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Hydroelastic Analysis of Upper Plenum Transients

R. ENGEL, L. OBEREISENBUCHNER, R. PUZALOWSKI, K.-M. PÜLSCHEN
Siemens AG KWU, Erlangen, FRG

ABSTRACT

During a postulated blowdown of a pressurized water reactor (PWR) upper plenum caused by a sudden break in one of the hot legs, the core support columns and control rod guide structures are subjected to a large pressure differential loading emanating from the decompression wave. A three-dimensional fluid-structure interaction analysis of a 'small-break' loss-of-coolant accident (LOCA) is performed by the computer code HAUPT (Hydroelastic Analysis of Upper Plenum Transients).

1 INTRODUCTION

In the licensing procedure for nuclear power plants in the Federal Republic of Germany a postulated fast-opening break with 10 percent flow area of the reactor coolant pipe in a PWR is considered as the most severe LOCA for core support structures. After the resulting blowdown, the reactor shutdown by control rods and post-accident heat removal must be ensured. The integrity of the core support columns and the operability of a sufficient number of control rod guide structures in the upper plenum must therefore be assured in the event of a hot leg break.

Traditionally, a fluid dynamic analysis is performed to determine the structural loadings that are then used as input for a structural dynamic calculation of displacements and stresses. More recently analysis that take fluid-structure interaction into account have shown much improved agreement with experimental data. Differences in calculation results between the traditional and coupled analysis are sometimes significant for the structural frequencies and peak loadings.

The recently developed computer code HAUPT (Rivard 1984) provides a coupled analysis of the tubular structures in the upper plenum for a prescribed break in an outled pipe. HAUPT represents the combination of four time-dependent programs: A three-dimensional, single-phase, acoustic program for the vessel fluid; a one-dimensional, variable-area, single-phase, acoustic program for the fluid in the attached pipes; a one-dimensional, variable-area, two-phase nonequilibrium program for the discharging fluid; and a two-dimensional, nonuniform elastic beam program for the structural part. HAUPT is an extremely efficient computational program and is based on the finite difference method.

SMiRT 11 Transactions Vol. F (August 1991) Tokyo, Japan, © 1991

2 MATHEMATICAL MODELS AND SAMPLE CALCULATION

The mathematical models are based on the following assumptions:

- For the vessel and pipes: (1) flow velocity is small compared with the sound speed, (2) water temperature is constant, and (3) water remains subcooled.
- For the flow discharging from the break: (1) droplet and vapor velocities and pressures are equal, and (2) vapor is saturated.
- For the structures in the upper plenum: (1) linear elastic material, and (2) zero displacement at top and bottom attachments.

A linearized equation system for conservation of mass and momentum at constant entropy governs the fluid dynamics within the reactor pressure vessel and the attached pipes.

The two-phase break flow is based on a nonequilibrium vapor production model (Rivard and Travis 1980).

The response model of the tubular structures in the upper plenum is described by the linear differential equation of motion for a beam without shear deflection and rotary inertia.

Coupling between the fluid and beams is achieved by continously applying the structure motion as a boundary condition to the fluid flow.

The approximate solution by direct numerical integration methods is obtained by representing the governing differential equations in discretized form, and solving the algebraic equations to obtain values for the variables at discrete grid points.

2.1 Fluid model

The whole primary circuit is nodalized by about 50 000 fluid cells, three-dimensional within the reactor pressure and one-dimensional within the attached pipes (Fig. 1).

Fig. 2 shows the horizontal distribution of control volumes for a plane through the centerline elevation of the three outlet pipes. The mesh consists of a 46x46 grid of square cross section cells, including the surrounding fictitious cells which are not shown. The large diameter circle is the core support barrel which is the outer boundary of the fluid region, that is, no fluid resides outside the core barrel. Furthermore the arrangement of 45 control rod guide structures (SSFE), 86 core support columns (ST) and 2 guide tubes for coolant level measurement (FR) is indicated. HAUPT automatically generates the mesh with an integrated preprocessor and also calculates the exact flow areas and fluid volume for each cell.

2.2 Structural model

For the structural analysis, a mesh of uniform two-dimensional cells is used for the three different types of structure as shown in Fig. 3. The total number of cells per beam is 26 or 22 including the two fictitious cells for specifying the boundary conditions.

The input data for each cell are a bending stiffness and a mass (metal and interior water masses) per unit length. Displacement and rotational stiffness boundary conditions are specified at the top and bottom of each beam to model the type of fastening. For all structures the boundary displacements are zero and the rotational stiffness arbitrary. These static and dynamic equivalent input data of the real structure may be determined by detailed structural analyses (Fig. 4), preoperational testing or by using other experimental data.

2.2 Results

A coupled calculation with the previously described mathematical models was carried out. The break at the biological shield opened linearly in 15 milliseconds from zero area to 10% of the pipe area. The problem time was 150 ms.

Figs. 5 and 6 show the time history of some pressures within the broken loop and the resulting horizontal fluid velocity vector field after 14 ms in the upper plenum.

As a result of the depressurization, a pressure oscillation of 42 Hz is induced into the primary system. This frequency originates from the propagation length of the sound wave between the reactor pressure vessel and the steam generator. The resulting effects on the structures in the upper plenum are shown in the following figures. In Fig. 7 the total hydrodynamic force acting on the control rod guide structure (no. 3) next to the broken loop is plotted as a function of time. From the resulting structural dynamic displacement (two horizontal components) of the center of this guide structure (Fig. 8) a resonance arises with enhancing amplitude that decreases after 100 ms. This resonance phenomena is due to an overlap of the structural fundamental frequency of 44 Hz of the control rod guide structure with the fluid frequency of 42 Hz mentioned above. This structural frequency was verified by preoperational testing of the plant. A structural damping value of 4% of the critical damping was used according to the relevant regulations.

The last two figures show the history of total hydrodynamic force and the corresponding central displacement components of the core support column (no. 8) in front of the pipe outlet of the broken loop. The local x-y-coordinate system of this structure is rotated through an angle of 45°. Here, the maximum structural dynamic loading results from the initial impact of the rarefaction wave within the first 10 ms. No resonance occures because the lowest eigenfrequency of the core support column with 78 Hz is far higher than the driving frequency of 42 Hz.

Of course vastly more printed and computer-plotted information is available than that presented here, however, we are confined to concentrate on the most important findings from our coupled calculations which already demonstrate the level of detail that can be examined using the three-dimensional HAUPT code.

3 CONCLUSIONS

For service engineering we have performed fluid-structure interaction analyses of 'small break' LOCAs for 4,3 and 2-loop PWRs. These analyses show that HAUPT is a very cost-effective and easy-to-use code and that three-dimensional effects of the developed fluid flow such as wave reflexions and interferences as well as fluid-structure resonance phenomena in the upper plenum do not lead to extreme strains and stresses in the relevant structures.

REFERENCES

Rivard, W.C. (1984). HAUPT: A computer Program for Hydroelastic Analysis of Upper Plenum Transients. Flow Science, Inc., Los Alamos, USA.

Rivard, W.C. and Travis, J.R. (1980). A Nonequilibrium Vapor Production Model for Critical Flow. Nuclear Science and Engineering, Vol. 74, pp.40-48.

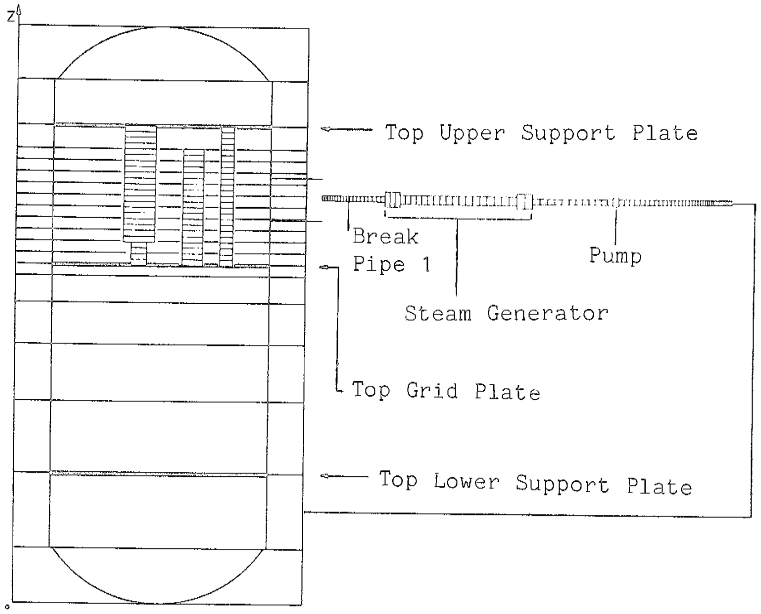


Fig. 1 Vertical distribution of control volumes within the vessel and control volume distribution used for the one-dimensional pipe flow solutions (only the broken loop is drawn)

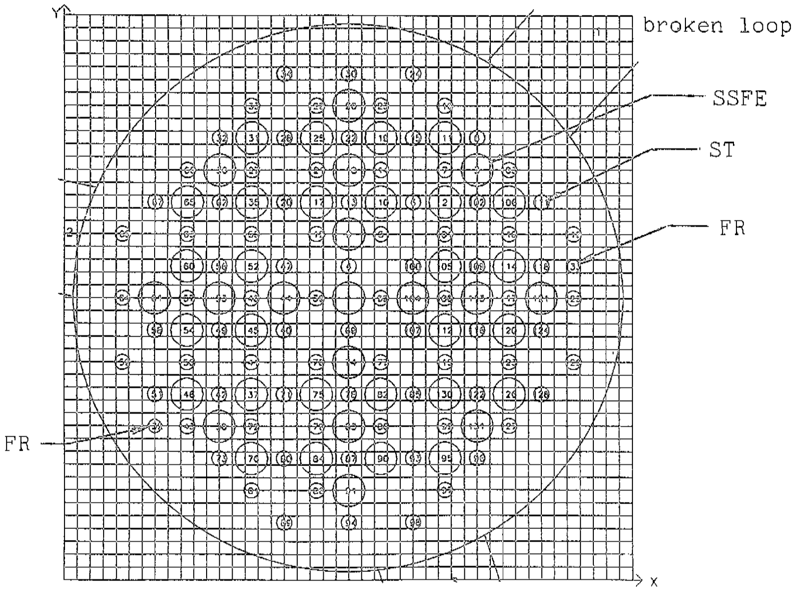


Fig. 2 Horizontal distribution of control volumes for a plane through the centerline elevation of the 3 outlet pipes

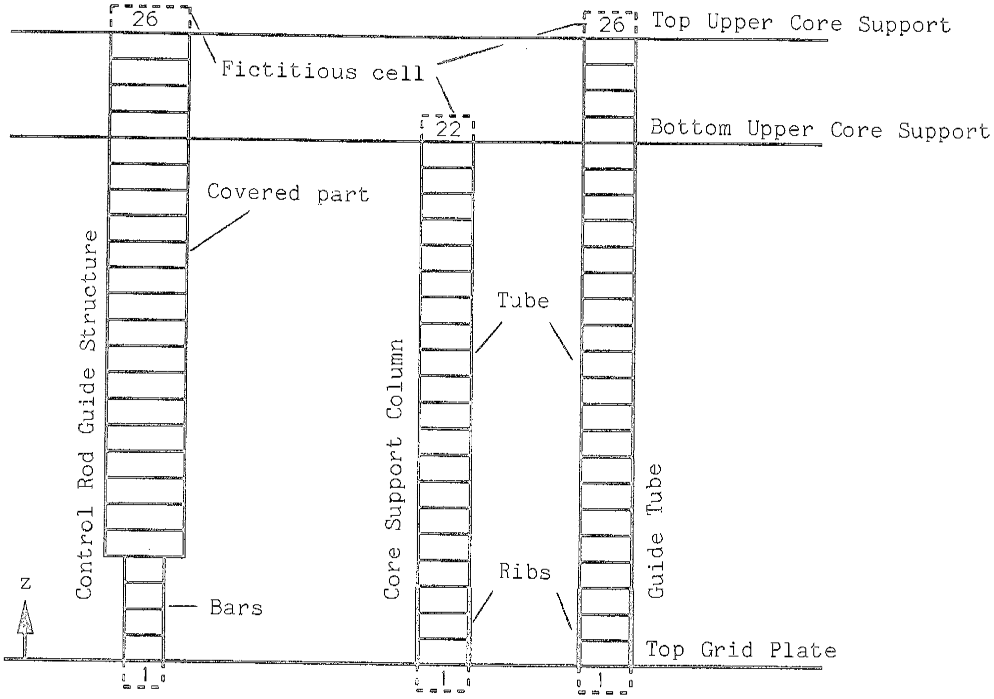
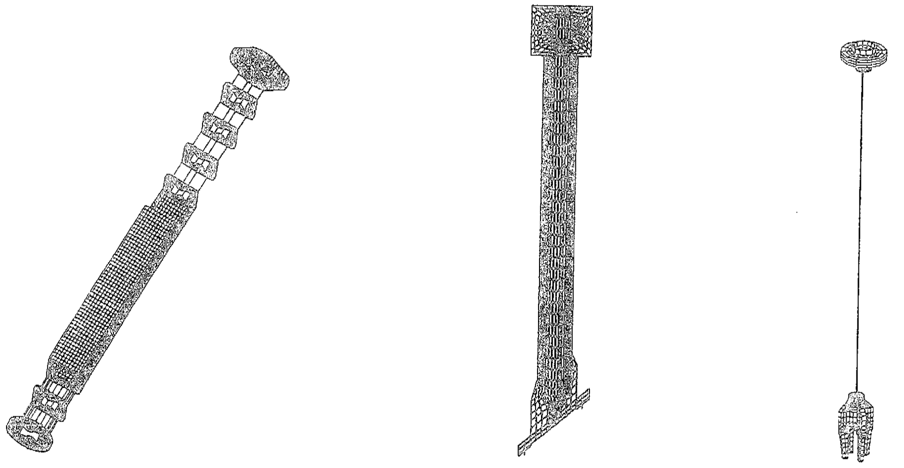


Fig. 3 Equivalent beam models of structures in the upper plenum of a PWR (Finite difference method)



Control Rod Guide Structure Core Support Column Guide Tube

Fig. 4 Mathematical models of structures in the upper plenum of a PWR (Finite element method)

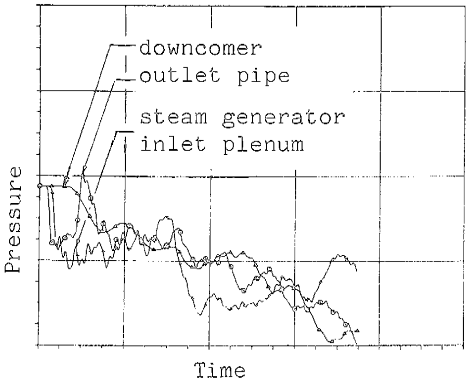


Fig. 5 History of pressure at the outlet of pipe 1, the inlet plenum of the steam generator and at the downcomer

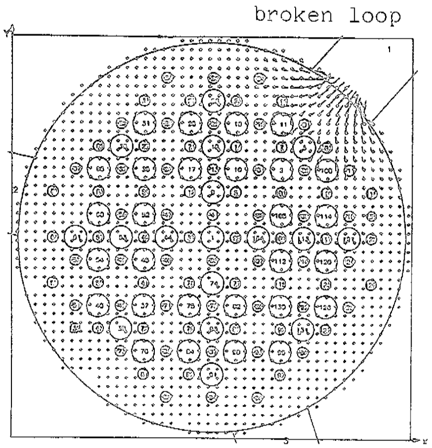


Fig. 6 Horizontal velocity field of the outlet pipe centerline

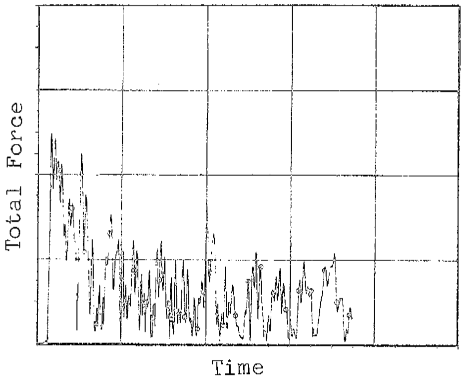


Fig. 7 History of total hydrodynamic force acting on SSFE no. 3

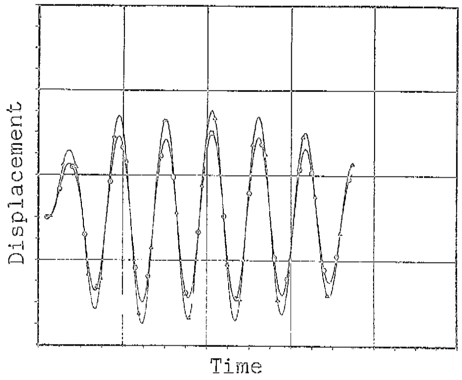


Fig. 8 History of central structural dynamic displacement of SSFE no. 3

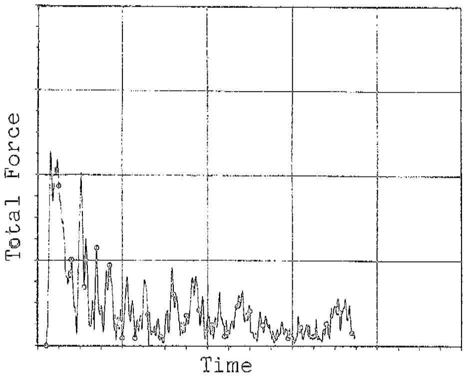


Fig. 9 History of total hydrodynamic force acting on ST no. 8

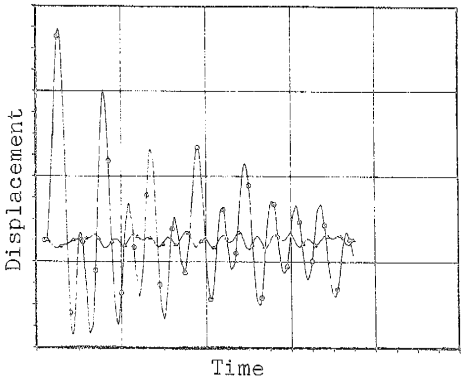


Fig. 10 History of central structural dynamic displacement of ST no. 8