FAILURE ASSESSMENT METHODOLOGY FOR PIPING UNDER HIGH TEMPERATURE AND PRESSURE DUE TO CREEP AND PLASTIFICATION

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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 PWR, before the bottom of the reactor pressure vessel experiences a significant temperature increase due to core melting. For a fast and simple assessment of components of the primary cooling circuit the simplified method ASTOR (Approximated Structural Time Of Rupture) has been developed. This method employs the hypothesis of linear damage accumulation for modeling damage progression. A failure time surface which is generated by structural finite element (FE) analysis of varying pressure and temperature loads serves as a basis for estimations of failure times. The paper exemplifies the method ASTOR further developed concerning the generation of failure time surfaces. For validation of the method especially concerning the failure criteria a large scale test on a pipe section with geometric properties similar to a reactor coolant line loaded under a constant pressure and heated up to the time of failure has been analyzed to simulate creep and plastification at high temperatures. Furthermore a severe accident scenario has been investigated concerning integrity of piping. The work has been predominantly performed in the framework of the Reactor Safety Research Program of the German Federal Ministry of Economics and Technology.

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 the integrity assessment of primary circuit devices requires a special concern. Due to the interdisciplinary aspects of primary circuit's failure assessment at severe accident scenarios the best estimate simulation with consideration of the interaction between the components is complex and time-consuming [4]. For the accomplishment of a simplified analysis concerning integrity of the components during a severe accident and especially the question which component fails first in framework of thermohydraulic analysis with system codes like ASTEC[11] or ATHLET[12] an efficient method has been developed.

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-hydraulical codes and may help to find results of structure mechanical properties which are required for coupled calculation of mechanical and thermo-hydraulical 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's 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 at the SMiRT 12 conference [3] 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. 1). The load can be characterized by a range of temperature and pressure.

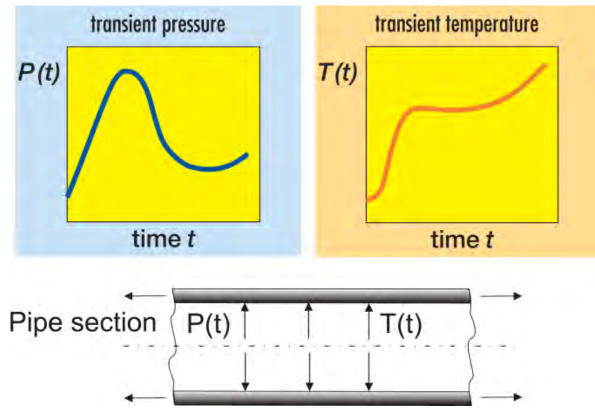

Fig.1: Transient loads on pipe

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 ADINA[5].

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. 2). 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.

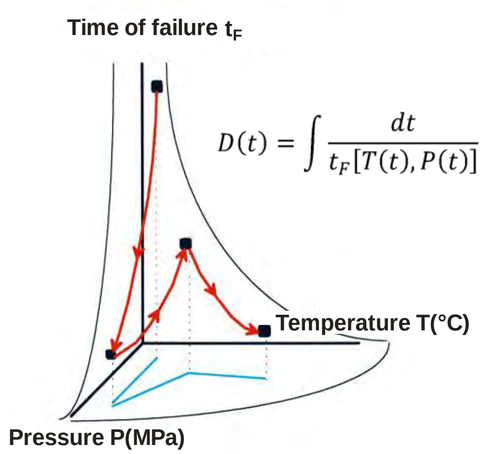

Fig. 2: Linear damage accumulation hypothesis in ASTOR

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 failures assessments. 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.

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 [8][9]. Temperature dependent stress-strain-curves were derived for the temperatures up to 1200°C (Fig. 3) to build up the basis for the material model of the FE-Program ADINA [5].

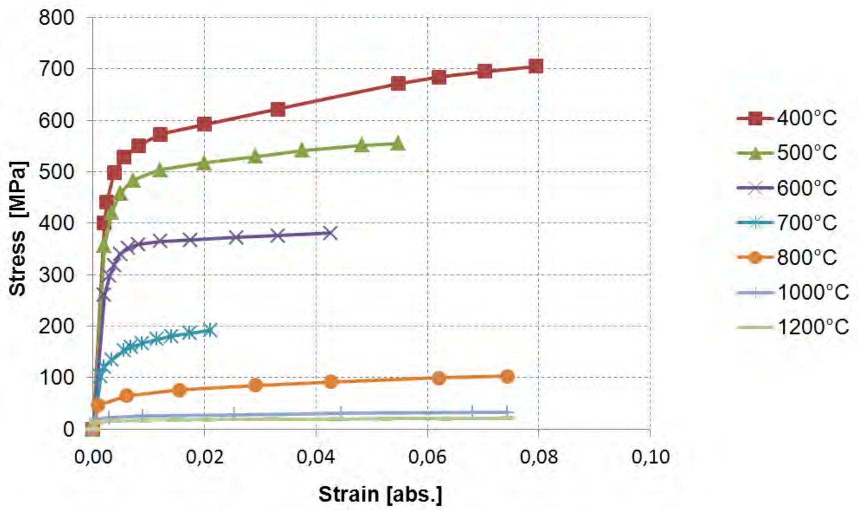

Fig. 3: Steel 20 MnMoNi 5 5: true stress-strain curves up to uniform elongation (400°C – 1200°C) derived from measured data

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. 4 the approximation of load controlled creep curves for a temperature level of 1000°C is displayed.

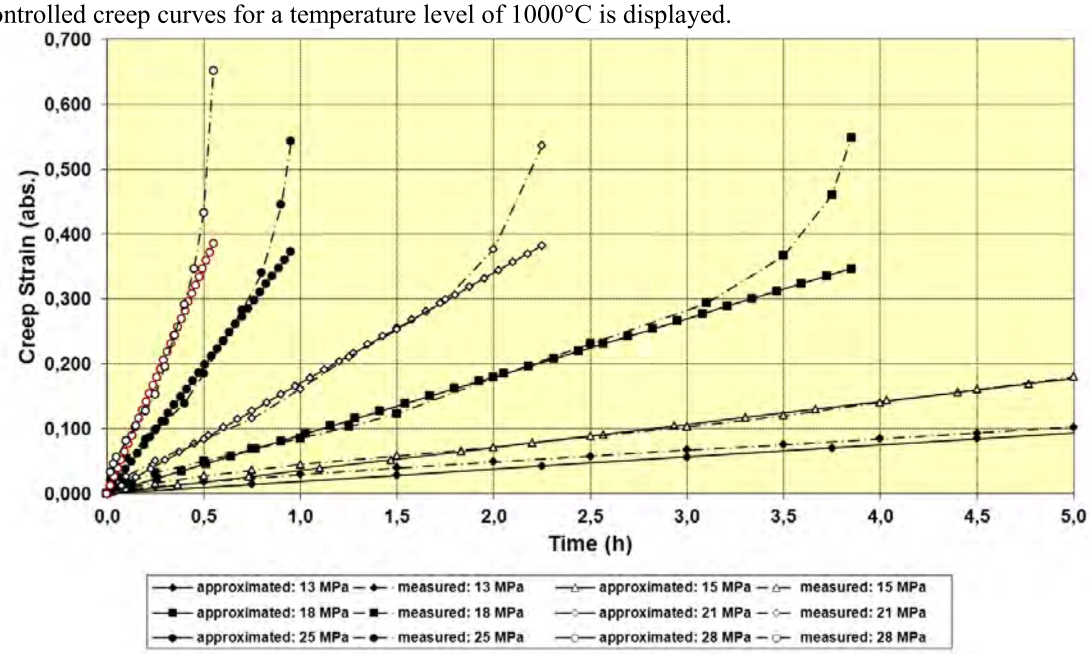

Fig. 4: Linear approximation of measured creep curves (load controlled) of steel 20 MnMoNi 55 at 1000°C

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

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 determinated 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 determinated by 100% of the creep failure strain of the uniaxial creep tests. The Fig. 5 shows the temperature dependency of the uniaxial limit of creep strain for the 60%- and the 100%-criterion.

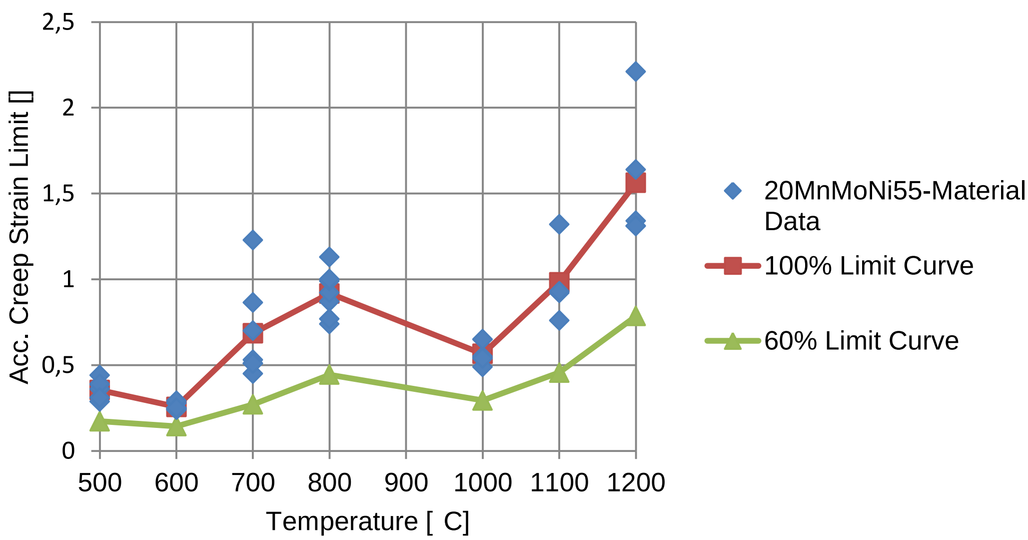

Fig. 5: Steel 20 MnMoNi 55 – Approach for definition of uniaxial creep limit

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 [7]:

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

The stresses σ1, σ2 and σ3 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.

FINITE ELEMENT MODEL

The abstraction from the pipe structure to the analysis model is displayed in Fig. 6. 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.

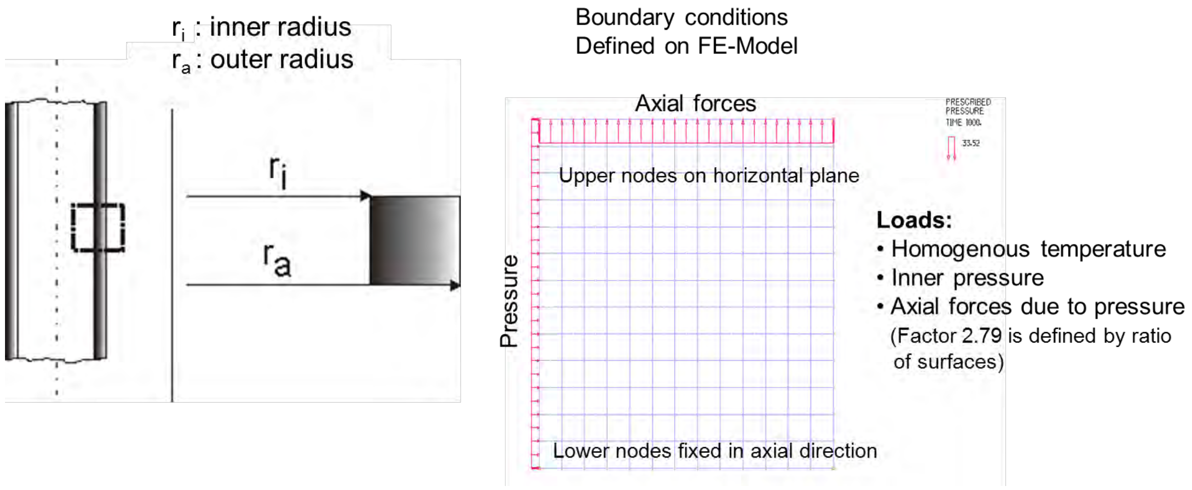

Fig. 6: 2D-Representation of pipe structure, dimensions, loads and boundary conditions

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

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. 7 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.

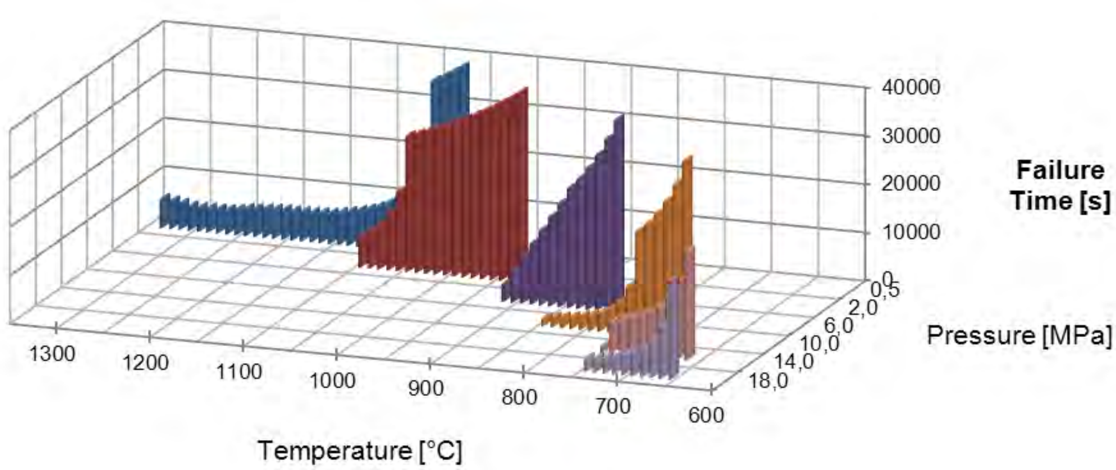

Fig. 7: Failure time diagram for a RCL of 20 MnMoNi 5 5

COMPONENT TEST AND SIMULATION

For validation of the employed FE-Simulation and the failure assessment procedure test data of a component test [1] 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 5was used as the test material. The conduct of this test was to simulate specific accident conditions; under a constant internal pressure of 16.3 MPa using air as the pressurizing medium the vessel was heated to about 700°C to determine the time to failure. 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[6] 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 (RUN 34A). The Fig. 8 compares time of failure of test and simulation run. The used criterion predicts a failure at 12470 s which is very close to the failure time of the test (12469 s).

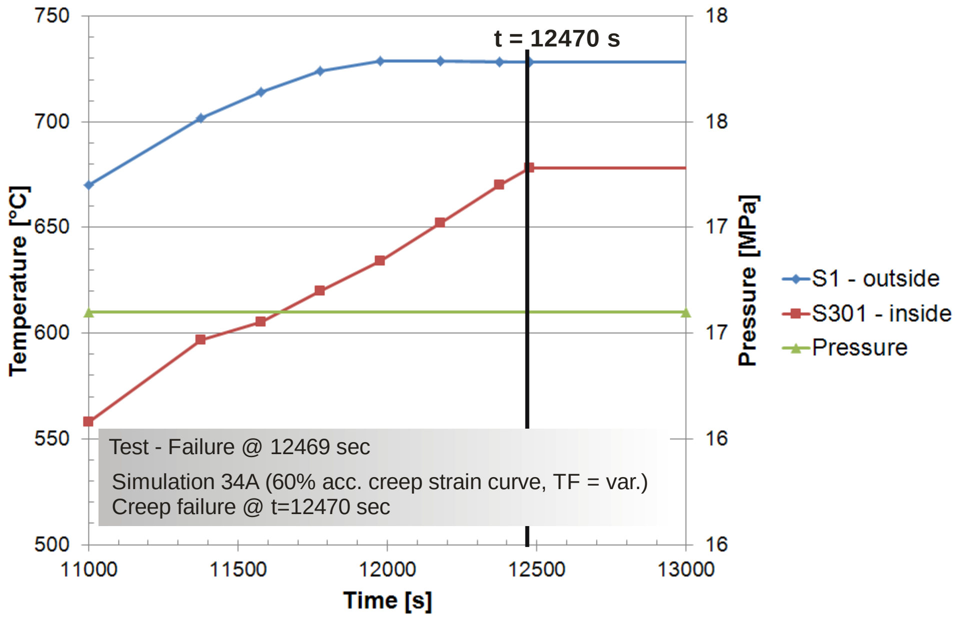

Fig. 8: Comparison time of failure (Test vs. simulation)

SIMULATION OF SEVERE ACCIDENT SCENARIO

In following 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. 9 reveals the temperature and pressure progression of the RCL calculated with MELCOR [10]. 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.

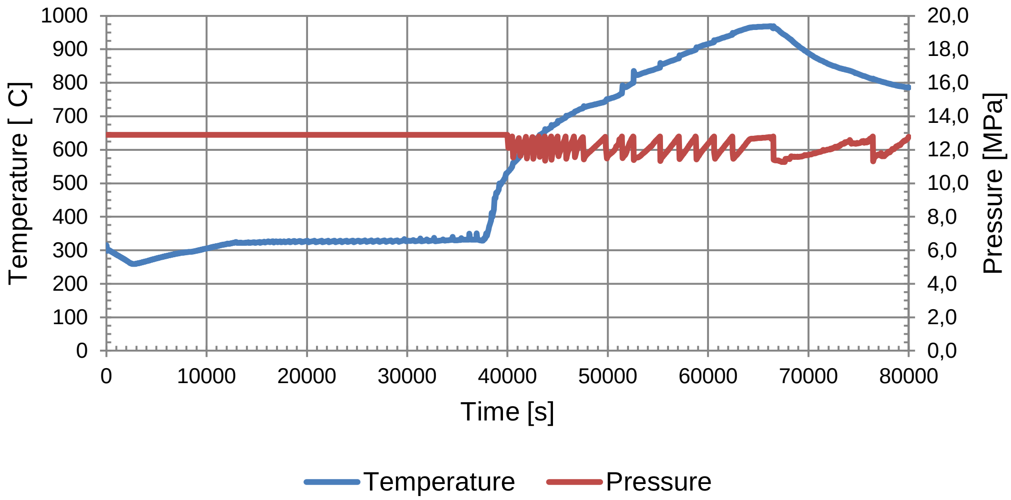

Fig. 9: Temperature and pressure progression

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. 10). From safety related point of view failure due to creep can not be excluded after that time.

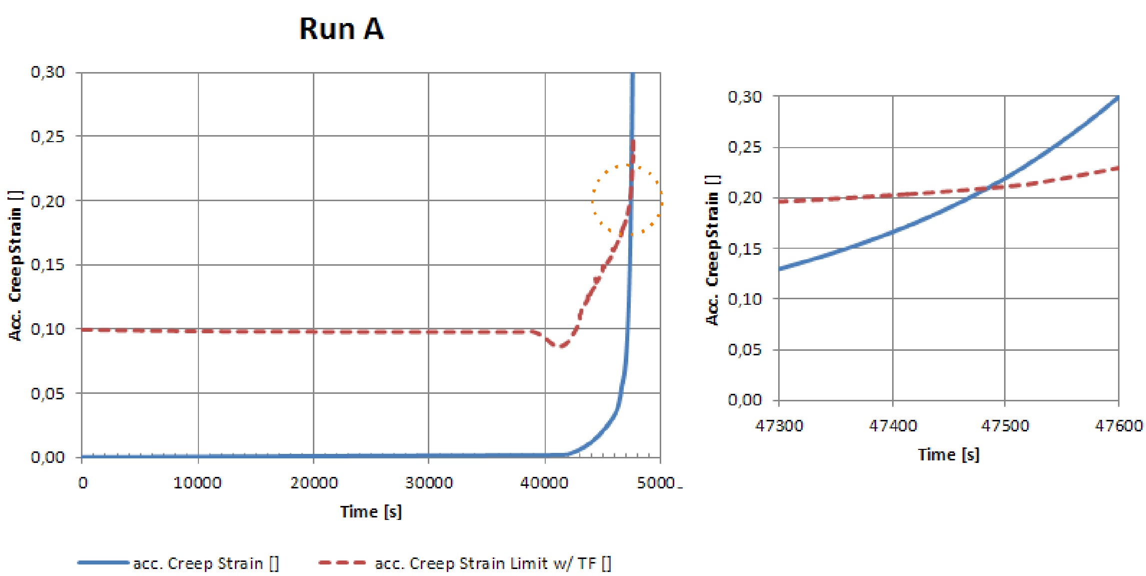

Fig. 10: Acc. Creep strain and strain limit curve (failure at 47471 s), overview and detail view

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. 11 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.

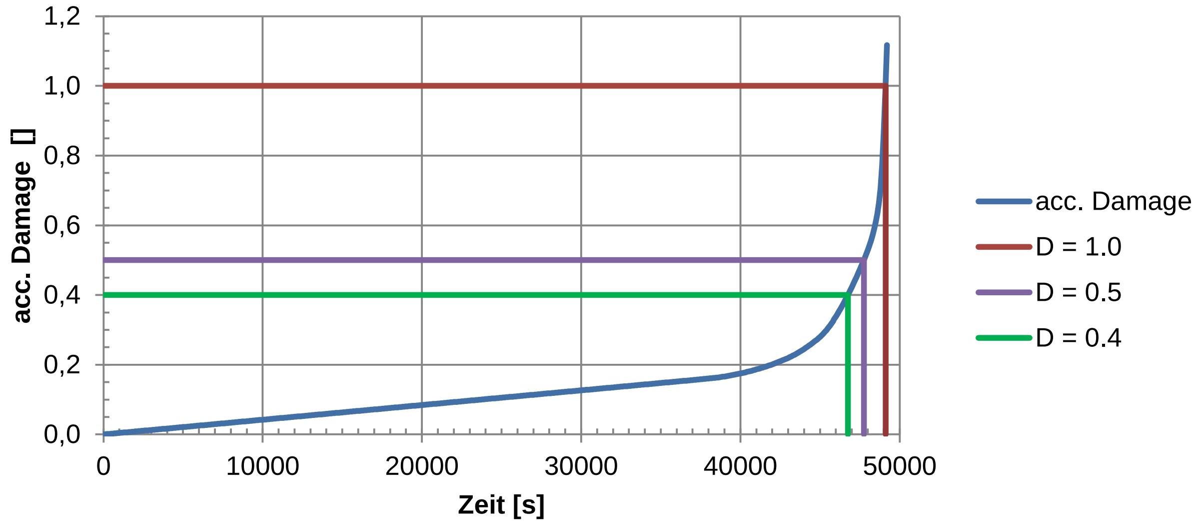

Fig. 11: Summation of damage increments (ASTOR)

The Fig. 12 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.

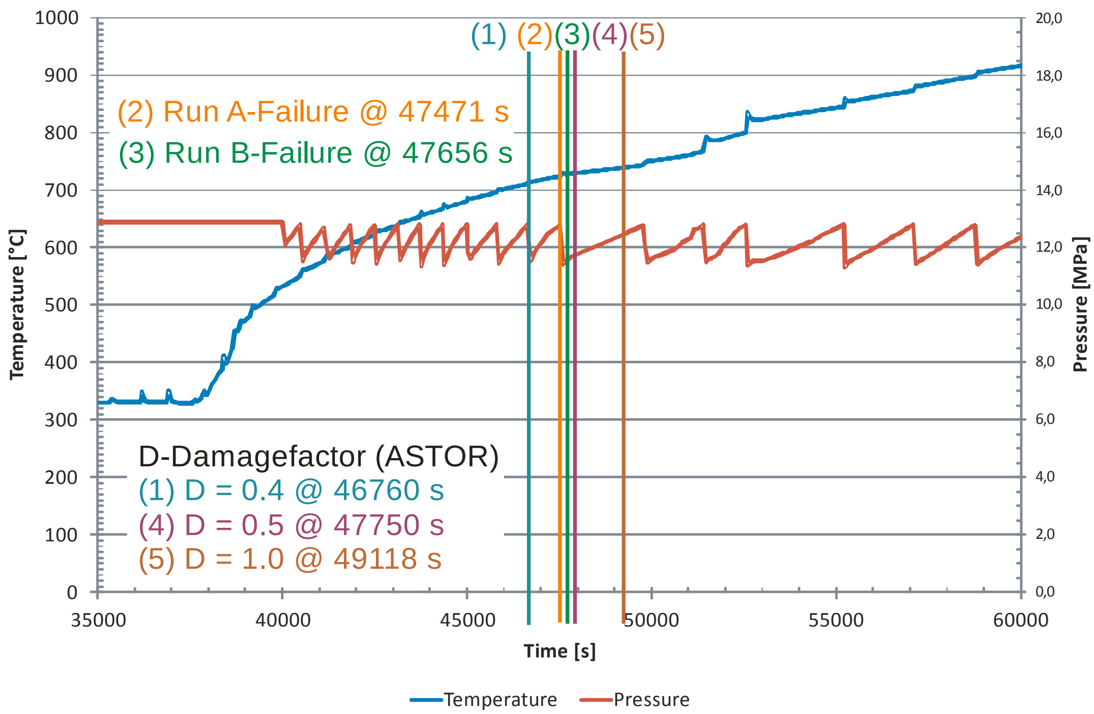

Fig. 12: Failure times and load progression

CONCLUSION

The comparison of failure times of a large scale creep test and FE-analysis confirms that the FE-analysis method including the used failure criterion is a best estimate method. The method ASTOR enables a fast estimation of failure times and can be integrated into the framework of thermohydraulical system analysis programs easily. 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 surface)
- 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 [4] (extensive concerning generation of analysis model, flexible concerning application, high accuracy).

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