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Simulation of structural response for extreme loads in the primary circuit of a PWR

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ABSTRACT

Finite element models of a loop of the coolant system of a PWR (primary side and parts of secondary side) have been developed. They were qualified by calculations of the start-up and comparison with displacement measurements at distinct locations. The models were used to analyze the structural response of the loop to extreme loads as occuring in accident management procedures (AM, e.g. primary or secondary side bleed and feed) and special loading situations as for instance thermal stratification in the surge line.

INTRODUCTION

In a research project sponsored by BMBF finite element models were developed by GRS and analyses performed to simulate deformation and stress in a coolant loop of a PWR under extreme loads.
Loads of this kind may be caused by AM measures, by phenomena not foreseen at the construction e.g. thermal stratification or by erroneus suppression of the movement of components. For the studies the pressurizer loop was chosen, as the thermal-hydraulic calculations of accident management procedures show in some cases rather high temperature values along the bleed path from upper plenum to the pressurizer, e.g. in the surge line.
In the present state of analysis the following parts of the loop are included in the finite element models: the main coolant line and pump, the surge line, the steam line until the containment outlet, the steam generator, the pressurizer and a section of the reactor pressure vessel. The models are build up either of pipe elements or of 20 - node brick elements.

FINITE ELEMENT MODELS

The finite element models of the loop consisting of pipe or brick elements are shown in Fig. 1. The pipe element model has two advantages. One is the easy generation of such a model and the other is the relatively low number of unknown degrees of freedom (about 15 000 in our case) resulting in short solution times. The main disadvantage of the pipe element model is the coarse reproduction of the components, e.g. without temperature variation in a cross-section of a component or pipe. Thus in cases where such temperature variations have to be considered, it is necessary to use the model with brick elements, although it is very much larger (nearly 100 000 unknown degrees of freedom).
The components of the loop are mainly fabricated of ferritic steel (20 MnMoNi 5 5), only the surge line is made of austenitic steel (X6 Cr Ni Nb 18 10). The behaviour of these materials is represented in the calculation by elastic-plastic multi-linear temperature dependent stress-strain curves.

The boundary conditions and supports of the loop are realistically simulated in the finite element models including the pendulum supports of the steam generator and the pump which are modelled by truss elements.

LOAD CASES

As mentioned before different temperature and pressure transients were studied in the finite element calculations. For test purposes and for the qualification of the models calculations of the operational start-up procedure were made, including cases with thermal stratification in the surgeline or with a fictitious suppression of the steam generator movement. As an application of the models calculations of two AM cases and of a further dynamic loading case were performed. For these calculations pressure and temperature distributions were used which were deducted from thermo-hydraulic evaluations (mainly with the program ATHLET [1]).

A short characterization of the load cases considered is given in table 1.

In the start-up calculations (with the exception of the stratification analysis) only three different temperature functions are used, one for the primary side coolant without pressurizer, one for the pressurizer and one for the steam line and secondary side of the steam generator. Between pressurizer and surge line temperatures a linear interpolation is made. As usually two pressure functions are used (primary and secondary side).

For the case of the calculation of stratification effects in the surge line a local variation of the temperatures in length and circumference direction is considered. Based on measurements of temperatures at five cross sections of the surge line during a real start-up a complete temperature field for the surge line has been evaluated at a certain time step. Fig. 2 shows an example of measured values at a cross section in the horizontal part of the surge line.

Table 1: Load cases considered

Number	Description	Finite Element Analysis Model
1	Start-up with pressure and temperature as prescribed in operation manual	pipe element and brick element
2	start-up with stratification in surgeline (measured temperatures)	brick element
3	start-up with suppressed steam generator movement	pipe element
4	accident management with primary side bleed and feed	pipe element and brick element
5	accident management with secondary side bleed and feed	brick element
6	leak-case with emergency cooling (dynamic calculation)	pipe element (part)

In the AM cases also different temperature functions are used for the different regions of the loop according to the results of the ATHLET-calculations. For the primary side AM procedure the wall temperatures of the loop evaluated in the thermo-hydraulic calculation were directly used to derive the temperature input for the structure mechanics analysis. Fig. 3 shows a typical example of temperature functions used in this case.

For the secondary side AM case two assumptions concerning the cooling of the steam generator wall have been considered. Besides an axisymmetric cooling also the case of a strip cooling has been studied. Here only the fluid temperatures of the ATHLET-calculation shown in Fig. 4 were used and calculations of the wall temperatures were performed separately using the cooling assumptions mentioned before.

For the dynamic calculations a part of a transient due to a leak with emergency cooling has been considered where strong pressure oscillations occur in the surge line.

RESULTS OF CALCULATIONS

The analyses have been performed using the GRS structural analysis chain based on the finite element programs ADINA [2] and ADINA/T [3] and the pre- and post-processor programs PATRAN [4], FEMVIEW [5], ADINA-IN [6] and ADINA-PLOT [7].

In the following paragraphs only examples of the results are given, further information may be found in [8-10].

The global deformation of the loop model due to temperature and pressure increase is shown in Fig. 5 for load case 1 and the end of the start-up. A maximum value of the displacement of about 80 mm is found at the highest point of the steam line.

The additional bending of the surge line due to the thermal stratification is shown in Fig. 6. The figure shows the state at the end of the calculation to load case 2, where a temperature difference of about 150 °C is realised in the horizontal part of the surge line. Some localised plastification occurs in the bends of the horizontal line part.

The deformation at the end of the calculation to load case 3 is shown in Fig. 7. Due to the fictively total suppressed movement of the steam generator at its pendulum supports large longitudinal forces and a strong bending of the hot leg part of the main coolant line would occur in this hypothetical load case, resulting in large plastification of the adjacent main coolant line bend.

Fig. 8 presents a result of load case 4, the primary side AM case. Due to the higher temperatures reached in some regions of the loop and the lower yield stress in this case, some small plastic zones develop in the surge line during the transient. The figure shows the development of the plastic zone in the surge line bend adjacent to the main coolant line. The plastic zone is growing with increasing temperature and diminishes due to temperature drop.

Significantly higher stresses than in normal operation are also found in the secondary side AM case. Especially in the steam generator wall effective stresses are calculated which nearly reach the yield stress of the ferritic material. Fig. 9 shows a typical distribution of the effective stresses in a part of the loop model for the case of strip cooling at the end of the transient.

Fig. 10 shows the maximum stress values in the five pipe bends of the surge line, calculated in load case 6. The values are far below yield stress.

SUMMARY

Finite element models of the pressurizer loop of a PWR have been developed. At present they contain a part of the reactor pressure vessel, the main coolant pipe lines, the surge line, the steam generator, the pressurizer, the main coolant pump and on the secondary side the steam line until containment penetration.

For the qualification of the models calculations of the start-up were performed. Comparisons with measured displacements show in general good agreement.

During start-up thermal stratification may occur in the surge line. Calculations with a typical temperature distribution show an additional deformation with small plastic zones at the pipe bends of the horizontal part of the surge line. From literature [11] the conclusion may be drawn that ratchetting can be excluded in this case.

The assumption of a fictitious total suppression of the steam generator movement shows significant influence on the stress distribution in the hot leg part of the main coolant piping. Maximum strain values of up to 3 percent would result from this hypothetical load case.

The application of two typical AM loading histories (bleed and feed on primary or secondary side) shows that the integrity of pipes and components is not endangered, although the stresses are significantly higher in some regions compared to the operational loads and the study of thermal shock loadings due to the feed procedure is not finished definitively.

A dynamic calculation shows the applicability of the models to problems of this type. Further simulations will focus on the evaluation of dynamic effects (e.g. water hammers caused by steam condensation and elevated earthquake spectra) on the structures of the loop.

Another part of the future work is concentrated on the simulation of leaks in the primary circuit with consideration of the fluid jet reaction forces.

ACKNOWLEDGEMENT

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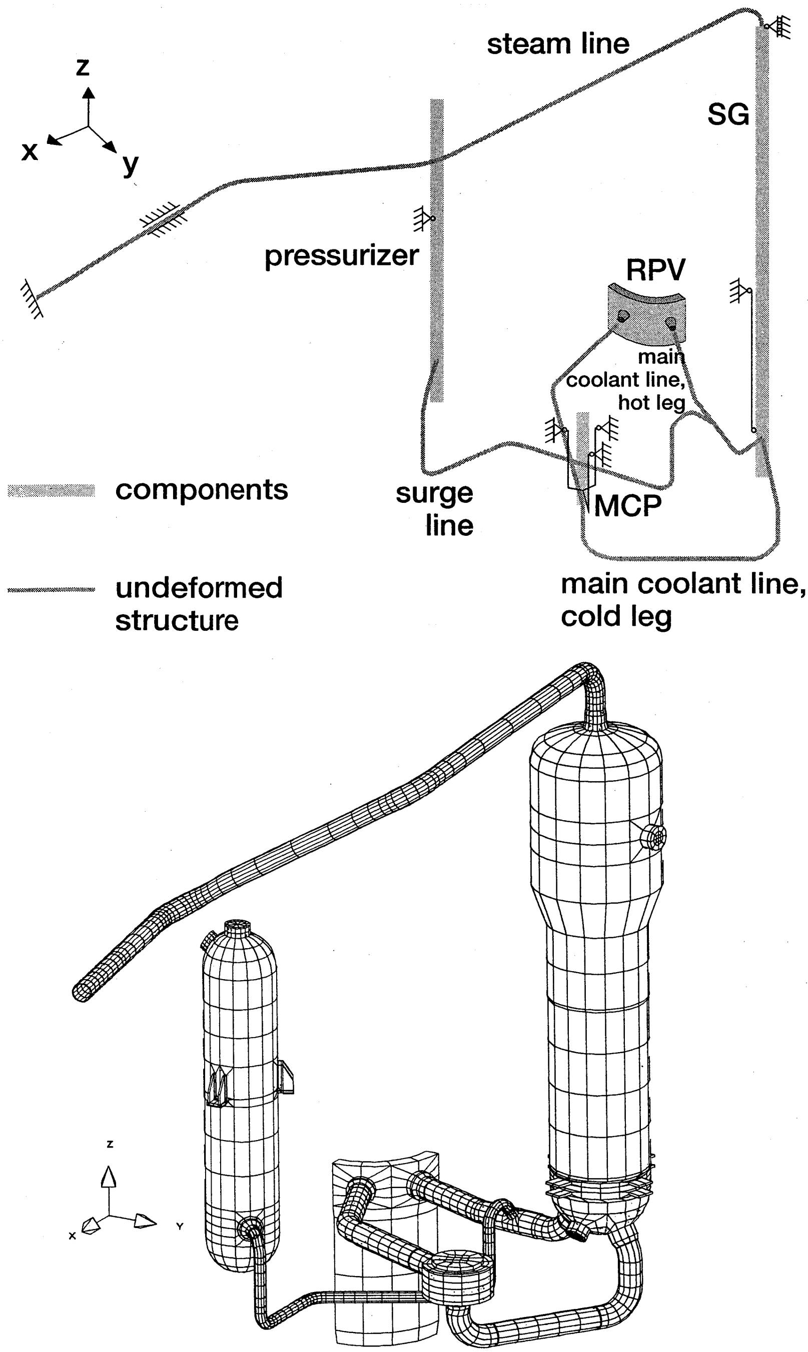

Fig. 1: Pipe element and brick element model of pressurizer loop of PWR

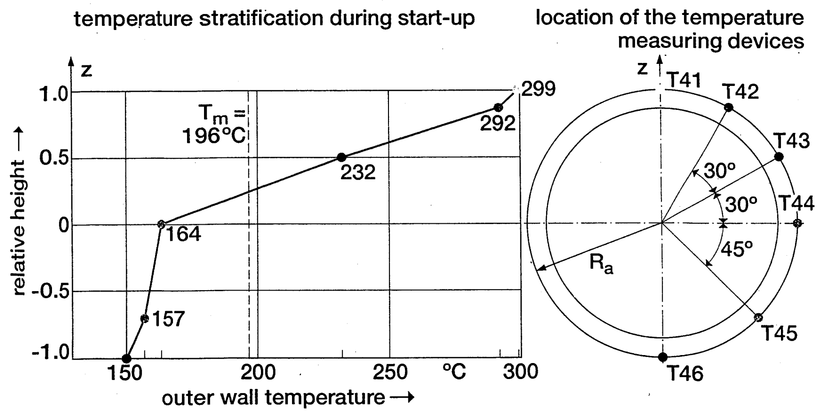

Fig. 2: Thermal stratification in horizontal part of surge line, vertical temperature profile

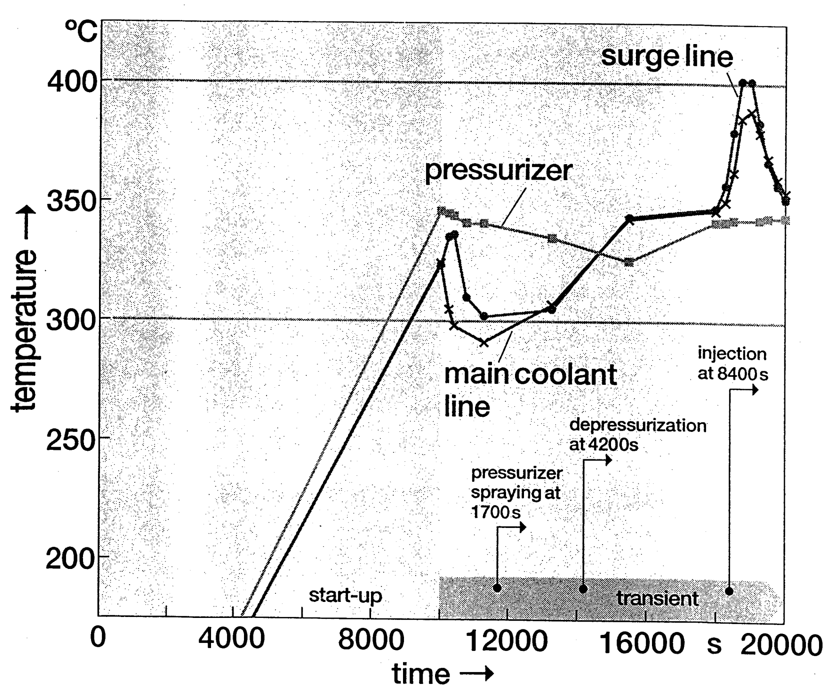

Fig. 3.: Primary side bleed and feed, typical temperature functions for calculation

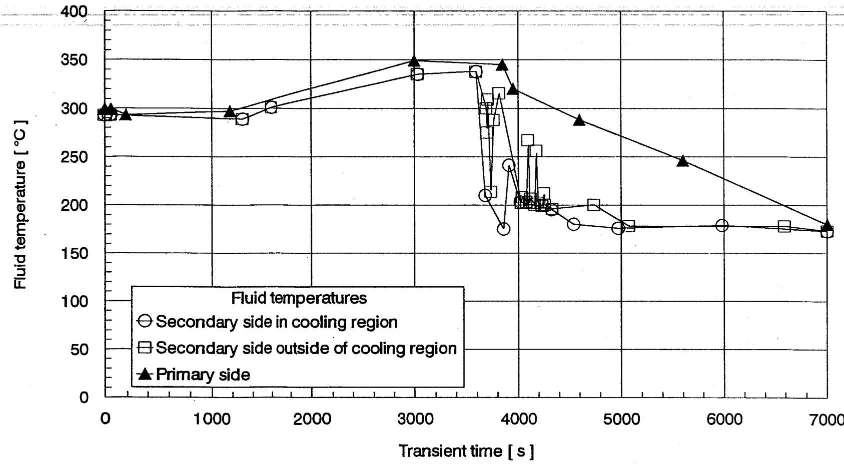

Fig. 4.: Secondary side bleed and feed after loss of feed water supply, fluid temperatures in the steam generator

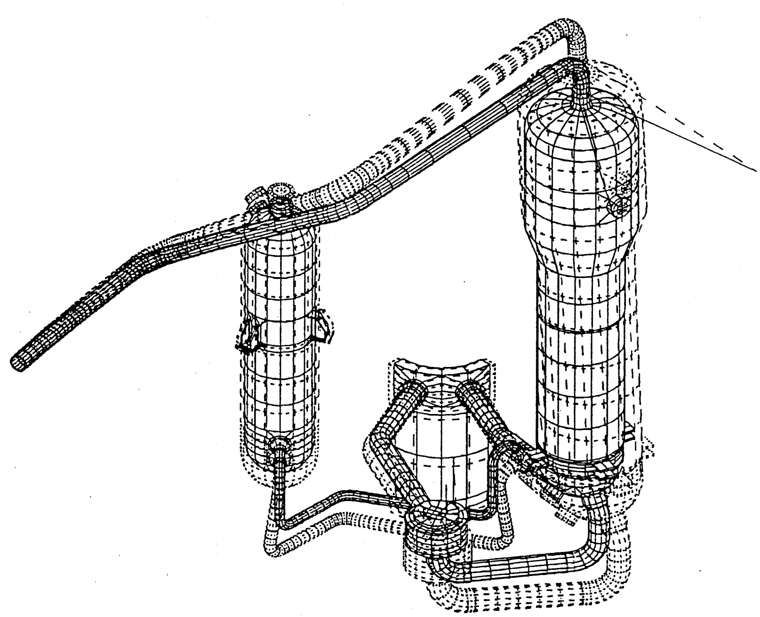

Fig. 5.: Undeformed and deformed loop model at the end of start-up (deformation factor 20)

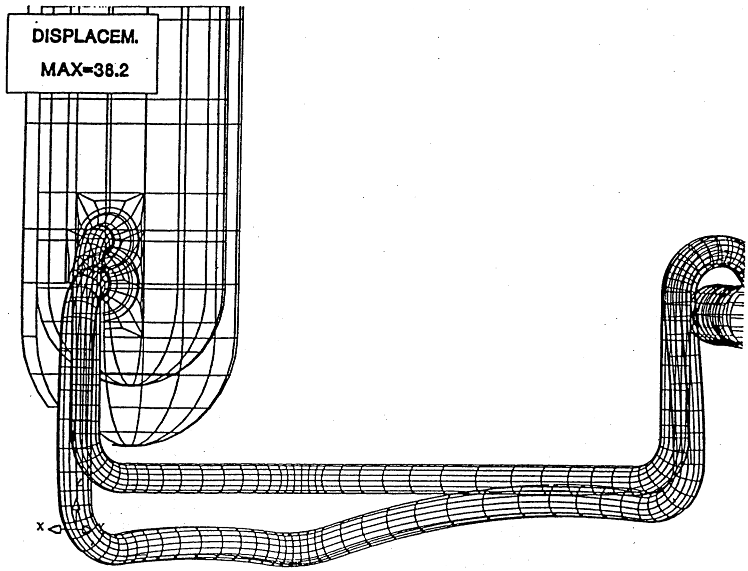

Fig. 6.: Deformation of surge line, additional bending due to stratification (deformation factor 20)

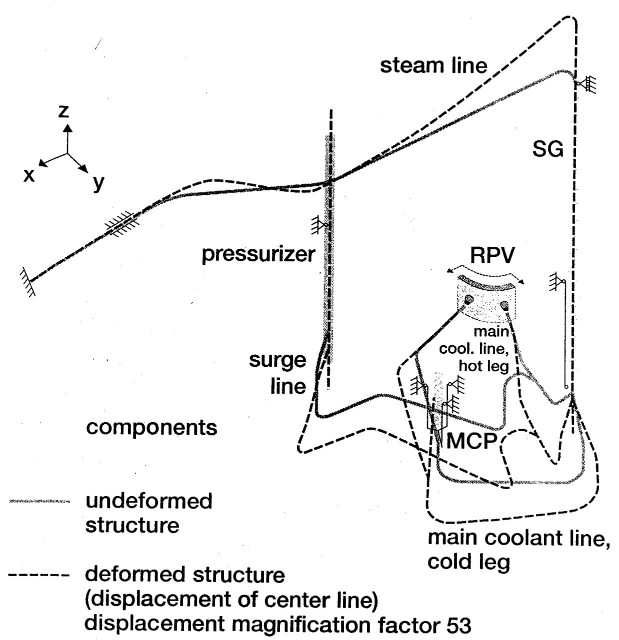

Fig. 7.: Undeformed and deformed loop model at the end of start-up, fictive total suppression of steam generator pendulum support movement

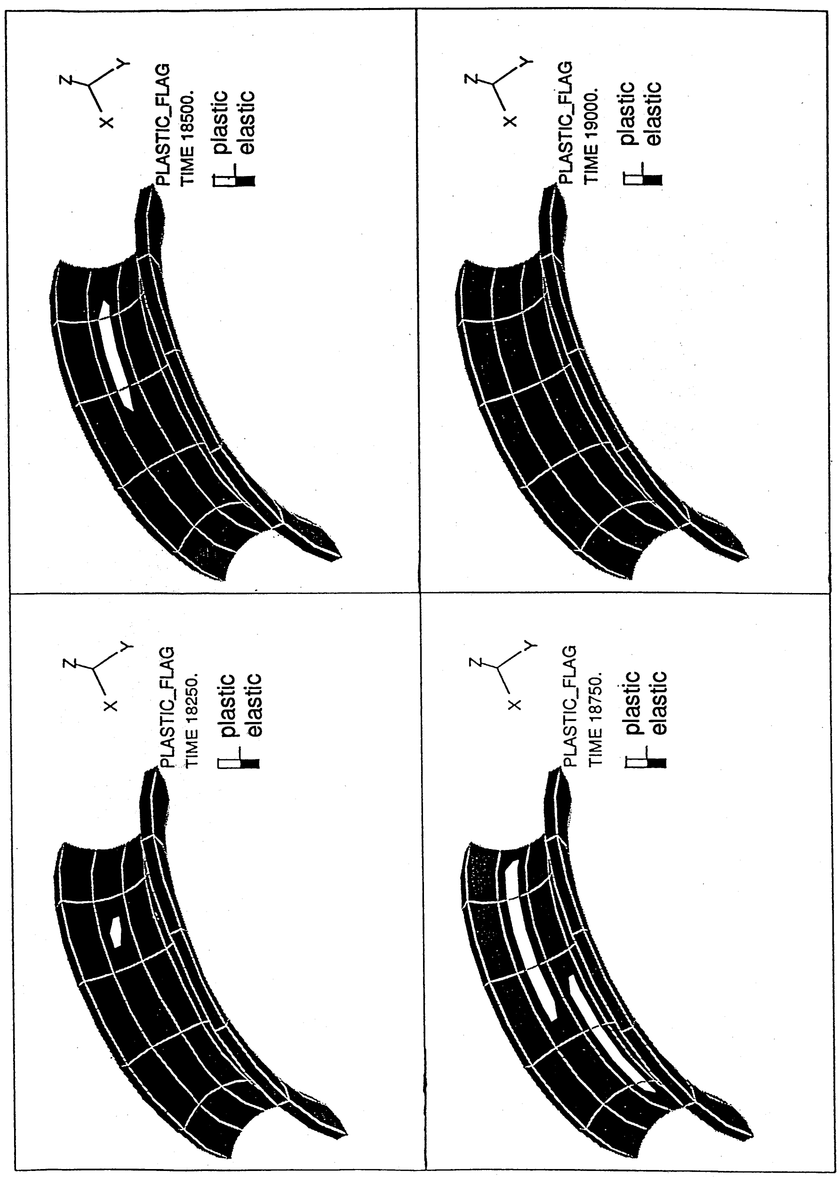

Fig. 8.: Development of plastic zone in surge line bend adjacent to main coolant line, primary side bleed and feed.

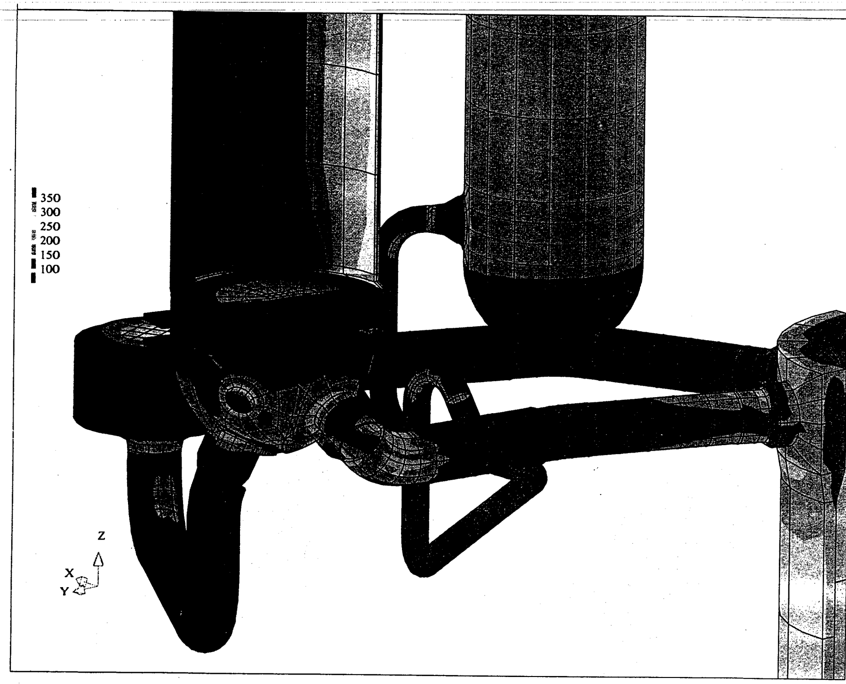

Fig. 9.: Distribution of effective stresses (in MPa) at the end of the calculated transient, secondary side bleed and feed, assumption of strip cooling in the steam generator

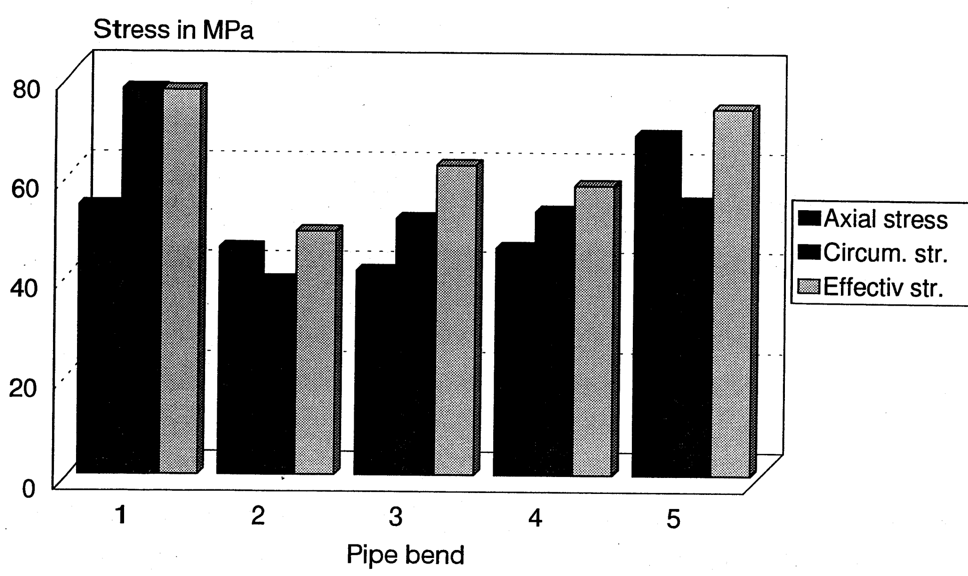

Fig. 10: Maximum stress values in surge line bends, dynamic load case