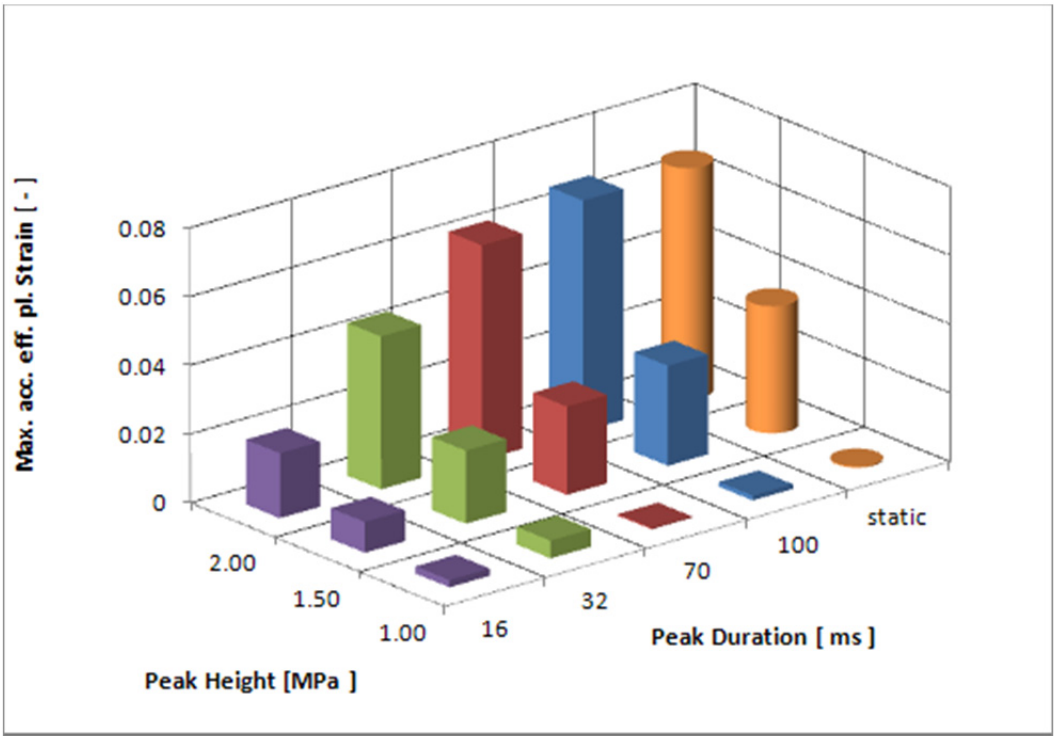

Fig. 24: Maximum values of accumulated effective plastic strain for several peak heights and durations, 3D model with symmetric loading

The results show a strong dependency on the peak height and that in most cases the quasi static analyses, i.e. peak durations of more than 100 ms cover the analyses with smaller peak durations. In cases with pressure peak heights ≤ 1 MPa peak durations with 32 ms effect largest strains because a global containment mode is excited.

6.4 Selected Results in Cases with Pressure and Temperature Peaks

The consideration of heat conduction due to local peak-like temperature loading needs a significant mesh refinement, especially the number of finite elements across the wall thickness of the steel containment has to be increased because steep temperature gradients can occur which can effect strong surface stresses and strains.

Besides a variation of the pressure (0.4 and 1 MPa peak height) also different maximum values of the temperature (1200°C and 800°C) were considered in combination with the several values of the duration of the peak.

For the integrity assessment of the steel containment and the determination of the load bearing capacity the strain based approach mentioned in chapter 2.3 is used. Besides the calculated effective strain and the triaxiality factor the temperature dependent uniform elongation is used as a material parameter. According to the approach integrity of the steel containment is assured if

$$\varepsilon_v < \frac{\varepsilon_g}{TF} \text{ , equivalent to } \varepsilon_v \cdot TF < \varepsilon_g$$

with the effective strain ε_v, the uniform elongation ε_g and the triaxiality factor TF (see chapter 3.2).

For the assessment all finite elements representing the wall thickness in the region of load application including adjacent elements are used. In this region of the model the highest temperature values are reached close to the inner surface, which effect lowest values of uniform elongation combined with the largest strains. Fig. 25 shows the assessment for a selected load case with peak heights 1 MPa and 800°C and peak duration 32 ms. The calculated values which change in different time steps during the peak loading are lower but close to the allowable values based on the above mentioned strain based approach. An increase of the peak height of temperature effect that in limited regions of the containment structure the failure criteria is not met, while a decrease of the peak height of pressure increases the safety margin against failure.

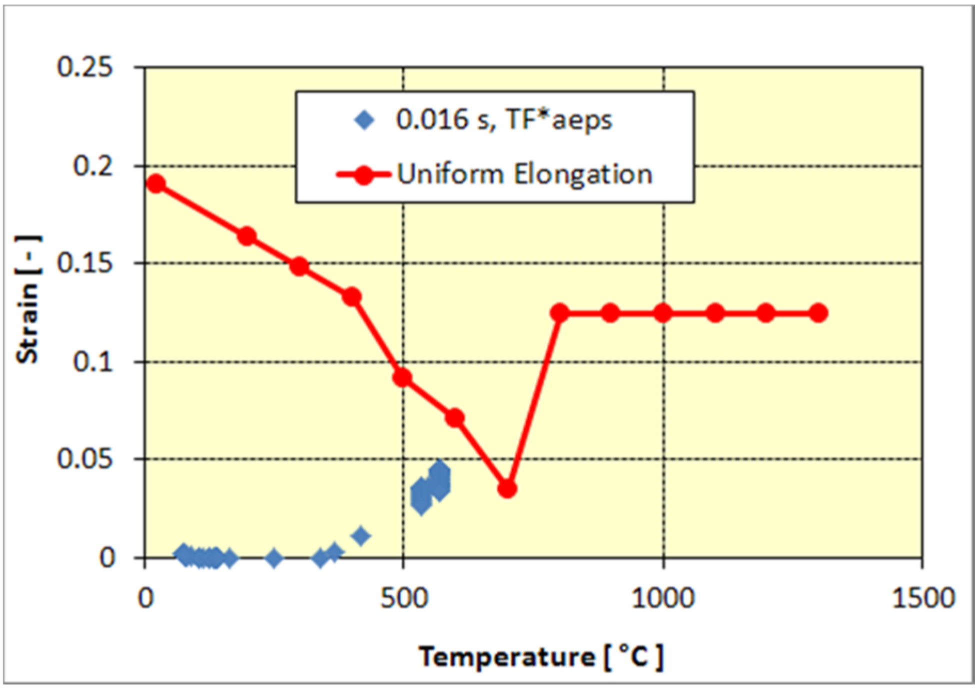

Fig. 25: Calcutated strains times triaxiality factor versus temperature for relevant elements of the containment model compared with uniform elongation after 16 ms, case: peak heights 1 MPa and 800°C, peak duration 32 ms

The recently finished thermo-hydraulic calculations on the effectiveness of hydrogen countermeasures for a Konvoi-type PWR show maximum pressure values of 0.05 MPa, maximum temperature values of 365°C and combustion times of more than 35 s [12].

Based on the performed structure mechanics calculations these loading conditions would result in stresses within the elastic region, i.e. failure is not expected. The safety margins could be quantified with the described methods.

7 CONCLUSIONS

An accident with a core melt scenario under high pressure loading caused by a station blackout is used as an example for an estimation of failure times by complex thermo-hydraulic and structure mechanic calculations. The thermo-hydraulic calculations with MELCOR show that in the course of the transient temperature values of above 800°C are reached at several positions of the cooling circuit. Using the temperatures and pressures evaluated by MELCOR as input for the structure mechanic calculation with ADINA results in terms of stresses and strains were gained for the primary coolant loop under the accident scenario considered. Using a strain based failure assessment failure times were estimated for the relevant positions of the loop model. While the temperatures in the RPV bottom are still relatively low, plastic strains in the main coolant and surge line reach limit values. Therefore it might be concluded that the MCL fails earlier than the RPV bottom. Since the failure times of the different positions do not differ very much more studies might be necessary for the quantification of uncertainties. Especially the influence of creep could be considered more precisely. Finally it has to be pointed out that here only a special accident has been treated. Other accidents with different temperature and pressure transients might give other failure sequences.

The method ASTOR enables a fast estimation of failure times and can be integrated into the framework of thermo-hydraulic system analysis programs. The application of ASTOR is limited to the boundary conditions concerning pipe geometry, material data and type of loading used for generation of the failure surface. An uncertainty of the calculated failure times exists but can be constrained by a decrease of the assumed damage limit value. The comparison of ASTOR results with more rigorous FE-analysis results requires verifications to quantify error bands. The results of the investigation show that the time of failure is strongly dependent on the changing stress level during the transient loading and the temperature dependent material properties characterizing plastification as well as the temperature/stress dependent material properties characterizing creep of the piping material. Also the uncertainty of the employed material data has to be mentioned. The required creep data are derived from load controlled creep curves by use of a simplification method. Because the material creep data are only available for a limited range of stresses and temperatures the FE-Code may use extrapolated data by trend analysis outside the range.

Dependent on the required accuracy of the time of failure of a pipe three failure assessment methods are accomplishable:

- ASTOR (useful for implementation in system codes, limited applicability, limited accuracy, extensive concerning generation of failure surfaces)
- FE-analysis with simplified FE-model (flexible concerning application, limited applicability concerning complexity, high accuracy)
- Complex FE-analysis model with consideration of interaction between components [3] (extensive concerning generation of analysis model, flexible concerning application, high accuracy).

Studies on the integrity of the steel containment of German Konvoi-type PWR plants including the limit load bearing capacity in case of increased peak-like pressure and temperature loads caused by beyond design accidents with postulated hydrogen combustion have been performed.

For the assessment of the structure dynamical behaviour of a Konvoi plant containment at postulated loads due to hydrogen combustions respectively detonations, structure dynamical elastoplastic calculations were conducted with the Finite Element computer code ADINA. Axisymmetric and full 3D models even simulating the penetrations of the containment have been used.

Characteristic loading assumptions were determined as peak-like pressure and temperature sequences from available test results and investigations on TMI-2.

The following results are gained from the calculations:

- Depending on the peak height in terms of maximum temperature and pressure as well as the peak duration a failure of the containment will be predicted or not. Based on recently finished thermo-hydraulic calculations on the effectiveness of hydrogen countermeasures for a Konvoi-type plant the expected stresses in the containment wall are in the elastic region, i.e. a failure of the containment can be excluded.
- If only pressure load with peak height of 1 MPa is considered as shown here for the 3D model with penetrations some plastification in the load region and its surrounding is found, but this will not lead to failure.
- The influence of the penetrations on the global containment behaviour is small; the local effects have to be evaluated in detail.
- The deviation of the load surface from a symmetric position (to an inclined position) has no strong influence on stresses and strains in the containment.
- The consideration of a temperature peak can result in limited plastification of the near surface region due to the temperature dependence of the material properties.

ACKNOWLEDGEMENT

The work has been predominantly performed in the framework of the Reactor Safety Research Program of the German Federal Ministry of Economics and Technology. The support of parts of the work by the German Federal Ministry for the Environment, Nature Conversation and Nuclear Safety is also acknowledged.

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ABBREVIATIONS

ADINA	automatic dynamic incremental nonlinear analysis
ASTOR	approximated structural time of rupture
FE	finite element
MCL	main coolant line
MELCOR	thermo-hydraulic system code
NPP	nuclear power plant
PWR	pressurized water reactor
RCL	reactor coolant line
RPV-LH	reactor pressure vessel-lower head
TF	triaxiality factor