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Structural Analysis of Pressure Surge by Calculation and Measurement for a Rapid Shutdown System

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ABSTRACT

A rapid shutdown system of a BWR consists of four tank pipes (ND 250) and two ring pipes (ND 150). The tank pipes connect three pressure tanks with the ring pipes, which distribute the hydraulic pressure to the so called scram pipes. The scram pipes drive the steering rods. Beyond the normal operation conditions shutdowns represent the main loading.

Within the concept for periodical examinations of the rapid shutdown system different testing methods as well as calculations are established. The major portion of the welding seams in this system is examined by non-destructive testing like ultrasonic measurement. For completion of the information about the integrity of the piping system mechanical measurements as well as numerical calculations are carried out.

At first measurements were performed during pressure surge at boundary conditions (20 bar reactor pressure) which are expected to result in increased loading for the system. The measurements are focused on positions at the test pipes outside the containment because with respect to the plant experience the two ring pipes are expected to remain in their static position during pressure surge. With the measurements the real accelerations, displacements and especially strains are documented at positions which are supposed to be representative for the whole system as well as near welding seams which cannot be examined by ultrasonic measurements.

Calculations were done after the measurements. In the calculation model the complete piping with ND 250 and ND 150 is included with the different supporting facilities like fixed points at the tanks, shock absorbers, sliding contacts, transitions at the containment shell and sliding contacts of the two ring pipes. Two load cases are investigated, normal operation and pressure surge. The pressure surge loading of the pipe is input to the piping code from compatible data files of a separate hydraulic code.

First a linear dynamic calculation gives some insight in the motion as well as in the stress distribution of the whole system, especially for the positions which are not accessible for measurements. With a detailed finite element model the stress concentration at the spherical fittings for the transitions tank-/ring-pipe are analysed.

Second a more refined calculation model with respect to non-linear effects of shock absorbers and friction at sliding contacts give more realistic results in comparison to the measurement.

But the comparisons of calculations and measurement results show that the real responses are overestimated by both calculations, somewhat more by the linear model and somewhat less by the non-linear model. Our interpretation of that misalignment is that mainly the formulation of the boundary conditions of the two ring pipes is not as realistic as needed for a good agreement between measurement and calculation. A further refinement of the calculation model will be possible after a future measurement campaign with the focus on the transient behaviour of the ring pipe during pressure surge is performed.

KEY WORDS: Boiling water reactor (BWR), rapid shutdown system, piping, calculation, measurement, strain gage, displacement, acceleration, pressure, pressure surge, non-linear effects, rupture.

INTRODUCTION

For a boiling water reactor (BWR) which started operation in 1976 the rapid shutdown system is analysed within the scope of a periodic safety assessment. The rapid shutdown system of the BWR consists of four austenitic tank pipes (ND 250) and two ring pipes (ND 150). The tank pipes connect three pressure tanks outside the containment at the lowest level of the reactor building with the ring pipes positioned inside the containment at a level of about 6 m higher. The ring pipes distribute the hydraulic pressure to the so called scram pipes which drive the steering rods. Functionality of the system is established by one opening valve (TOV) and one closing valve (TCV) situated close to the tanks in each of the four tank pipes. The geometry of the piping system with valves and with the transition elements through the containment is presented in Fig. 1.

The analyses with respect to the structure-mechanical behaviour were initiated because of significant progress in the state of the art since the design calculations were carried out about 30 years ago. Essential for the new calculations is the generation of a new Finite-Element-(FE) calculation model. With this model beside the normal operation conditions (dead load, small temperature difference and especially internal pressure) the dynamic load cases pressure surge during several rapid shutdown conditions are investigated. In addition to these operational loads external load cases like earthquake and blast pressure wave are calculated using the same FE-model.

Because of the importance of the rapid shutdown system there exists a concept for periodical examinations with different testing methods as well as calculations. The major portion of the welding seams in the system of pipes and tanks is examined by non-destructive testing like ultrasonic measurement. For completion of the information about the integrity of the piping system numerical calculations as well as mechanical measurements are taken into account. Measurements of strains at a representative location for strength and at positions near welds which cannot be examined by ultrasonic measurements as well as calculation results for the whole piping system shall bring the information about the integrity of the system to the best possible level.

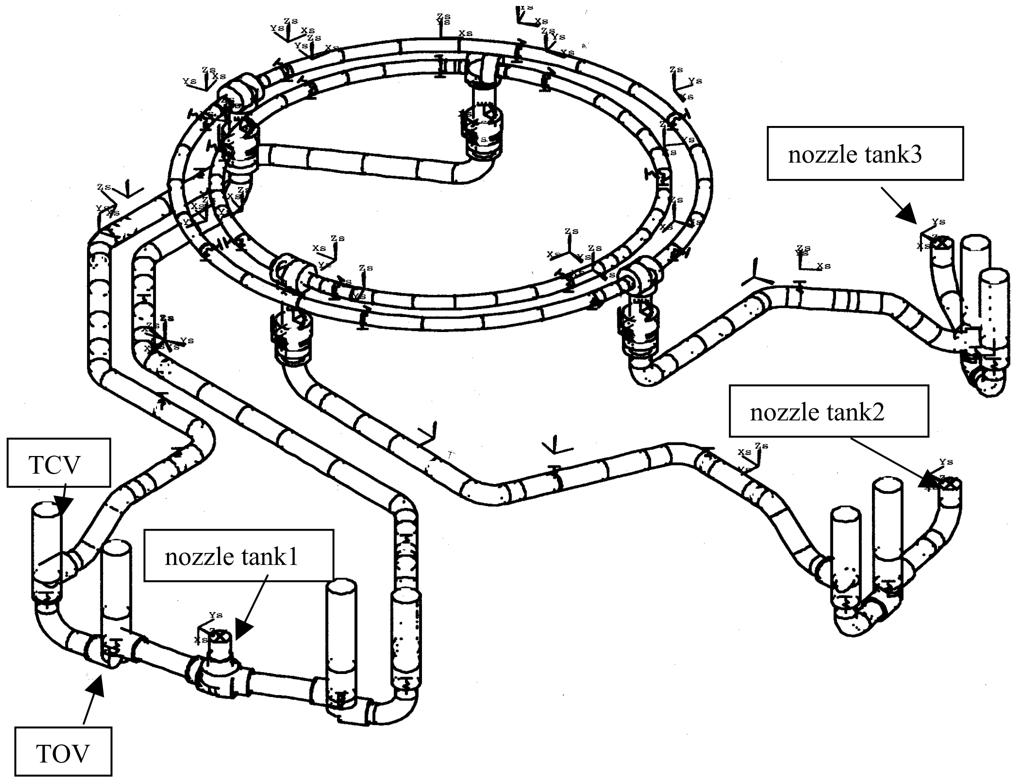


Fig. 1 Geometry of the piping system

Before starting the industrial power generation with the plant starting up tests with the rapid shutdown system were carried out with measurements of strains at several structural elements of the piping system. The documents of the tests cannot be completely reconstructed. Therefore in addition to the above-mentioned calculations new measurements during rapid shutdown events are carried out. The application of sensors is chosen in compliance with the above-mentioned concept of periodical examinations.

Within the scope of this paper mainly the investigations for pressure surges are reported. Other interesting aspects like the non-linear stability analysis of the tall tanks under the impact of external loads will only be mentioned shortly.

MEASUREMENTS

With the measurements three aims are targeted. First sampling information about the grade of stress in the piping structure at representative positions of the piping system, second completion of data within the periodical examination program, third registration of important fluid dynamical data to be input into the fluid dynamical analysis as described before.

Different sensors are applied respectively used, strain gages (SG), displacement and acceleration transducers (DT and AT) as well as pressure sensors (PS). Additional plant documents like time-histories of inner tank pressure and water level in the tanks are available. Four positions of the tank pipes are instrumented with strain gages (SG). At one representative position with respect to the level of stress 5 channels for the three section moments as well as for normal force and for the circumferencial strains respectively stresses are installed. At three positions close to welding seams which cannot be completely examined by ultrasonic measurements 3 channels each are installed for measurement of the three moments. Accelerations are measured at two of the tank closing valves (TCV) and at the tank pipe YT 10 which is focused preferably for the analyses. At pipe YT10 also displacement transducers for all three directions of space are applied. For measurement of fluid pressures two always available sensors are used. All signals are recorded and processed by the company owned software MEDA, [3]. The positions of measurement are signed in Fig. 2. The tank pipe position with applied five SG channels which means 12 active strain grids is shown in Fig. 3.

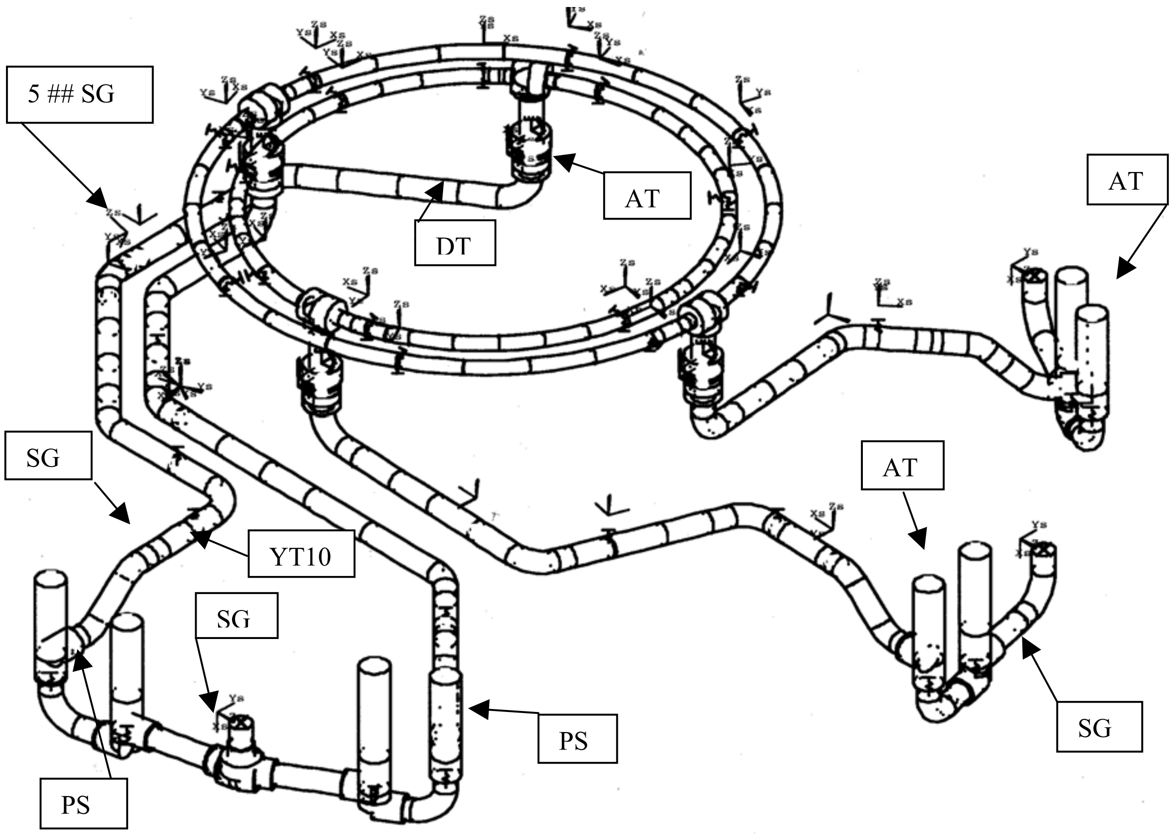


Fig. 2 Instrumentation of the piping system with strain-, pressure-, displacement- and acceleration sensors

During two rapid shutdown tests within 20 days measurements are carried out and documented for totally 28 channels (28 ##). A rapid shutdown starts with opening of the tank opening valve within less than 0.2 s and ends with closing of the tank closing valve after about 120 s. The sensors are active during the complete duration of the rapid shutdown and the signals are recorded continuously with enough time before and after the real event. The strain results are transformed to stress results applying Hooke's law.

The maximum measured acceleration is less than 40 m/s², the maximum resulting horizontal displacement amplitude is 4.4 mm. The maximum strains according to bending are 0.075 mm/m which is equivalent to a bending stress less than 15 N/mm². The maximum strain according to torsional moment is 0.035 mm/m which is equivalent to a shear stress of 5.3 N/mm². The maximum measured strain at all is 0.38 mm/m (circumferencial at position 5##SG).

A representative strain signal in Fig. 4 reflects the time-history of a complete rapid shutdown event as described above. In time sections of 1 s of the strain responses in circumferencial direction at 5##SG and of the fluid pressure in tank pipe YT10 a frequency content of about 10 Hz may be deducted, Fig. 5. The peak pressure is reached within 0.1 s.

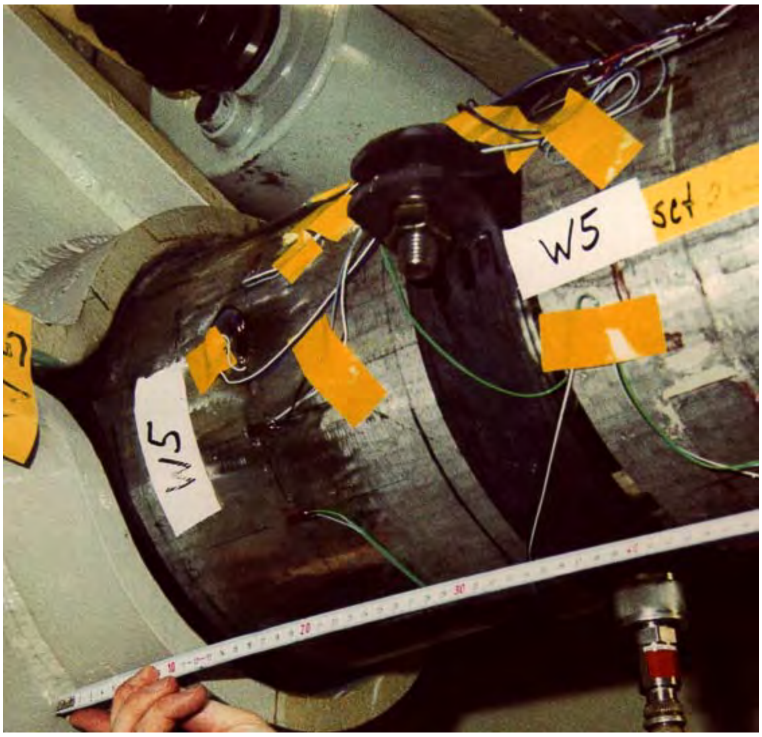


Fig. 3 Strain gage instrumentation at tank pipe position 5##SG, close to shock absorber

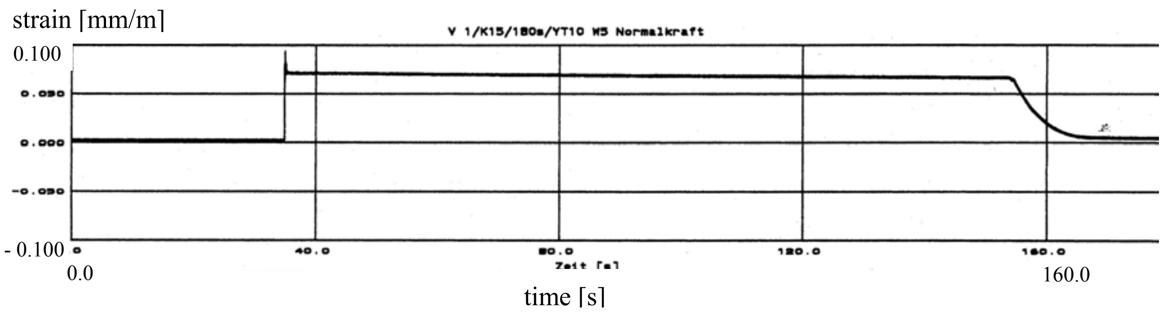


Fig. 4 Time-history of strains related to normal force at position 5##SG

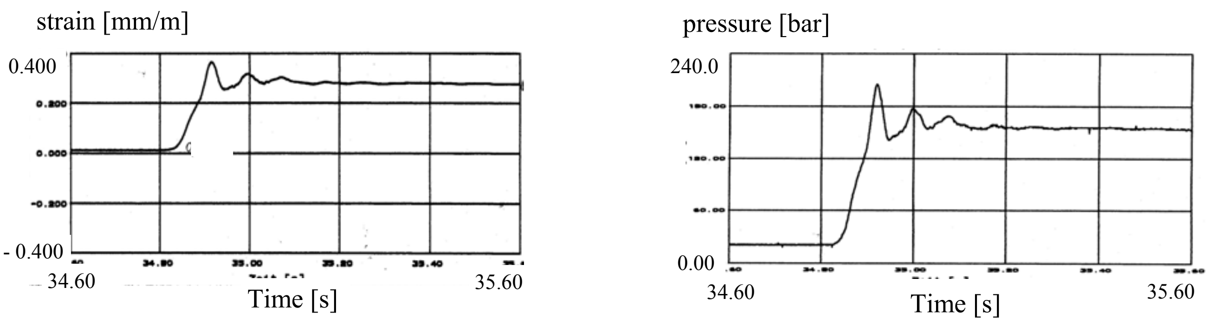


Fig. 5 Time-history (1 s) of strains related to circumferencial strain and of fluid pressure in pipe YT10

CALCULATIONS

Calculations are established in several steps. First pressure surge is analysed with a fluid dynamic code for different fluid dynamic boundary conditions which are the test conditions during two different measurement events, rapid shutdown at normal operation conditions as well as rapid shutdown at zero bar reactor pressure. The results of in total four boundary sets are evaluated.

Finally the load time-histories from pressure surge induced by rapid shutdown at normal operation conditions are applied to the calculation model for structure dynamic analysis in the second step of analysis. The chosen load case is assessed to effect maximum stresses in the system.

Because of special spherical fittings at the transitions between the tank pipes and the ring pipes a detailed analysis of these fittings is carried out in a third step to get information on real stress intensity factors for the fittings.

In addition to prove the stability of the tall pressure tanks under the impact of external loads a non-linear time-history analysis was established with a specially generated calculation model. The tanks are fixed points for the pipe and they are needed for the functionality of the system.

Piping

For the structure-mechanical analyses a beam-model was generated containing the four tank pipes (ND 250) as well as the two ring pipes (ND 150). The tank pipes connect the tall pressure tanks with the ring pipes. The nozzles at the three tanks are fixed points of the system. Sliding contacts under the valves and under the ring pipes as well as shock absorbers are additional supporting elements. The bellow constructions of the four pipes penetrating the containment shell are modelled in detail with realistic spring stiffness.

The stand-by situation of the system is 164 bar pressure within the tanks and the joining tank pipes up to the opening valves as well as approximately reactor pressure between the opening valves and the scram pipes inclusively. The structure-mechanical influence of the flexible scram pipes between the ring pipes and the steering rods is neglected in the structure-mechanical model but not in the fluid dynamical model.

The pipes always are filled with water at room temperature. The pressure 164 bar is realised by a pressurised nitrogen volume in the uppermost part of the water filled tanks. A rapid shutdown starts with opening of two of the opening valves in a manner that the inner as well as the outer ring pipe is supplied with hydraulic overpressure by just one tank pipe. Tank 1 which supplies two tank pipes alternatively is requested at each rapid shutdown event. According to this process engineering, and regarding measurement results for details like time delay in opening of the two active opening valves at one rapid shutdown the hydraulic dynamical analysis is carried out. The resulting fluid force time-histories are prepared and documented in data files for the structure dynamical calculation. Altogether 102 individual fluid force time-histories are available to be applied as forcing functions in the FE-model, see Fig. 6.

The system lines of the pipes were transferred from isometric drawings to the computer code ROHR2, [4]. In this code a non-linear option ”surge pressure” is available. In the first step a linear modal time-history analysis neglecting non-linear effects like friction was established. Baffle bows along the ring pipes are not considered in the model because of a clearance of 10 mm to the pipe. Details of the structure like wall thickness, linearized stiffness of the shock absorbers, stiffness of supports are introduced on the basis of measurements or with best estimate assumptions respectively. Regarding the frequency content of the fluid force time-histories eigen-frequencies up to 80 Hz are calculated and considered in the modal analysis. In the sense of best estimate calculation the option frequency-shift is not applied.

With the described calculation model loaded by the 102 time-histories of the rapid shutdown at normal operation conditions responses of the structure are calculated. The results are stresses in the pipes, loads on the supports, displacements and section loads at the tanks as well as at the transitions through the containment, at the valves and at the spherical fittings. Using the described linear model the two ring pipes are significantly moving in the plane of the rings which is contradictory to the plant experience. The maximum displacements at building wall transitions are 8 mm which is less than the available clearance. The maximum displacements of the rings are 13 mm. Therefore impact with the baffle bows may happen. On the other hand friction effects which may reduce the displacement response are not regarded in the linear model.

Because of the relative large deflections the results should be conservative regarding the calculated stresses from the linear piping model. So the model is usable to get a conservative estimate of the stress state in the piping during pressure surge. The maximum calculated stress is 61 % of the allowable one of service level B (upset conditions).

Despite of the conservatism of the linear piping model a non-linear model was established to get more realistic results. The refinement towards non-linearity consists of simulating friction on sliding supports which are located mainly in the ring pipes, clearances of baffle bows (gaps) also in the ring pipes and non-linear behaviour of shock absorbers / snubbers located in the four tank pipes. The characteristics of snubbers are derived from function test protocols. The friction factor at the sliding support was estimated to be 0,3 which has been a good choice in former non-linear calculations. Using these boundaries in analysing the same shutdown as before mentioned leads to a reduction of the calculated movement in the ring pipes of roughly a factor 2, but the displacement still remains significant. Even the next refinement stage in calculation quality the consideration of fluid structure interaction (FSI) hardly lowers the calculated displacements in comparison to the pure (without FSI) non-linear solution.

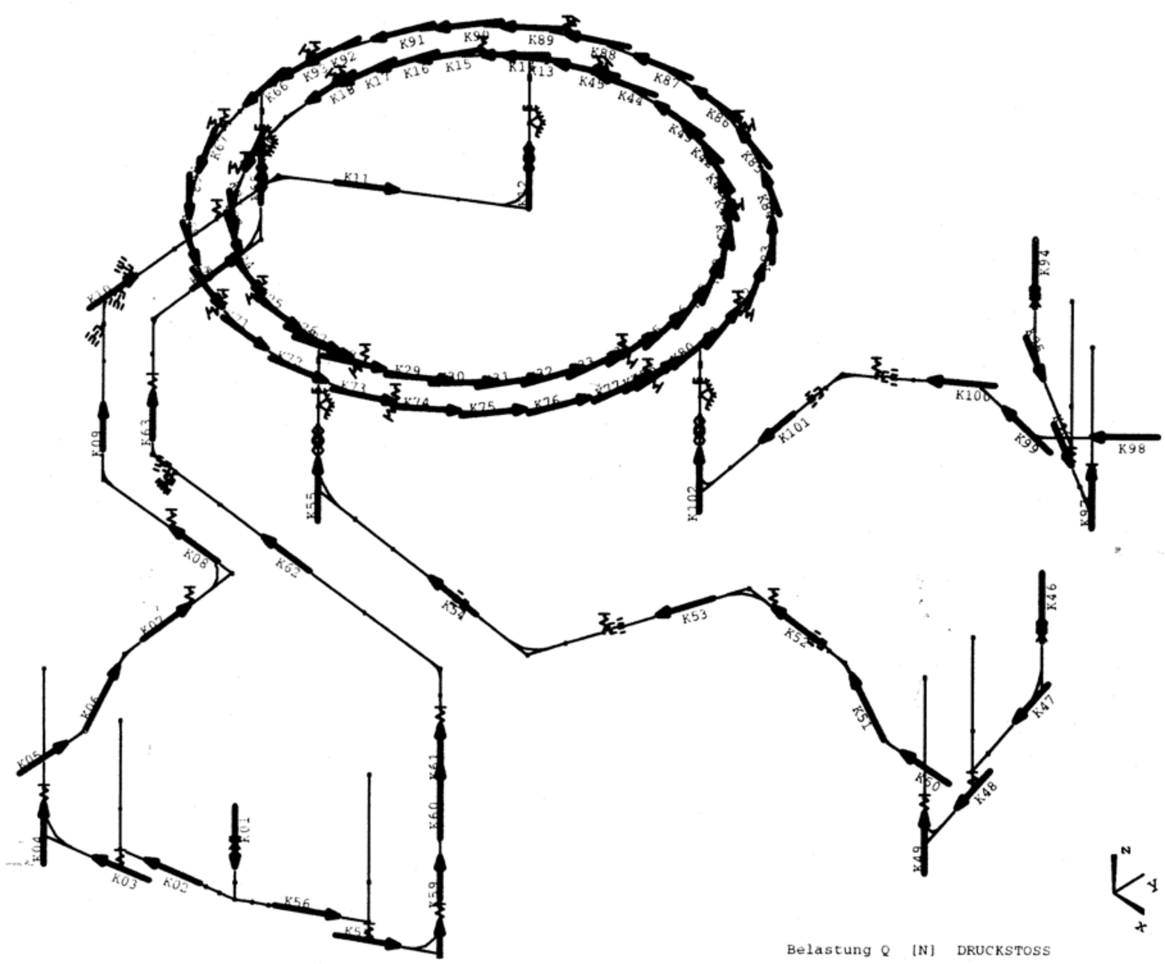


Fig. 6 Finite-Element(FE)-Model with applied hydraulic forces

COMPARISON CALCULATION/MEASUREMENT

Strains and stresses

The comparison between measured strain/stress results and calculated results is done for the linear calculation only. The maximum measured strain at all is 0.38 mm/m (circumferencial at position 5##SG). The corresponding strain due to axial force is 0.095 mm/m. Thus without the strains due to moments the maximum circumferencial stress is evaluated to 87.5 N/mm² and the maximum longitudinal stress is 44.8 N/mm². Taking the static values of fluid pressure difference and strains at about 1 s after opening of the valve (t = 35.6 s) the circumferencial stress deduced from the measured strains are 10 % lower than the calculated ones – taking the available pipe diameters.

Combining in the sense of the German KTA, [1], respectively the American ASME-Code, [2], the stresses of the three moments and also the axial pressure term the resulting equivalent stress σ_v at position 5##SG is 67.4 N/mm². The calculation result is 88.4 N/mm² which is 31 % higher. At the three other positions with strain measurements of the moment parts the equivalent stress portions due to these moments are less than the one of position 5##SG which is 22.6 N/mm². The stress level at the measured pipe positions is low, especially lower than the calculated one.

The rate of maximum calculated stress 132 N/mm² compared to the allowable ones for service level B 216 N/mm² is 61 %.

The results of the comparison show that the linear calculation is sufficiently to get a conservative estimate of the stress level in the piping.

Displacements

The measured maximum horizontal displacement amplitude of 4.4 mm is the displacement response of a representative tank pipe position near to the ring pipe. The electric measurement of displacements is supplemented by coarse documents of simple pin writers with maximum peak to peak ranges of about 10 mm at other positions of the tank pipes.

For the ring pipe the maximum system displacements have been linearily calculated to 13 mm. The real horizontal displacements in the rings are expected to be much smaller respectively very near to zero with regard to plant experience. Even the consideration of friction effects at the ring supports does not lead to calculated displacements near to zero in the rings. So there is an evident contradiction between plant experience and calculated results. This contradiction is compatible to measured displacements in the tank pipe of about an amplitude of 5 mm. Assuming a displacement amplitude of 13 mm in the rings and a certain dynamic amplification of the ring motion one could expect even higher amplitudes in the tank pipes than seen in the measurement result.

It is so far not very clear why the contradiction between measurement and calculation occurs. There are 3 basic causes possible: the first resolution is given if one assumes that the calculated fluid forces are too strong, the second is given by the approach the calculation model of the piping is not good enough or third the plant experience taken from visual control of the system during system tests is not as worthy as it seems to be. But we guess that the first and the second option or a mixture of both will be the truth. To get more information about the causes it is planned to perform further displacement measurement on the piping mainly on the ring piping to learn about the dynamic behaviour of this part.

Spherical fitting

The four spherical fittings in the ring pipes are manufactured of wrought steel. Their geometry is not in compliance with the ASME-code or with the German KTA. Therefore in the computer code ROHR2 no tee-geometry is available which meets the conditions of this tee. To evaluate the stress distribution in the tee-structure under the action of mechanical loads and of internal pressure a detailed model of the structure is generated by automatic mesh generation. The load cases internal pressure as well as representative unit load cases are calculated with this model. In Fig. 7 the FE-model of the spherical fitting integrated in a ring pipe section is plotted. The ring pipe section is fixed at positions of real supports. The mechanical loads are applied at the lower end of the vertical tank pipe part added to the vertical tee part.

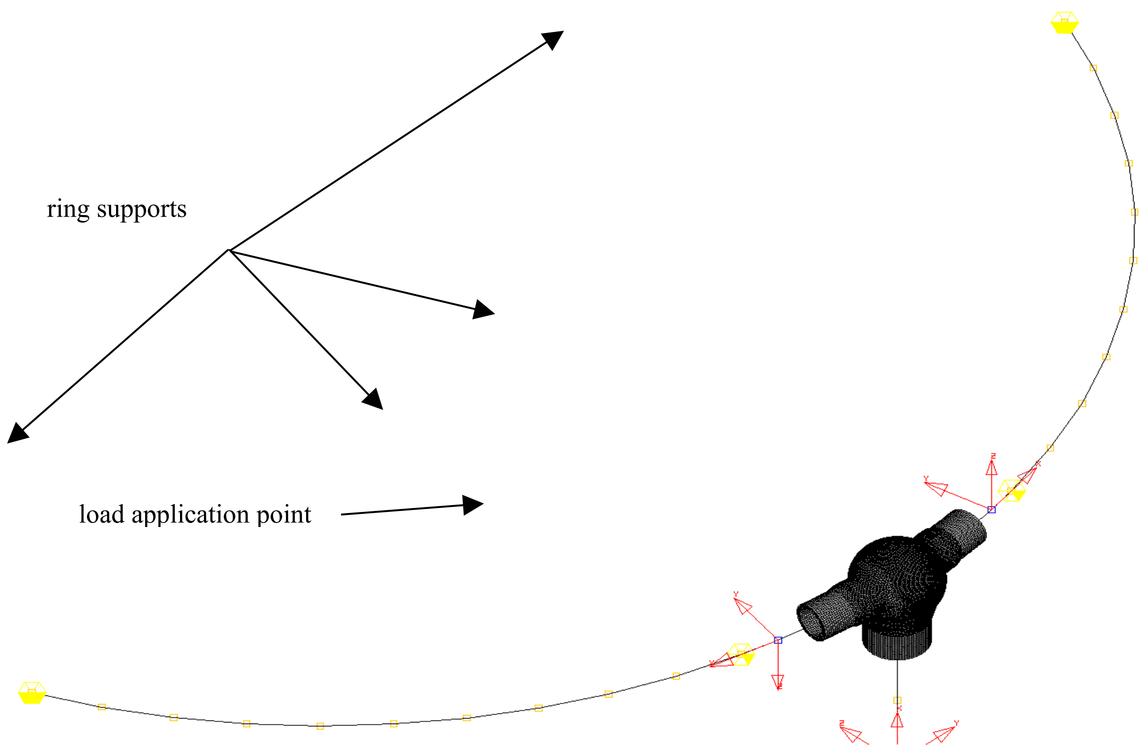
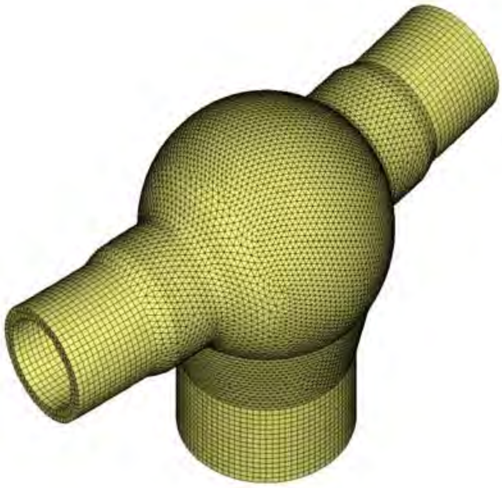


Fig. 7 FE-geometry of a ring pipe section with spherical fitting



In Fig. 8 the stress result for the unit moment 10 kNm in tangential direction of the ring pipe is documented. The stresses show less than 10 % amplification in the tee compared to the undisturbed pipe sections at the model boundaries. Because of the classification of these 10 % as peak stresses for the proof of stresses no amplification has to be regarded. The pipe stresses at the transition from ring to fitting may be used for the stress evaluation according to the KTA-rule implemented in the ROHR2 code.

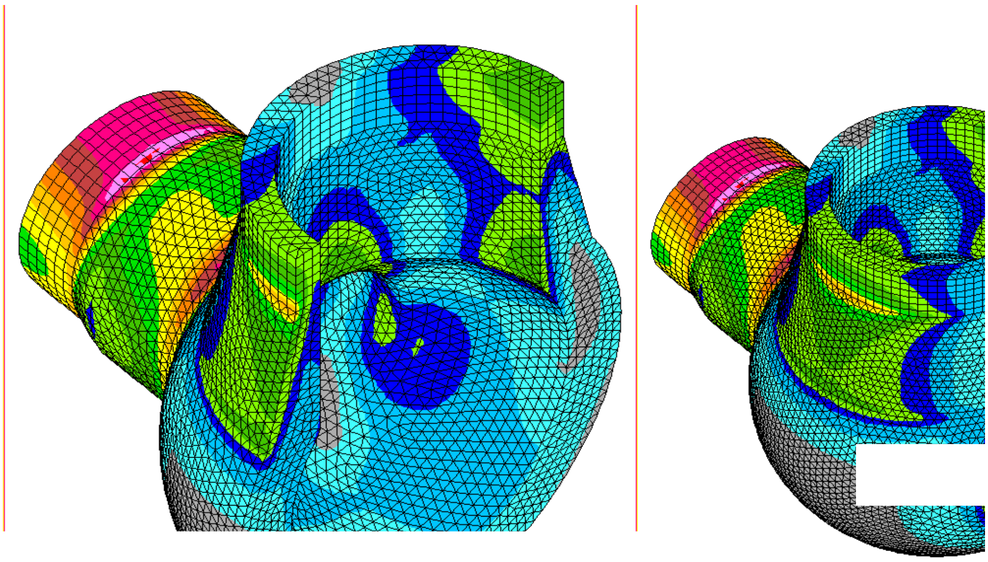


Fig. 8 Stress result for the unit moment 10 kNm in tangential direction of the ring pipe

CONCLUSION

The comprehensive analyses by calculation and measurement for the different pressure surge load cases yielded important knowledge of the rapid shutdown system with respect to the dynamic behaviour and the state of stress under the impact of these load cases. With the calculation results for all details of the system and with the fact that the measured responses are overestimated by the calculated results there exists a closed information on the state of stress throughout the whole system. Looking at the periodical examination program this knowledge together with the results of the non-destructive tests which repeatedly are carried out at much more than 50 % of the present welds should be sufficient to prove the reliability of the system. Furthermore the level of stress in the examined welds reaches nearly the level in the sections with maximum calculated stresses.

For finishing the analyses measurements of accelerations and displacements at the ring pipes are planned during the next rapid shutdown experiment.

REFERENCES

[1] KTA 3211.2 Druck- und aktivitätsführende Komponenten von Systemen außerhalb des Primärkreises Teil 2: Auslegung, Konstruktion und Berechnung (6/92)

[2] ASME Boiler and Pressure Vessel Code, Section III, Subsection NC

[3] MEDA_AD Version 3.11, WÖLFEL Messsyteme Software GmbH + Co.

[4] ROHR2, Version 30.0e from July 2002