

Analysis of the PWR Core Support Columns Under Blowdown Loading

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Summary

A failure of the primary coolant system in a pressurized water reactor has been assessed to be very unlikely. Nevertheless a sudden and very large break of the primary coolant circuit at an outlet nozzle of the reactor pressure vessel is postulated in this paper. It causes a fast blowdown of the primary system accompanied with strong transient bending loadings of the core support columns. These loadings must not result in major plastic deformations or breaks of several columns.

In order to investigate the transient bending loading and the resulting stresses during the initial phase of the blowdown, the accelerating flow in the upper plenum is calculated. The closely spaced core support columns located in this plenum are treated as circular obstacles. For solution of this problem having a very unfavourable geometry a boundary integral method (computer program SING1) is used which has been developed recently for highly transient internal flow problems. In this method the unknowns describing the problem are distributed over the outer fluid boundary and along the axes of the columns only. In this way the computational effort has been considerably reduced in comparison with usual methods, where the unknowns are distributed over the whole three-dimensional flow field.

Based on the calculated pressure field, the transient bending loadings, deflections and stresses of the columns are determined. The results show that even under severe blowdown conditions major plastic deformations do not occur in the core support columns, except one small diameter column which is not essential for the overall integrity of the system.

The same problem has been investigated by Dienes [1]. However, in his problem the diameter of the columns were somewhat smaller but the gaps between the columns considerably larger. Since these changes in geometry influence the structural response in opposite direction similar results have been obtained. For solution he was able to use a finite difference method, since his larger gap width allowed for an appropriate spatial resolution with a still tractable number of mesh cells.

More details of the investigation presented here may be found in [2, 3]. A description of the boundary integral method used is given in [4].

1. Definition of the Problem

A typical PWR with the upper plenum and the core support columns is shown in fig. 1. A simplified description of the upper plenum with the core support columns is given in fig. 2.

The postulated break of the outlet nozzle causing the blowdown flow is assumed to occur in a rather short distance from the upper plenum. Furthermore the break is simulated by a complete opening of the outlet nozzle with a prescribed sudden pressure drop of 40 bar. In reality this pressure drop which is approximately the difference between the operating and saturation pressure may be somewhat larger. However, an extrapolation to other pressure drops is easy since the calculated stresses are proportional to the pressure drop. In contrast to these assumptions, if a break is postulated at all, it is more likely to occur in a larger distance from the upper plenum and the pressure drop is expected to take some time being in the order of a few milliseconds at least. Furthermore it may happen that only a part of the cross-section of the outlet nozzle will be opened. With respect to these facts the above simulation leads to overestimations of the resulting stresses.

At both horizontal boundaries of the upper plenum a large central opening is introduced, where the pressure is assumed to be constant all the time. In reality this pressure will decrease when the flow from the reactor core into the upper plenum increases. For the first milliseconds this effect will not exceed reasonable limits and thus the structural response will be overestimated only to a certain extent. However, for later times the results will become unrealistic.

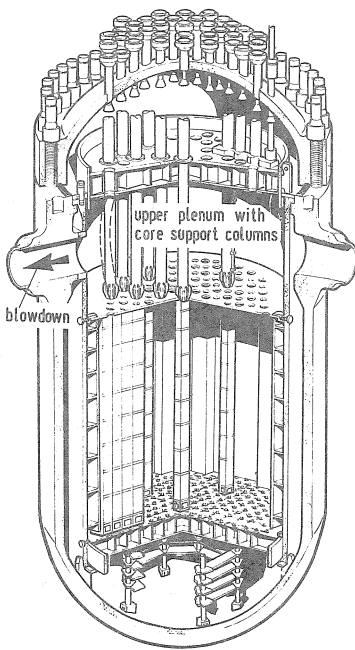


Fig. 1 Geometry of a typical PWR

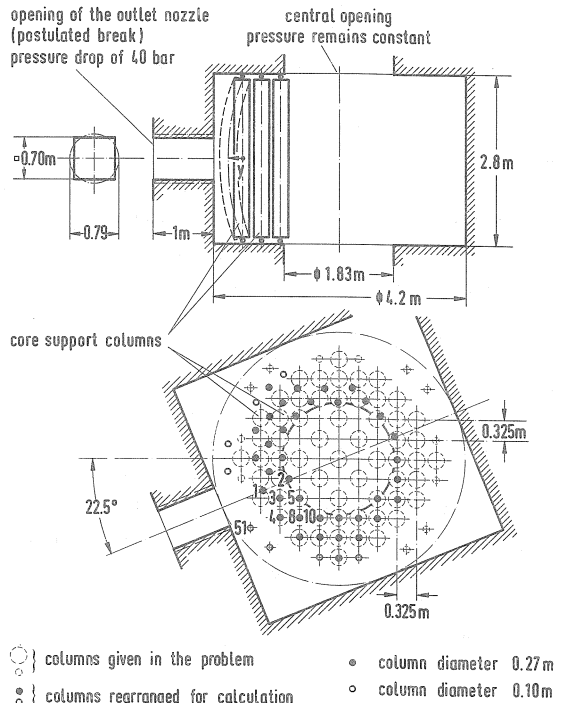


Fig. 2 Simplified Description of upper plenum and outlet nozzle of a typical PWR

The fluid in the upper plenum and the outlet nozzle is assumed to be incompressible with a density of 665 kg/m^3 . This means that propagation of depressurization waves cannot be described. Therefore the blowdown flow is not accelerated by velocity steps generated by passing waves. Rather the flow is accelerated by smooth velocity increases. Consequently, the core support columns will not be loaded by an number of pressure peaks, but by smooth pressure increases where the mean values taken over a certain time are the same. This simplification has no essential influence on the column stresses as long the characteristic wave propagation time in the fluid is less than about one third of the smallest oscillation period of the structure. In the problem investigated here this criterion is fulfilled. A more detailed discussion of these facts and additional proofs by comparing analyses with and without consideration of the fluid compressibility may be found in [2] and [5]. According to these studies the error caused by neglecting the fluid compressibility does not exceed 20 %.

The fluid is assumed to be inviscid and the dynamic pressures¹⁾ are neglected. A rough estimate shows that the maximum viscosity forces acting on the columns are smaller than the maximum inertia forces. Furthermore, the viscosity forces and the influence of the dynamic pressures are almost zero at the beginning. Therefore the neglected effects have little influence on the flow problem within the first milliseconds and the resulting forces are primarily due to inertia effects during this time. However, the calculations are not able to describe the reductions of the forces due to the pressure drop inside the vessel expected for later times.

For simplicity the circular cross section of the outlet nozzle is approximated by a quadratic cross section having the same area. Thus the flow resistance due to inertia effects is almost the same. The circular cross section of the upper plenum is also approximated by a quadratic cross section by adding four corner regions, where the flow is almost stagnant. Thus the added corner regions will be inessential for the calculation of the forces acting on the columns.

The arrangement of the columns is changed such that the geometry is symmetric with respect to the nozzle axis. Furthermore some of the columns are neglected. In [2] it has been shown that such modifications are of little influence on the maximum forces and deflections of the core support columns.

All the fluid boundaries formed by structural elements are assumed to be rigid for calculation of the transient flow field and the resulting pressures. As far as the walls around the upper plenum and the nozzle are concerned, the transient displacements expected are rather small. Consequently, the above assumption is acceptable in this respect.

However, as far as the core support columns are concerned, the transient deflections toward the nozzle may reach higher values. They are still small in comparison with other relevant dimensions. But the corresponding accelerations are no longer small in comparison with the fluid acceleration. From this fact it follows that the effect of fluid-structure interaction should be taken into account for the columns. Under the assumption of an incompressible fluid, this implies that the added fluid masses should be considered for determination of the eigenfrequencies of the column. On the other hand, as a consequence of the special geometry,

1) The dynamic pressure also known under the term pressure head defined as half the fluid density times the square of the fluid velocity.

the eigenfrequencies of the relevant column oscillations are almost the same. In this case the value of the eigenfrequencies only influences the time scale of the process but not the maximum deflections and stresses of the columns. Consequently, if one is interested in these maximum values only, the neglect of the effect of fluid-structure interaction is acceptable, too.

In conclusion it can be said that all the particular assumptions and simplifications discussed above usually cause overestimations of the structural response for the core support columns. Furthermore the overestimations are felt to be within reasonable limits for times up to about 20 ms after the postulated break. Within this time interval the maximum stresses are expected.

2. Description of the Cross Flow Around the Core Support Columns

The advanced boundary integral method used here is based on closed form solutions for the three-dimensional acceleration and pressure field around a plane rectangular dipole panel. Solutions for such panels are superimposed in order to describe the given flow problem. The dipole intensities of the panels are determined such that the boundary conditions of the flow problem are satisfied in discrete points. The number of unknowns describing the dipole intensities must agree with the number of the discrete boundary points. Then a linear equation system for these unknowns is obtained which in general allows for unique solutions. More details of the solution method and the corresponding computer program SING1 are given in [4].

The dipole panels introduced here generate a pressure step between both sides of the panels. Therefore, dipole panels used to form the fluid boundaries caused by walls are able to model the pressure difference between both sides of these walls. Furthermore, dipole panels used to form boundaries with sharp edges do not generate awkward flow singularities at these edges. This presents an important advantage in contrast to standard source panels where such singularities cause considerable unintentional leakages.

The arrangement of dipole panels used for the outer boundary of the upper plenum is shown in fig. 3a. It includes a total of 190 panels. Due to symmetry conditions only one quarter of the geometry is considered. Two different types of boundary conditions occur. At walls and symmetry planes the normal acceleration must vanish; at the openings the pressure must assume prescribed values. The boundary conditions are satisfied only at the midpoints of the panels. Consequently certain deviations occur at the other points of the boundary. In order to minimize these deviations small panels are used for the intersection region between the nozzle and the upper plenum where strong accelerations and pressure gradients are expected.

In order to describe the flow around the core support columns, dipole panels are put along the column axes. This is shown in fig. 3b. Here 30 panels are used, six in circumferential direction and five in axial direction. This means, a total of 675 panels is used for the 21 complete and the three half columns in fig. 3a.

So, altogether 865 panels are introduced for modelling the accelerating flow in the upper plenum.

In order to assess the accuracy of the modelling, test calculations have been carried out with only three columns in the upper plenum, but with different numbers of panels around each column axis. The results are presented in [3]. Here only the calculated bending moment in the columns for different numbers of panels are shown in fig. 4. It turns out that analyses

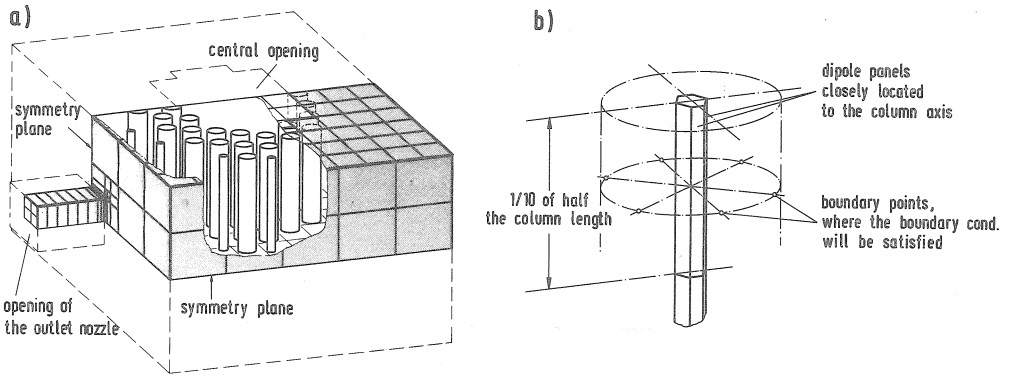


Fig. 3 Arrangement of the dipole panels
 a) Boundary of the upper plenum
 b) Core support columns in the upper plenum (enlarged detail)

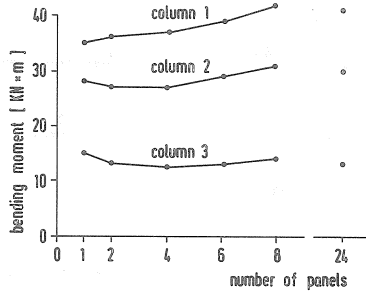


Fig. 4 Bending moment in the columns versus the number of dipole panels around each column axis

with six panels yield almost the same bending moments as analyses with 24 panels around each column axis. Thus the modelling used in this paper can be expected to provide reliable results.

4. Forces and Stresses Obtained for the Column Tubes

With the model described above the transient flow field and the resulting forces acting on the columns have been calculated. ¹⁾ Some flow accelerations and column forces in the horizontal symmetry plane are shown in fig. 5. The forces are related to one fifth of half the column height which amounts to 0.28 m. The values decrease if the distance from the outlet nozzle increases. In other horizontal planes the forces are smaller and the directions are somewhat different. In this way certain axial load distributions are obtained. They become smoother if the distance from the outlet nozzle increases. For the forces at the columns 1, 2, 3, 4, 5, 8, 10 and 51 this may be seen in fig. 6. Only the forces close to the contour of the central opening exceed the corresponding forces in the symmetry plane. However, this is a consequence of simplifications in the model and does not represent a real effect. In reality the coolant is fed into the upper plenum not by two central openings, but through many small openings.

1) CPU time for IBM 370/3033 was 30 minutes

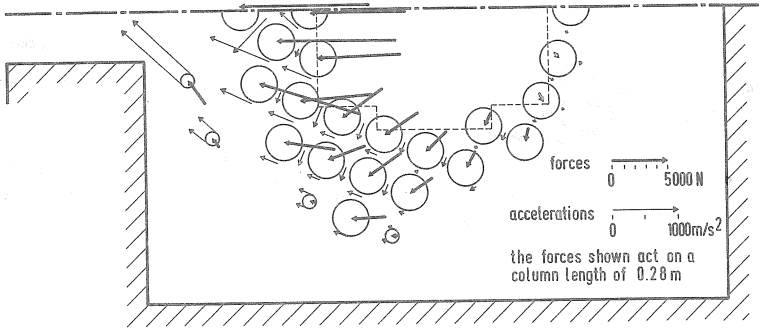


Fig. 5 Flow accelerations and column forces in the horizontal symmetry plane of the upper plenum

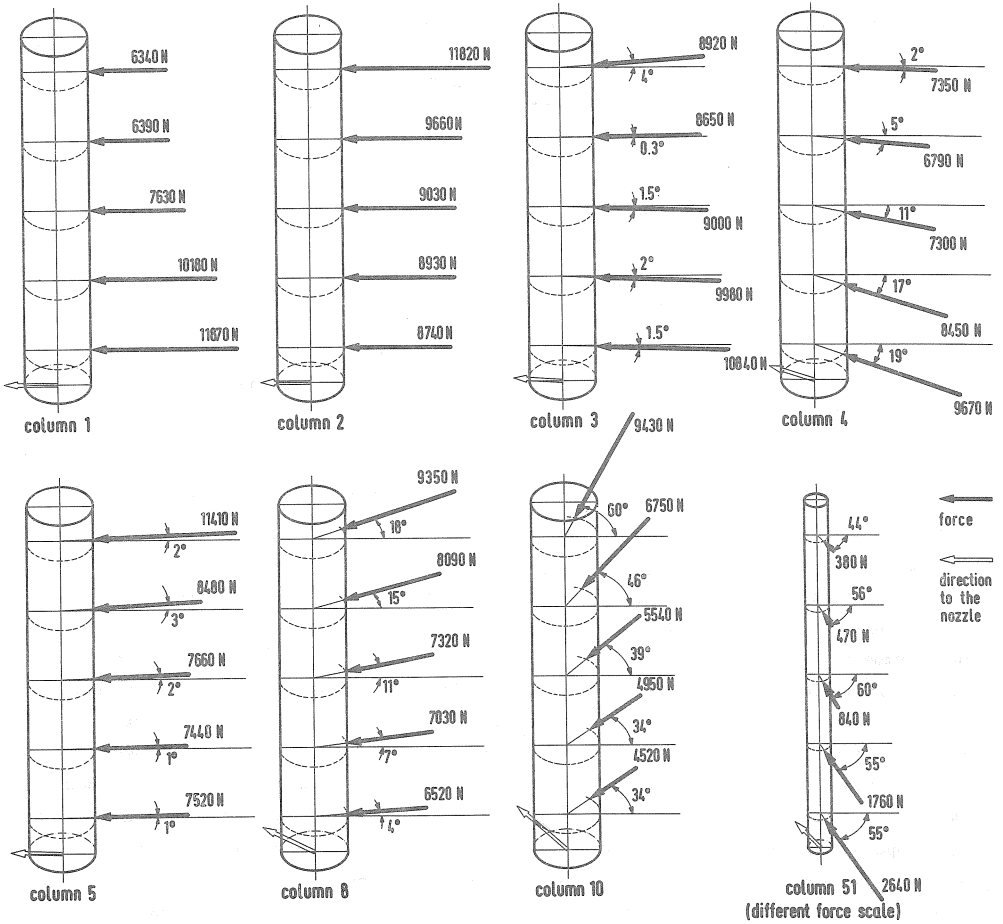


Fig. 6 Column forces distributed in axial direction

Based on the load distributions obtained, the maximum dynamic bending moment, bending stresses and deflections can easily be calculated. The results for columns with relatively high stresses are presented in Tab. I. In order to account for the dynamic character of the problem, the values are twice the static once. For the large diameter columns the wall thickness was assumed to be 8 mm and for the small diameter columns it was assumed to be 6 mm. Young's modulus $1.8 \times 10^5 \text{ N/mm}^2$.

Tab. I Maximum dynamic bending moments, stresses and deflections of some columns

Column No.	Max. dynamic bending moment KNm	Max. dynamic stress N/mm^2	Max. dynamic deflection mm
1	67.6	161.2	5.3
2	63.6	151.8	5.1
3	69.2	165.3	5.5
4	58.6	140.2	4.6
5	54.6	130.3	4.4
8	49.8	118.7	4.0
10	36.8	88.1	3.0
51	11.8	299.8	25.8

5. Conclusions

The maximum bending stresses obtained for the large diameter columns do not essentially exceed the elastic limit of about 160 N/mm^2 . Therefore it may be concluded that in case of a severe blowdown accident the load carrying capacity of the large diameter columns is fully used, but major deformations and failures are not expected.

The situation is different for one small diameter column. Its maximum bending stress exceeds the elastic limit considerably. Therefore, in case of a severe blowdown accident its integrity cannot be guaranteed. However, the small diameter columns do not present crucial structural elements.

6. Literature

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