ASSESSMENT AND STRUCTURAL ANALYSIS OF A PCPV WITH HOT LINER AND ADJUSTABLE WALL TEMPERATURE

A. NESITKA, E. ETTEL, M. GANGL, H. HINTERLEITNER

Reaktorbau Forschungs- und Baugesellschaft, mbH & Co., A-2444 Seibersdorf, Austria

The great adaptability of the concept with elastic hot liner and adjustable wall temperature can be seen in design and assessment of the PCPV for different reactor types.

The first part of the paper presents an overview of the influence and possible reactions on the main existing assumptions for this special concept.

One of the most essential features - the limitation of liner stresses for elastic compression - can be attained by balancing liner and structural concrete temperatures. The temperature difference between these two components mainly influences the stress-state of the liner. Transient conditions mostly extend only to the region of liner and thermal barrier.

The knowledge of material properties is a fundamental requirement of every analysis. A study demonstrates how temperature and long-term behaviour of materials influence the stress and strain history of the vessel.

The concept offers the possibility of vessel stabilization before operation. This method which anticipates visco-elastic deformations has particular importance for high operating temperatures. The decision whether to stabilize or not depends both on the thermal assessment and on the long-term restraints of the liner and requires an optimization of these effects.

The second part of the paper deals with the analysis methods and their results used in the development of the Austrian PCPV. By means of two- and three-dimensional calculations for the reference design of a PWR with 15oo MWe some of the above mentioned aspects are explained. Stress and deformation diagrams indicate the possibility of safe operation. These extensive investigations and analyses also yielded a feeling on analytical possibilities for vessel design and their costs.

1. Introduction

The progress in development and the experiences of the PCPV technology in connection with increasing demands for operational safety expressed by utilities lead to new, advanced vessel concepts responding to these demands. The Austrian PCPV concept with elastic hot liner offers significant advantages with regard to functional and operational safety / 1 /.
The reliability of this vessel is demonstrated by basic material investigations and in large - scale model tests as well as by the use of improved analysis methods.

The paper deals with the particularities of analysis in the assessment of a vessel characterized by an elastic hot liner. By means of functional improvement of vessel elements e.g. the temperature regulation system of the concrete wall new tools are given to influence the short and long-term vessel behaviour. This leads to an optimal adjustment to different operational conditions and geometries and yields an improvement of the vessel stress- and deformation state during its whole lifetime. In the following chapters some typical examples of elastic hot liner assessment are discussed.

2. Thermal Assessment

In the composite structure-liner, thermal barrier, prestressed concrete - the individual materials undergo mechanical and thermal loads in such a way, that their respective properties are exploited optimally. This is achieved by a balanced temperature distribution over the vessel wall. Thus, the resulting liner stress is limited to the elastic compression range, which on the one hand offers constructive advantages and on the other hand increases the safety against low cycle fatigue according to accepted rules. The improvement of the conventional liner cooling into a temperature regulation system, distributed over the vessel wall, also improves the operational conditions like start-up and shut-down. The concrete temperatures can be adjusted in both directions by cooling and heating and allow an adaptation to changing operating conditions throughout the lifetime of the plant.

In fig.1 the stresses in the martensitic liner as a function of the temperatures acting on the liner (primary coolant) and the chosen concrete temperature are illustrated. The design temperature of the liner is given by the highest short or long-term temperature. The diagram primarily considers the effect of constraints caused by the temperature difference between liner and concrete, but also includes stresses due to prestress and internal pressure. In the picture, which only gives a first impression of the liner stress state, the behaviour of the martensite is compared with ferritic and austenitic materials in the elastic range. The significant differences result from differences in yield stress and / or thermal expansion.

3. Long-term behaviour

The above mentioned temperature regulation of the vessel is also significant for the long-term behaviour of the prestressed concrete. In fig. 2 two possible loading cases are investigated with the geometry of the prototype vessel in Seibersdorf. On the right side of the picture the stress state of the vessel wall without temperature regulation is shown. The temperature of 70°C in the area of the cooling system between thermal barrier and prestressed concrete decreases to about 30°C on the outer surface. The picture on the left shows the temperature-regulated vessel with constant 70°C. The temperature of the liner also was assumed to be 70°C because of its lesser importance for this investigation.

The compressive stresses due to prestress are reduced by creep and relaxation effects depending on the temperature. In the case of a non-temperature-regulated vessel additional temperature constraints yield increased redistribution of stresses in the vessel wall. From prestressing during construction until shut-down after 30 - 40 years the stress-state is significantly influenced by the temperature conditions of concrete. To prevent tension in the vessel wall, an increase of reinforcement and prestressing steel in connection with a larger wall thickness will be required. Contrary to the consequences of natural temperature gradient / 2 /, a temperature regulation system causes balanced stresses in the vessel wall and, thus, savings in material costs.

The overall vessel deformations due to creep mainly depend on the medium temperature of the prestressed concrete. In the example shown deformations correspond to the specific creep of 50°C and 70°C . The increased creep constraints in the liner in the case of uniform concrete temperature are more than compensated by temperature stresses in the non-regulated vessel. By this fact better stress conditions in the liner can be achieved with the temperature regulated vessel wall. The influences of these facts on the assessment, demonstrated on a simple cyclindrical vessel and the resulting stress-state, become even more significant with a geometrically complex multicavity vessel for HTR-application. Due to the many irregularities and disturbances in geometry the advantages of clear temperature conditions are intensified.

4. Construction methods

The temperature regulation system offers the possibility of accelerating and anticipating long-term deformations before operation. A thermal treatment yields a stabilized vessel before operation. By this operating conditions of reactor installations, such as closures, seals, control rods, refuelling installations, are significantly improved. Prestress losses can be accounted for after stabilization or long-term operation by prestressing. Thermal prestressing can be achieved by keeping the wire-wound hoop prestress on the outer surface of the vessel cold.

5. Two- and three-dimensional analyses

In the framework of the development program for the Austrian PCPV concept emphasis was given to analysis methods considering the special vessel aspects. The material properties at elevated temperatures, the long-term behaviour and the specific construction methods were included in specially developed analysis programs / 3 /. Results of experimental investigations were considered as soon as available.
As example for the practical performance of an analysis for a PCPV with elastic hot liner the results of three-dimensional stress- and deformation - analysis for a PWR with 1500 MWe are shown / 4 /. After preceeding two - dimensional investigations an evaluation was performed with three - dimensional finite elements using the program SMART I / 5 /.

Emphasis was given to singular areas of the vessel, e.g. lateral gas ducts, upper liner edge construction, hemisphere shaped bottom head with multilayer prestressing and the buttress anchorages. Existing symmetry plains reduced the analysis to a 30° sector of the vessel.

A vertical section of the chosen mesh can be seen in fig.3. This geometric model is characterized by a wide-meshed idealization of the structure, a limiting fact due to computer costs. Concrete is modeled by isoparametric cube elements with 27 nodes and 81 degrees of freedom with a quadratic displacement field. Liner is represented by membrane elements. Stiffness of prestressing and reinforcement is neglected because of its little influence. The whole system was sliced in 4 substructures. This gave both the possibility of a good data organisation and the basis for detailed analyses by idealizing areas of interest in a fine mesh and assuming the displacements as boundary conditions of the substructure. The structure included 357 elements and 2730 nodes. The number of external degrees of freedom was 1062, the number of unknowns 5042.

The analysis was performed for the most important construction and service conditions:

- 1 Partial prestressing on the prestressed concrete after thermal stabilization
- 2 Residual prestressing on the completed structure after coupling liner and insulating concrete with the prestressed structure by grouting
- 3 Service conditions

o 178 bar internal pressure
oo 316°C liner temperature
ooo 120°C concrete temperarure

In the third loading case temperature depending material behaviour was considered.
The results of the analysis were represented by an interactive graphic program (INGA) and after selection of stress- and displacement fields plotted in suitable sections, substructures and projections. Fig. 4 shows deformations of the structure due to prestressing. Fig. 5 illustrates principal stresses as a combination of the three individual loading cases in a vertical section.

The results were compared with those from preliminary calcuations with axisymmetric idealizations performed by the aid of the programs ZYKRIS and ROTFIN. In undisturbed regions good agreement of all analyses can be seen (fig. 6). In the specific areas of the vessel like gas ducts or load concentrations originating form the anchors of tendons only a detailed fine meshed analysis with finite elements yields the local stress state.

Besides the above mentioned elastic calculations and long-term investigations of a PCPV with elastic hot liner for a 1500 MWe PWR, the vessel behaviour under overpressure was also analyzed.
This failure mode analysis, performed by the "Institut für konstruktiven Ingenieurbau der Ruhr-Universität Bochum" yielded a sufficient safety factor against failure / 6 /.

6. Conclusion

Some typical examples showed the particularities of the assessment of a PCPV with elastic hot liner. The temperature regulation of the vessel offers a wide range of design potential and, thus optimal adaptations of a PCPV to different service conditions. These new possibilities in PCPV assessment yield a tool for regulation of stress and deformation conditions and thus improved long-time safety conditions.

A three-dimensional analysis of a large scale vessel with elastic hot liner verifies the aspects.

References

/ 1 / KOPP, H., JUNGMANN, A., GANGL, M., MUTZL, J., NEMET, J., WALLUSCHEK, W.; "Spannbeton-Reaktordruckbehälter mit heißer Dichthaut für Druckwasserreaktoren", Deutscher Ausschuß für Stahlbeton Heft 264, 1976.

/ 2 / SCHNELLENBACH, G., HARTMANN, G., ICK, U.; "Systemanalytic and Parametric Studies of Prestressed Concrete Reactor Pressure Vessels", 2nd International Conference on Structural Mechanics in Reactor Technology, Berlin 1973.

/ 3 / NESITKA, A., WALLUSCHEK, W.; "Statische Berechnung, Sicherheitsüberlegungen und Untersuchungen des Bruchvorganges von Reaktordruckbehältern aus Spannbeton", 2nd International Conference on Structural Mechanics in Reactor Technology, Berlin 1973.

/ 4 / GANGL, M., JUNGMANN, A., KOPP, H., MUTZL, J., NEMET, J., NESITKA, A., WALLUSCHEK, W.; "Reference design of a prestressed concrete pressure vessel for pressurized water reactors" - Experience in the Design , Construction and Operation for PRESTRESSED CONCRETE PRESSURE VESSELS and Containments for Nuclear Reactors, York 1975.

/ 5 / ARGYRIS, J.H., FAUST, G., ROY, J.G., SZIMMAT, J., WARNKE, E.P., WILLAM, K.J.; "Finite Elemente zur Berechnung von Spannbeton - Reaktordruckbehältern", Deutscher Ausschuß für Stahlbeton Heft 234, 1973.

/ 6 / SCHIMMELPFENNING, K., BÄÄTJER, G., ECKSTEIN, U., ICK, U., WRAGE, S.; "Studien zur Auslegung von Spannbetondruckbehältern für wassergekühlte Reaktoren", Deutscher Ausschuß für Stahlbeton Heft 294, 1978

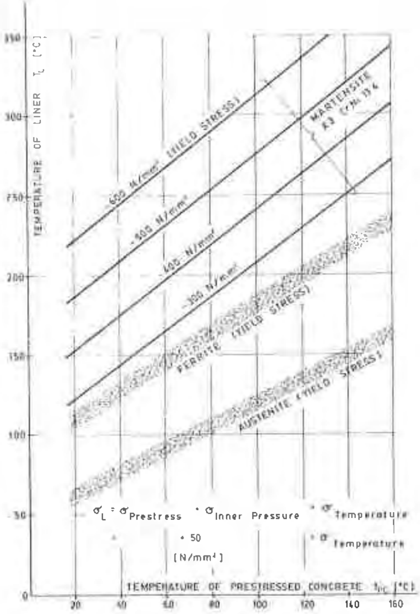

Fig. 1 Elastic liner stresses as a function of liner and concrete temperature

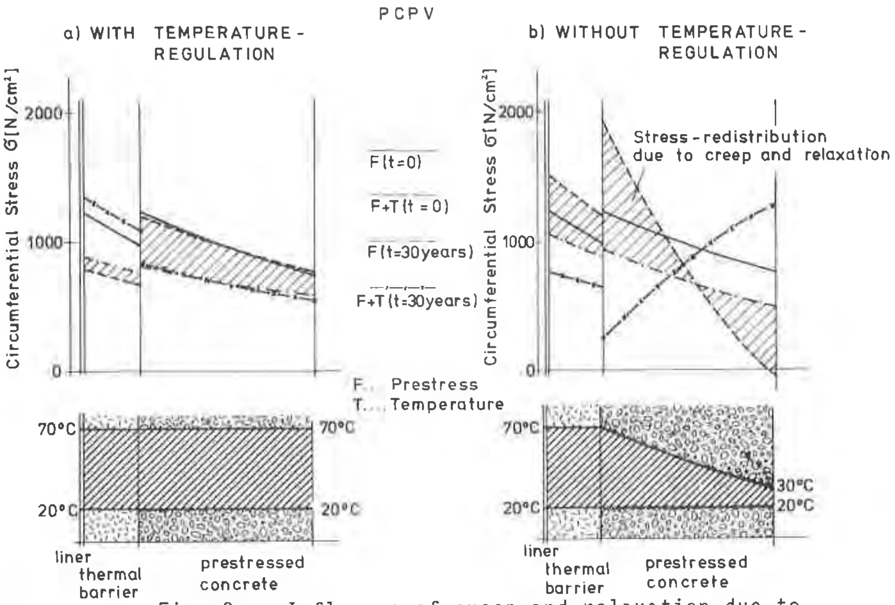

Fig. 2 Influence of creep and relaxation due to different thermal assessment of a PCPV

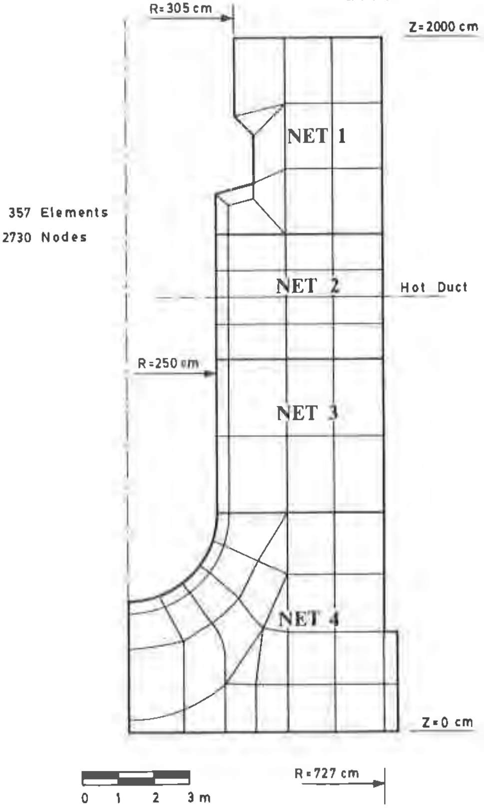

Fig. 3 Main section of the 3-D structure

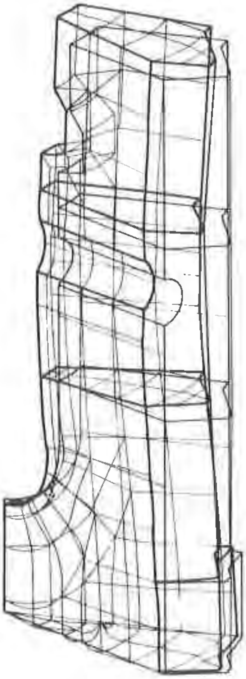

Fig. 4

Deformations due to prestress

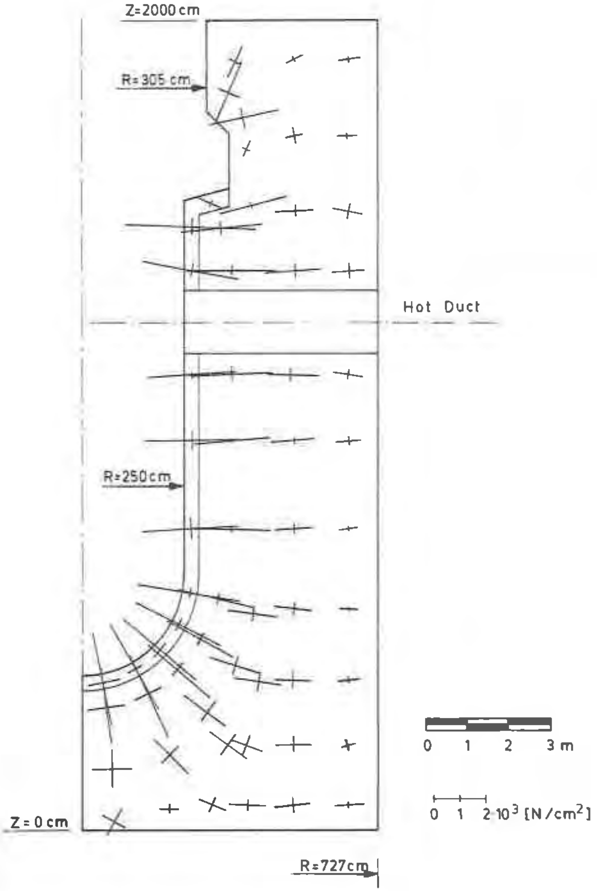

Fig. 5 Principal stresses due to prestress, design temperatures and pressure

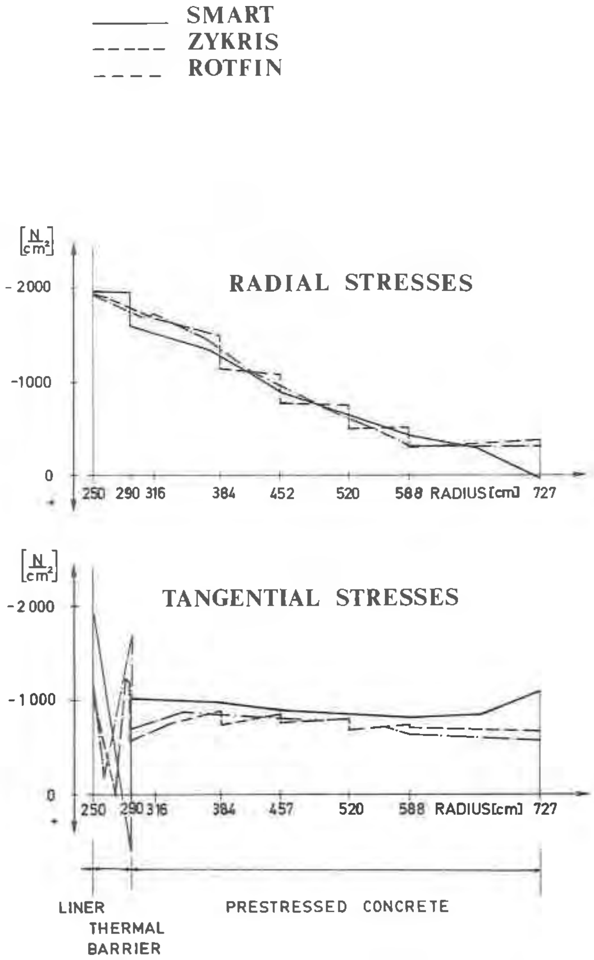

Fig. 6 Comparison of stresses in undisturbed region calculated with 2- and 3-dimensional programs