COUPLED STRUCTURE-FLUID ANALYSIS FOR A PWR BURST PROTECTION DESIGN

A. HUBER, H. HOFMANN

SDK, Ingenieurunternehmen für spezielle Statik, Dynamik und Konstruktion GmbH,
Zeppelinstrasse 26, Postfach 2227, D-7850 Lörrach, Germany

SUMMARY

The burst protection considered is designed to withstand hypothetical ruptures which might occur in certain components of the primary circuit including RPV rupture. It mainly consists of cylindrical concrete vessels for the RPV and the steam generators and steel tubing for the primary pipes. The burst protection structures are placed tight to the primary loop.

A hypothetical RPV failure will result in direct excitation of single components and will lead to complex interactions between all components of the protecting structures, the primary loop, reactor core, core support structures and the coolant.

The overall investigations to determine the magnitude of deformations and stresses are summarized. Economical aspects with respect to the investigations are treated briefly. The coupled structure-fluid analysis of the core and core support structure due to horizontal and vertical RPV failure will be presented in detail.

Assumptions for the RPV failure modes were made which were expected to lead to extreme conditions in any part of the system. The assumptions include vertical, horizontal and screw-shaped rupture of the RPV, the detachment of RPV nozzle as well as other types of failure. On the basis of the failure modes, types of credible extremal load conditions were estimated.

For vertical RPV failure modes, which mainly cause horizontal response, these loads were applied to a global beam-model consisting of burst protection and primary loop structures. By altering the load parameters and boundary conditions, the structural behaviour of the integrated system was studied and boundary conditions for different components of the system were generated. Nonlinear coupling between structural parts was taken into account.

The deflections of the RPV calculated in the global analysis were used to analyse the core structure under short-time system interaction effects produced by a vertical rupture of the RPV. The three-dimensional axisymetric F.E. model consists of core structure, core supports, coolant and the RPV. Shell and volume elements are used. The nonsymmetric boundary conditions were taken into account by Fourier-expansion in circumferential direction. The mathematical solution is based on the governing equations for pressure wave propagation in fluids and vibrations in solids.

Horizontal rupture of the RPV was assumed to occur in the welding connecting spherical bottom and cylinder. The short-time effects due to pressure relief were analysed. This mainly results into vertical and radial motions of the structures. The three-dimensional axisymmetric F.E. model consists of core structure, core support, RPV, and concrete burst protection structure for the RPV. Inertia terms of the fluid were incorporated in the equations of the system. Resulting forces due to the pressure acting on either side of complex core and grid structures were taken into account by load terms. In determining the pressure field, thermodynamic effects had to be considered.

1. Introduction

Burst protection for a PWR is meant to withstand effects due to hypothetical rupture of any of the components of the primary circuit including RPV. A rupture of the RPV, which is referred to in this paper, will lead to complex physical processes such as wave propagation within the fluid, vaporization of the fluid within the RPV, two phase flow through the rupture, pressurization within the gaps between burst protection and the primary loop components. Dynamic excitation of single components as well as of the entire interacting system consisting of the protecting structures and the coolant will occur.

The phenomena mentioned shall be investigated with respect to finding possible extreme conditions. This means, to find at least the magnitude of deformations and stresses. Since it is very difficult to analyze the process of rupturing of the RPV, assumptions for failure modes will have to be made. The following failure modes are expected to lead to the most extreme effects:

- vertical failure mode: vertical rupture of the RPV between the lower end of the cylinder and the main coolant nozzle
- horizontal failure mode: rupture through the circular welding connecting the spherical bottom (or top) and the cylinder of the RPV. Horizontal rupturing of the cylinder can be excluded due to vertical prestressing.
- screw shaped rupture of the RPV
- detatchment of a discrete fraction of the RPV
- detatchment of one of RPV's main coolant nozzles
- rupture of a primary coolant pipe

On the basis of these failure modes, extreme load and boundary conditions can be estimated and investigated. Parametric variations of loads and boundary conditions with relatively simple computational models should yield information on effects which should be analyzed in greater detail.

In this presentation, only the investigations concerning fluid-structure interactions due to the vertical and horizontal rupture shall be treated.

2. Design of Primary Loop and Burst Protection

The primary system including core structures and the burst protection structures are shown in Fig. 1-4. The four steam generators are connected with the RPV by straight double-chambered pipes. Each pipe is divided into two sections by a horizontal plate, which separates the hot from the cold leg of the main coolant. The fuel elements are supported by grid plates and the core barrel, which in turn is attached to the RPV at the barrel-top. The burst protection structure for the RPV consists of a cylindrical concrete vessel, which is open at the top. The wall contains vertical cables. These cables are anchored at the bottom and at the top of a concrete ring lying on the concrete vessel. The concrete ring is connected with the RPV by pin-ended supports. The vertical cables are prestressed by the thermal expansion of the RPV. The gap of about 70 cm between RPV and burst protection vessel is filled with heat insulating concrete and bulk material for cooling purposes.Between insulating concrete and RPV remains a gap of about 1-3 cm. The steam generators are protected by prestressed concrete vessels. For the pipes steel rings are used. Burst protection structures for RPV and steam generators are connected by hydraulic shock absorbers, placed below the double-chambered pipes.

3. Vertical Failure Mode: Effects on Core Structures Resulting from Global System Behaviour

3.1 Analysis

During operation of the plant before rupture, all forces are in equilibrium, see Fig. 19. By assuming a vertical rupture, this state of equilibrium will be disturbed. The pressure transients within and outside the RPV will produce complex dynamic motions of the entire system. Impact and rebound of structural parts may occur.

In this part of the analysis, the short time effects on the global system and their influence on the response of the core structure due to resulting horizontal forces are investigated, see Fig. 25. The resulting horizontal load functions and amplitudes are estimated by assuming that the most extreme physical conditions occur. Parametric variations of the load functions and boundary conditions are used to cover a range of uncertainties, see left side of Fig. 9 and 10.

The global interaction effects of burst protection structures and primary circuit components including steam generators are analyzed with a global beam model, using cylindrical beam cross sections, see Fig. 5. The impact of the RPV on the burst protection vessel and its rebound is simulated by introducing additional contact stiffnesses to the system of equations resp. omitting them. The deflection transients of the RPV computed with the global model are used as boundary conditions for the detailed analysis of the RPV and interior structures including the fluid.

The deflections, strains and stresses of the core barrel, grid plates and fuel elements are computed with the structure-fluid model, see Fig. 7 and 8. The fluid is modeled within the annulus between RPV and core barrel and the annulus between core barrel and core container, see Fig. 6 and 8. The fluid surrounding the suspension structures and the fuel element assembly with its thousands of vertical rods is simulated by superimposing its masses to those of the rods. Since motions are mainly horizontal, the simulation appears to be sufficient.

The fluid behaviour within the two annuli is first investigated by using a model with compressible fluid characteristics. This model of unit height is analyzed for a sudden unit acceleration in order to decide whether compressibility must be taken into account, see Fig. 11 and 12. Fortunately, results show that the consideration of an incompressible fluid is sufficient for the present problem. Therefore, it is permissible to extract the influence matrices of the fluid and to superimpose them to the matrix of the solid structures. By this procedure the total number of degrees of freedom is reduced by those of the fluid, which definitely is of advantage for the dynamic analysis with respect to computer costs. It should be mentioned that the combination of structures and compressible fluids can be treated by the computer code.

3.2 Load Assumptions (see Fig. 5,25 and left side of Fig. 9,10)

Load no. I: This load represents an approximation for only horizontal forces resulting from pressure inside the RPV decreasing along the circumference, corresponding to the propagation of waves, see Fig. 25. Contact forces between RPV and the burst protection vessel are included.

Load no. II: Up to 2.6 ms the load represents only horizontal forces resulting from pressure inside the RPV decreasing along the circumference, corresponding to the propagation of waves, see Fig. 25. Contact forces between RPV and the burst protection vessel (3-8 ms) are included.

Load no. III: This is equal to load no. II up to 8 ms. For times greater 8 ms, contact between RPV and burst protection vessel is assumed in the central region due to the widening of the RPV, see Fig. 25.

3.3 Modelling (see Fig. 5-8)

The global system consists of cylindrical beam elements (pipes) which permit for effects of transverse shear deformation, thus representing membrane shell behaviour of the cylindrical parts of the structures. The fluid was considered by additional mass terms. Horizontal sliding was assumed at the RPV support.

It is possible to carry out a detailed three-dimensional axisymetric structure-fluid analysis under the following assumptions.

- Up to approx. 10 ms, the vaporization effects within the RPV are negligible.
- The RPV wall may be considered uncracked, since it is only used to introduce the boundary deflections computed in the global analysis.
- Only small amplitudes of motion will occur (gap between RPV and burst protection = 2 cm).

Fourier expansions in circumferential direction are used to describe non-axisymetric deformations. Since the horizontal and vertical motions of the RPV wall, which are computed by the global beam model, may be represented by the first harmonic, only this harmonic has to be analyzed. The fluid is modeled by volume elements. For the shell and grid structures shell elements are used. The fuel elements are represented by special elements used in the process of coupling the grid plates normal to their surfaces.

3.4 Results (see Fig. 9-15)

The horizontal deflections at the RPV support and at the level of the nozzles are shown in Fig. 9 and 10 for load no. I to III. The time points where impact or refraction of the RPV occurs are marked. Fig. 11 and 12 show the steady state and transient pressure field in the annulus between RPV and core barrel under unit boundary acceleration. The deflections of the structures at discrete time points can be seen in Fig. 13. The stresses in the core barrel close to the connection with the RPV are shown in Fig. 14 and 15.

4. Horizontal Failure Mode: Effects on the Core structures Resulting from a Rupture in the Welding Connecting Spherical Bottom and RPV Cylinder

4.1 Analysis

A horizontal rupture of the RPV cylinder is considered unlikely, since the system is prestressed vertically. The amount of prestressing yields approx. zero vertical stress in the cylinder during normal operation. Therefore only horizontal rupture in the spherical top or bottom seems possible. For the analysis a rupture through the welding connecting the spherical bottom to the cylinder is assumed. This leads to the detatchment of the whole RPV bottom and after its acceleration permitted by a gap of about 2 cm width, to an impact on the burst protection structure. The short time effects on the core and burst protection structure due to vertical and radial forces are investigated with a system shown in Fig. 16 and 17.

During operation of the plant before rupture, all forces are in equilibrium. At the time of rupture, this equilibrium will be disturbed in the RPV wall and in the fluid bordering the location of failure. A shock wave (expansion) proceeds upwards within the fluid and within the RPV wall. Forces due to pressure differences between the upper and lower surfaces of the complex core and grid structures result into further dynamic excitation of the system.

It will hardly be possible to analyze the entire system in an economical way by modelling every important detail such as holes in the grid plates, the flow of the fluid in the vicinity of the holes and thousands of fuel rods, see Fig. 2 and 4. Therefore, the pressure distribution within the fluid is analyzed separately. Due to the vaporization of the fluid below saturation pressure, it is imposed that the pressure cannot drop below saturation pressure. On the basis of the time dependant pressure distribution, resulting forces due to pressure differences between either side of the complex core and grid structures are determined, see Fig. 18. These forces are applied to the structure-fluid model.

The deflections, strains and stresses of RPV, interior and burst protection structures are computed by the structure-fluid model shown in Fig. 16 and 17. The fluid was taken into account by added masses.

4.2 Modelling (see Fig. 16,17 and 21-23)

The three-dimensional axisymetric model mainly consists of shell elements. Suspension structures and fuel elements are represented by special elements which provide for appropriate coupling between the grid plates normal to their surfaces. Vertical inertia effects of the fluid are simulated by a separate set of elements, which can move independantly from the structural elements between the grid plates. Thus, vertical sliding between the fluid and the fuel rods is insured.

Provisions are made to incorporate the following nonlinearities:

- The sliding between fuel rods and fuel element holders as well as the possible impact and rebound of the fuel rod on the fuel element head or bottom is simulated by the material characteristic shown in Fig. 23.

The characteristics to some extend are based on tests. The same technique is applied to describe the mechanism between grid plate and fuel element head, see Fig. 22.

- Detatchment and impact of fuel element bottom and lower grid plate are simulated by the elimination or introduction of stiffnesses from or to the global system of equations, see Fig. 21. The same technique is used to describe the behaviour of burst protection vessel and concrete ring element (Fig. 16) as well as RPV support spring and the burst protection (Fig. 21).

4.3 Results (see Fig. 20-24)

The deflections of the structures at discrete time points are shown in Fig. 20. The bending stress transients at the center of the upper and lower grid plate are plotted in Fig. 24. Deformations for structures where detatchment and impact may occur can be seen in Fig. 21 and 22. The fuel element strains are shown in Fig. 23.

5. Theory

The analysis is based on the governing equations for pressure wave propagation in fluids and vibrations in solids. The discretisation by the finite element technique yields (see O. Zienkiewicz, The Finite Element Method).

$$[H]\ \{p\} + \qquad + [G]\ \{\ddot{p}\} + [S]\ \{\ddot{\delta}\} = 0 \tag{1}$$

$$[K]\ \{\delta\} + [C]\ \{\dot{\delta}\} + [M]\ \{\ddot{\delta}\} + \frac{1}{\rho}[S]^T\{p\} = \{R\} \tag{2}$$

K = stiffness matrix
C = damping matrix
M = mass matrix
H = pressure distribution matrix

G = pressure acceleration matrix
S = coupling matrix
p = pressure amplitude of fluid
δ = deflection of solid structure

For incompressible fluids, the second term of eq. (1) disappears and eq. (1) may be solved for {p}.

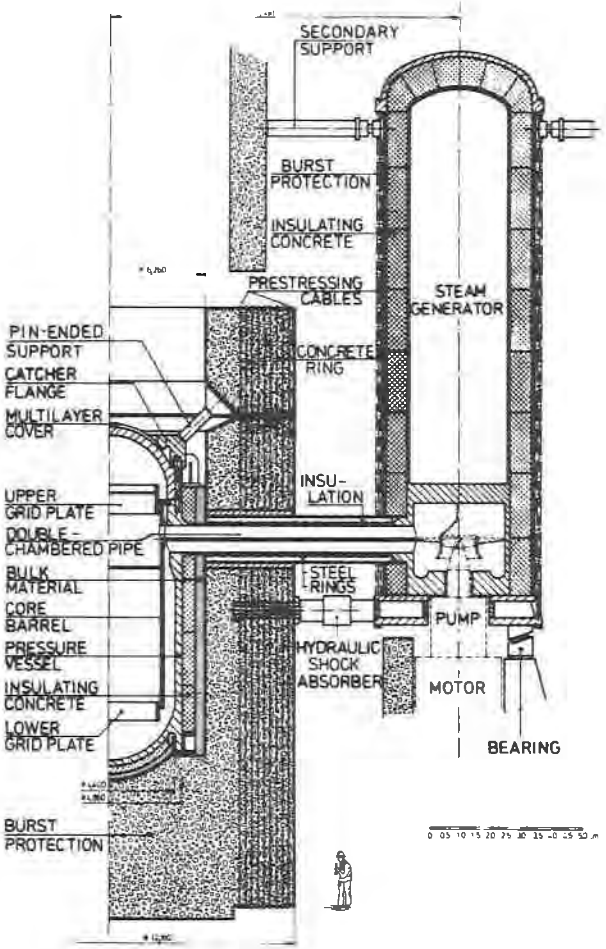
$$\{p\} = [H]^{-1}\{\ddot{\delta}\}\ [S]$$

Hence {p} in eq. (2) may be replaced by $\{\ddot{\delta}\}$. Eq. (2) may be solved only for the structural degrees of freedom.

An implicit solution technique on the basis of O. Zienkiewicz, The Finite Element Method, is used.

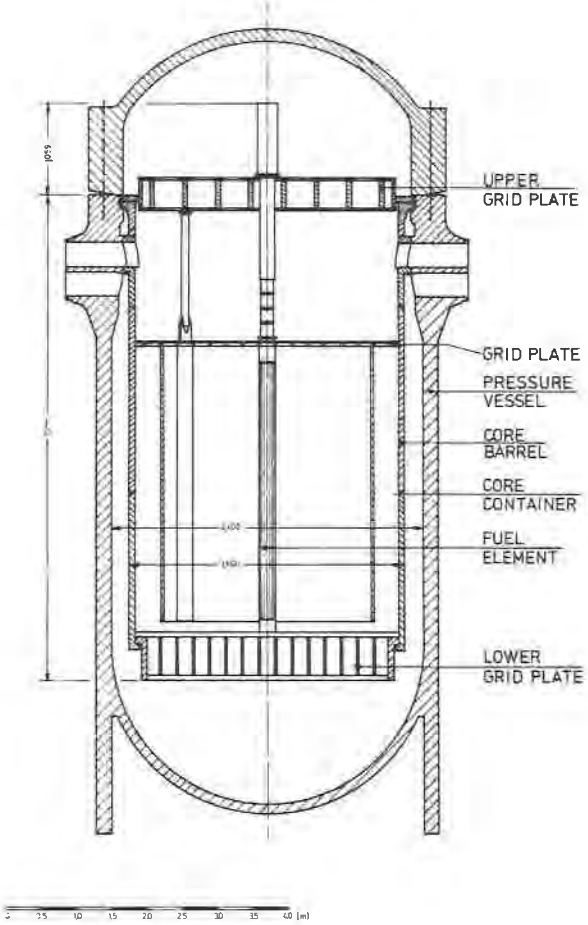
References

|1| Proceedings of the "1st, 2nd, 3rd SMiRT Conference", 1971, 1973, 1975
|2| ELCALAP-Seminar, Berlin, 1975



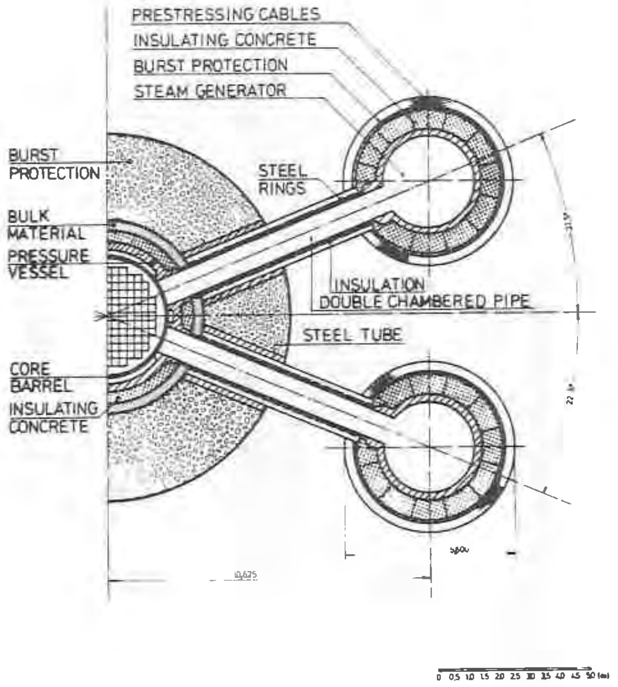
BURST PROTECTION DESIGN - VERTICAL SECTION

FIG. 1

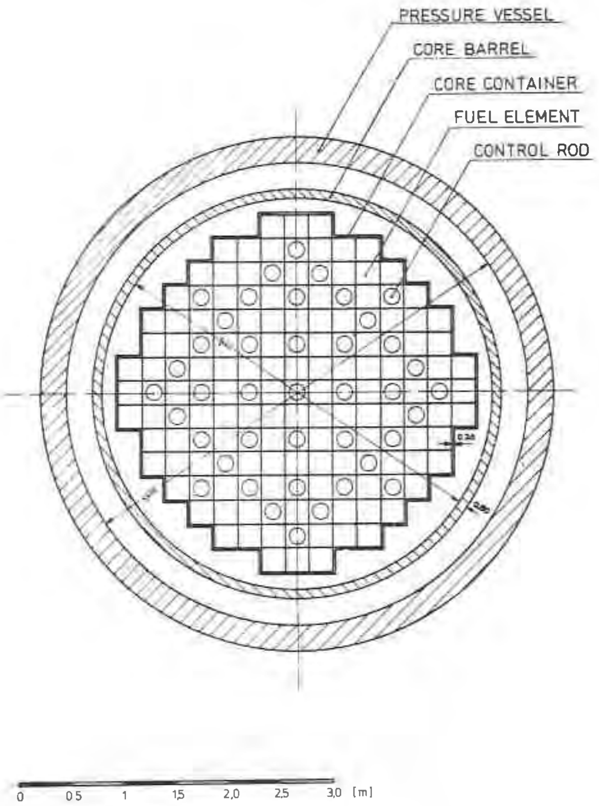


REACTOR PRESSURE VESSEL (RPV) VERTICAL SECTION

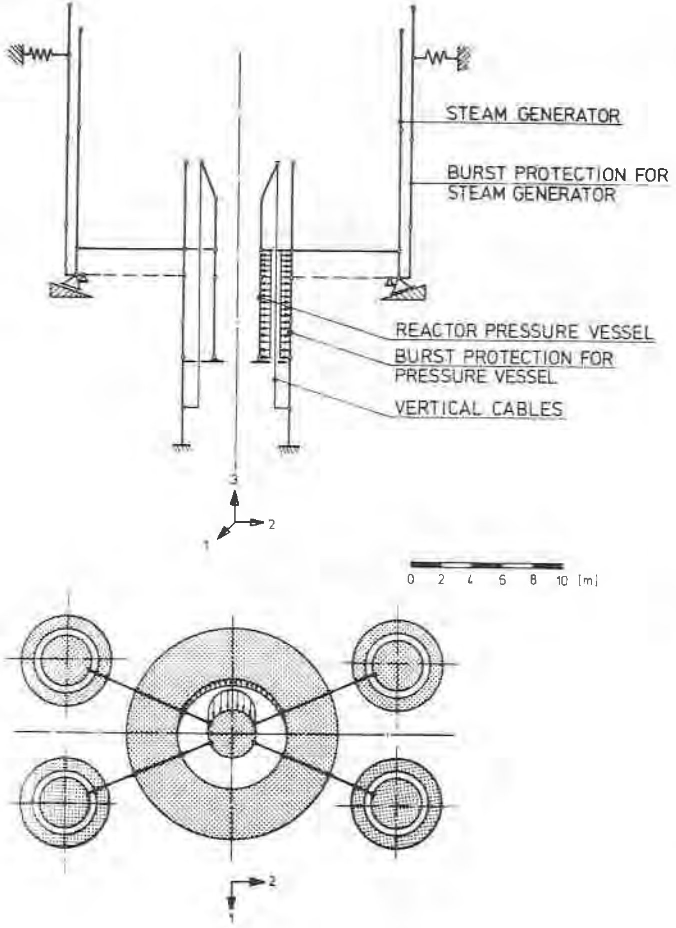
FIG. 2



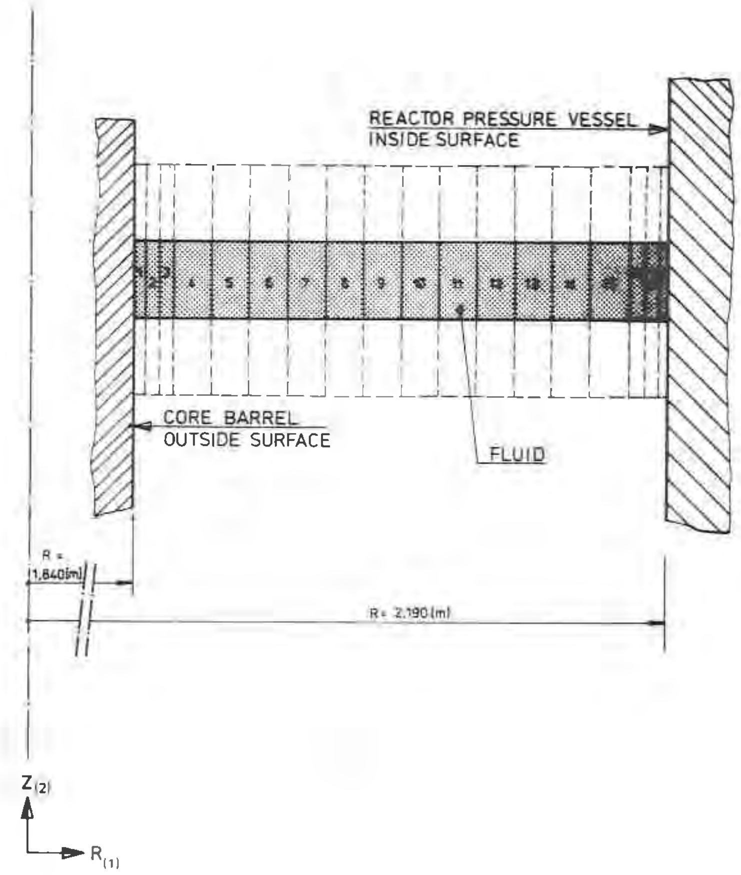
BURST PROTECTION DESIGN - HORIZONTAL SECTION FIG. 3



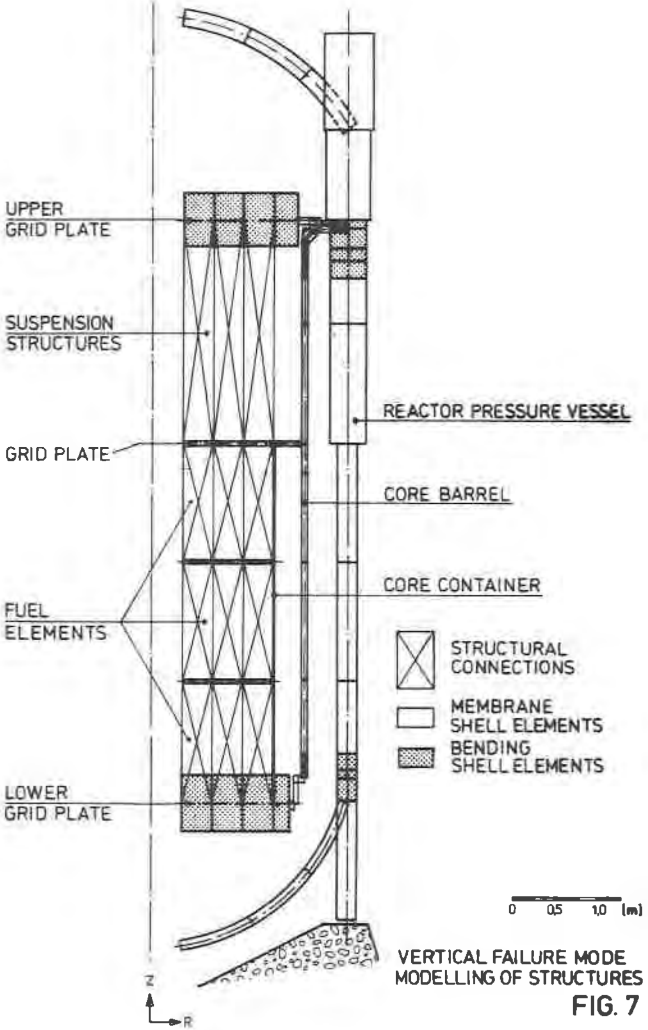
RPV HORIZONTAL SECTION FIG.4



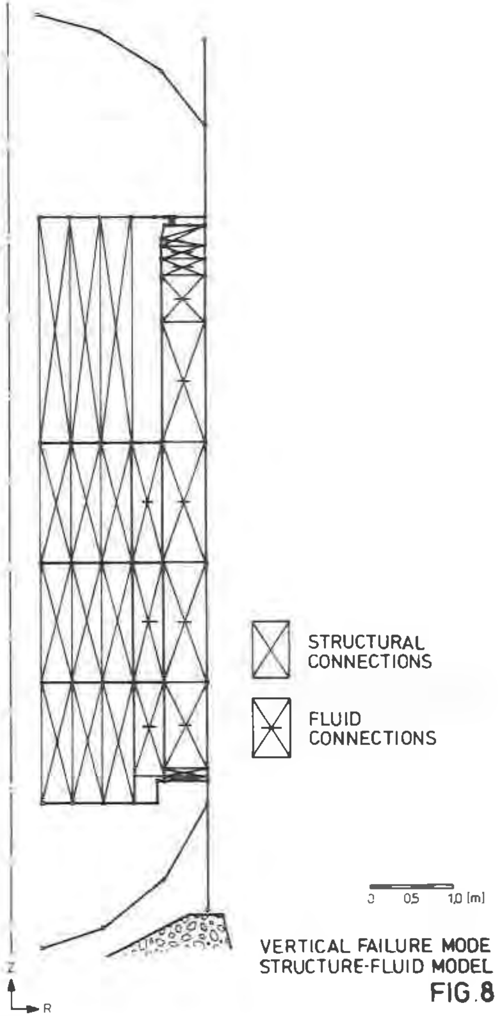
VERTICAL FAILURE MODE GLOBAL BEAM MODEL **FIG. 5**



VERTICAL FAILURE MODE MODELLING OF FLUID **FIG.6**



VERTICAL FAILURE MODE
MODELLING OF STRUCTURES
FIG. 7



VERTICAL FAILURE MODE
STRUCTURE-FLUID MODEL
FIG. 8

VERTICAL FAILURE MODE
GLOBAL BEAM MODEL: DEFLECTIONS IN 1-DIRECTION AT LEVEL OF RPV-NOZZLE

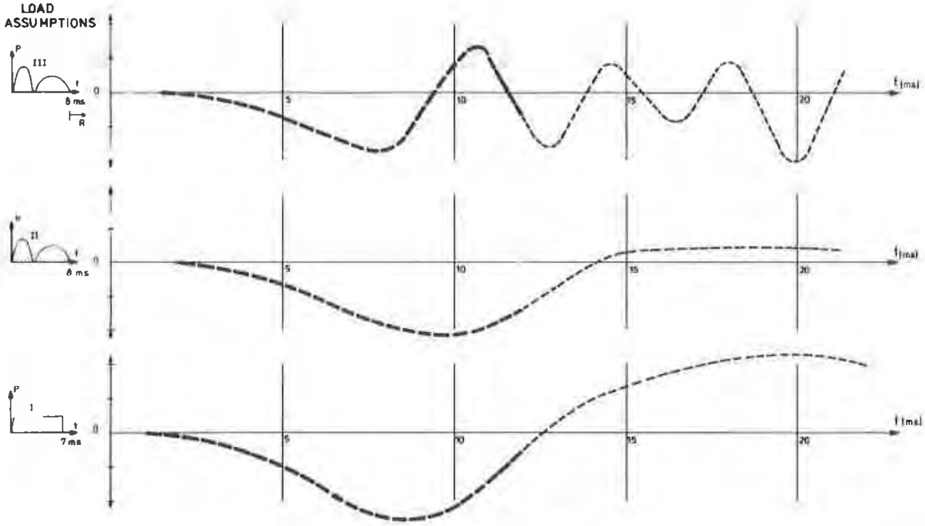


FIG. 9

VERTICAL FAILURE MODE
GLOBAL BEAM MODEL: DEFLECTIONS IN 1-DIRECTION AT RPV SUPPORT

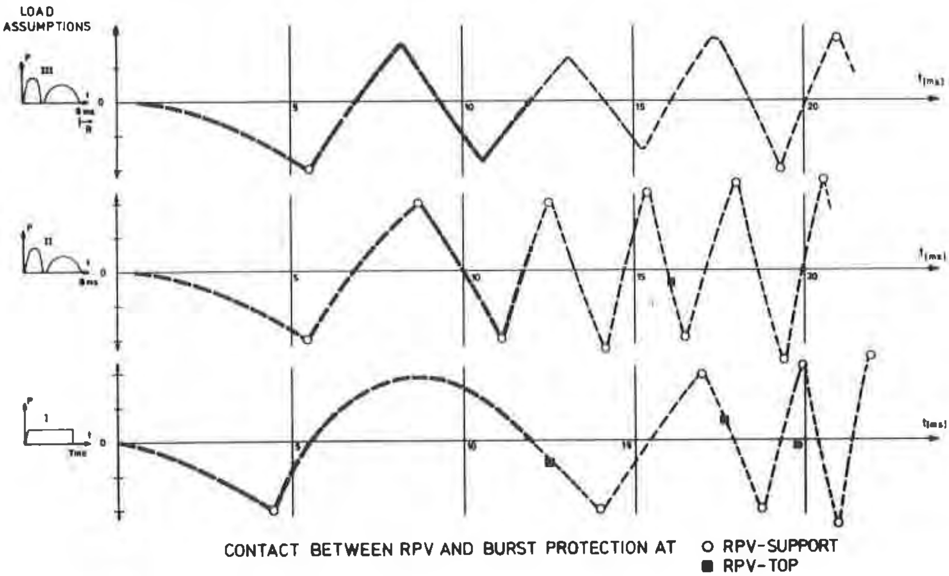


FIG. 10

PRESSURE DISTRIBUTION IN THE FLUID BETWEEN CORE BARREL AND RPV RESULTING FROM UNIT ACCELERATION 1 m/sec²

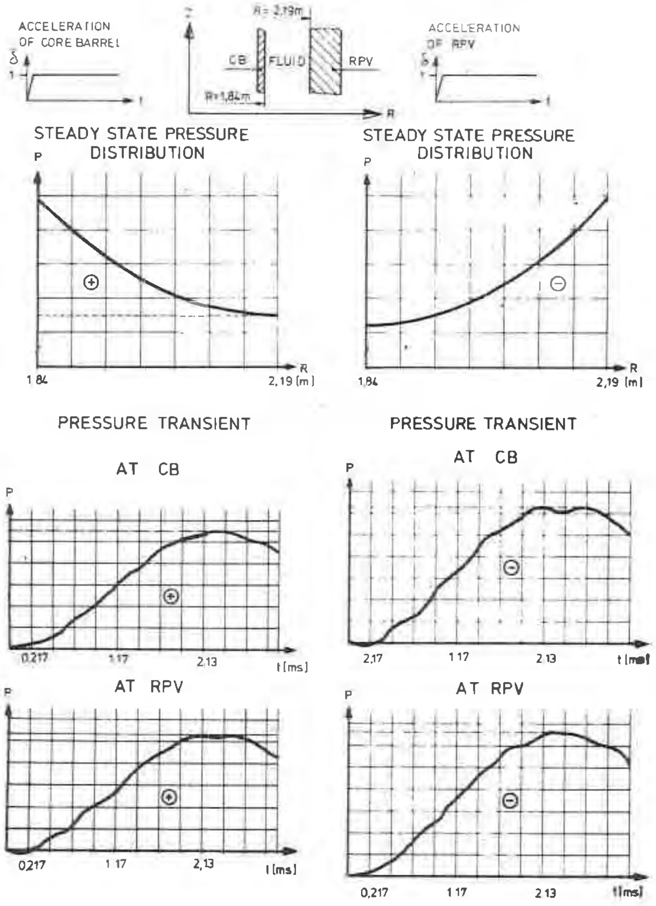
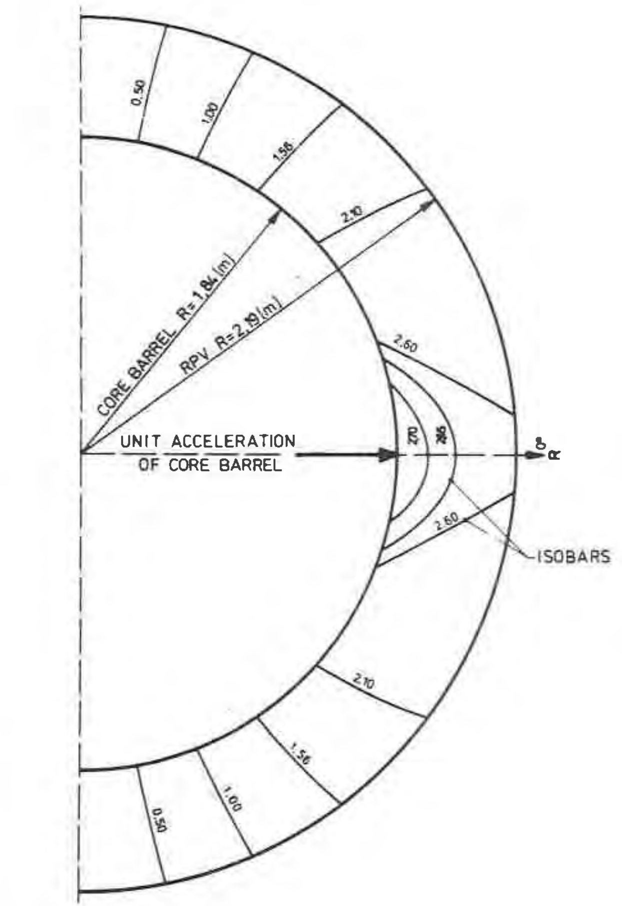
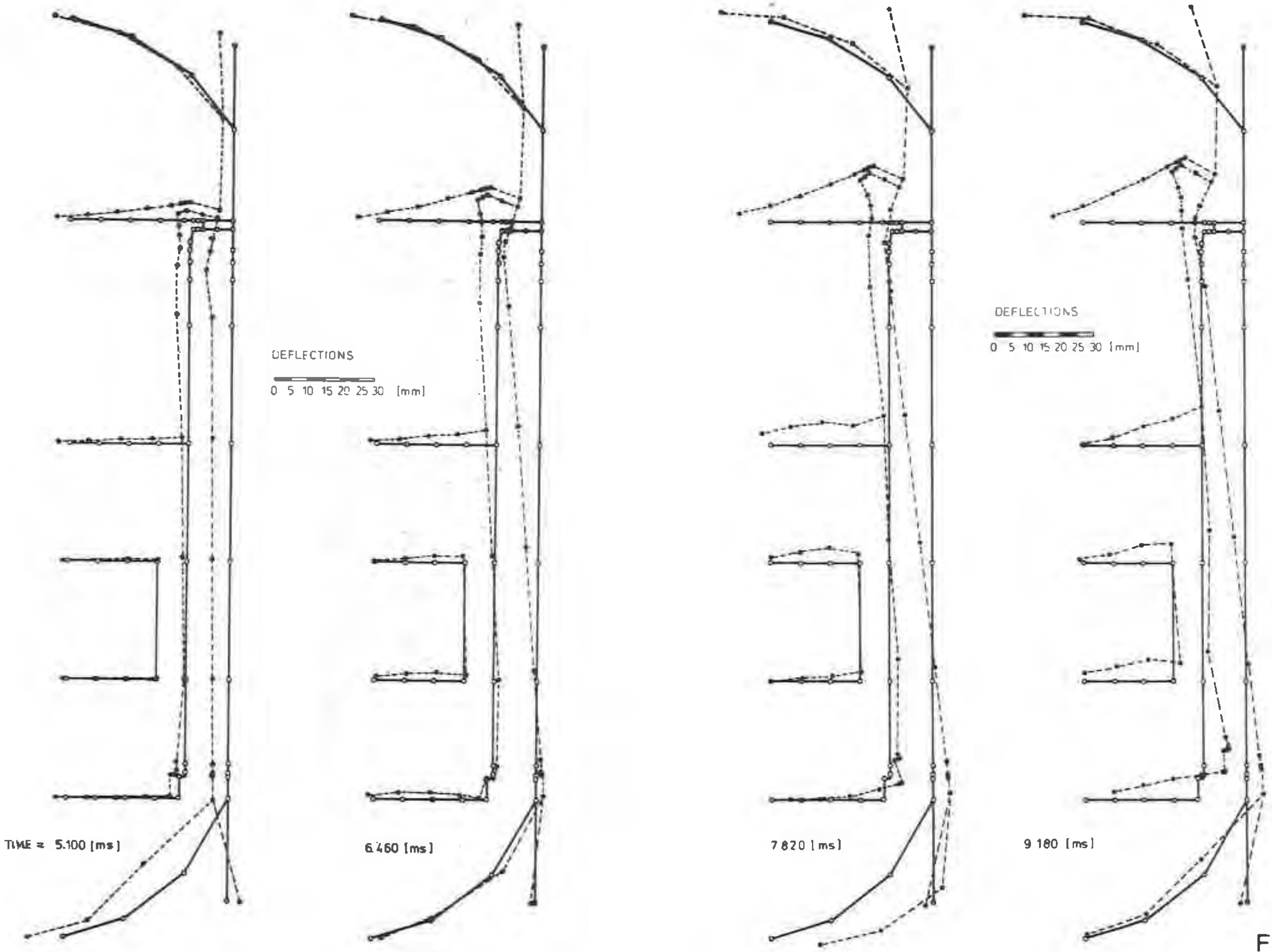


FIG.11



STEADY STATE CIRCUMFERENTIAL PRESSURE DISTRIBUTION
FOR UNIT ACCELERATION OF CORE BARREL

FIG.12



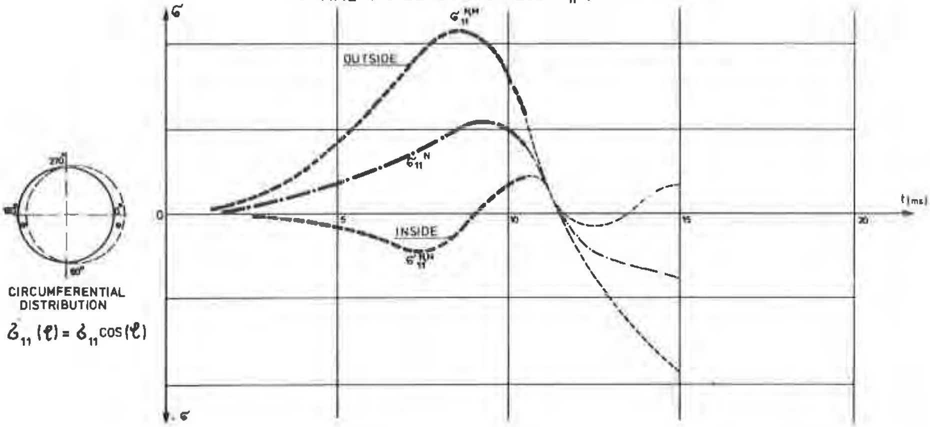
VERTICAL FAILURE MODE DEFLECTIONS

FIG.13

$\sigma_{11}^{N} \triangleq \sigma$ NORMAL STRESS

$\sigma_{11}^{NM} \triangleq \sigma$ NORMAL+ BENDING STRESS

NORMAL AND BENDING STRESS σ_{11} (AXIAL DIRECT.)



CIRCUMFERENTIAL DISTRIBUTION

$\sigma_{11}(\varphi) = \sigma_{11}\cos(\varphi)$

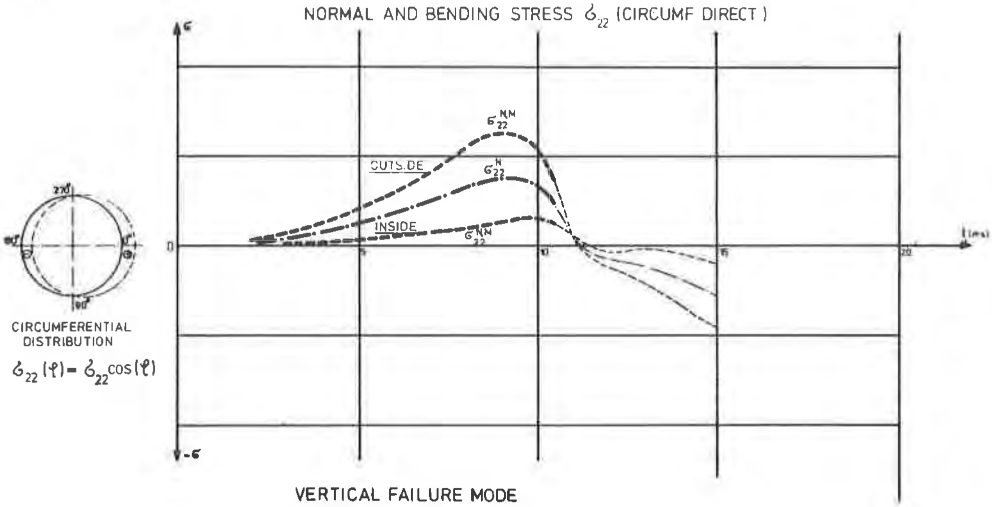
VERTICAL FAILURE MODE
STRESSES AT CORE BARREL SUPPORT

FIG.14

$\sigma_{22}^{N} \triangleq \sigma$ NORMAL STRESS

$\sigma_{22}^{NM} \triangleq \sigma$ NORMAL + BENDING STRESS

NORMAL AND BENDING STRESS σ_{22} (CIRCUMF DIRECT.)

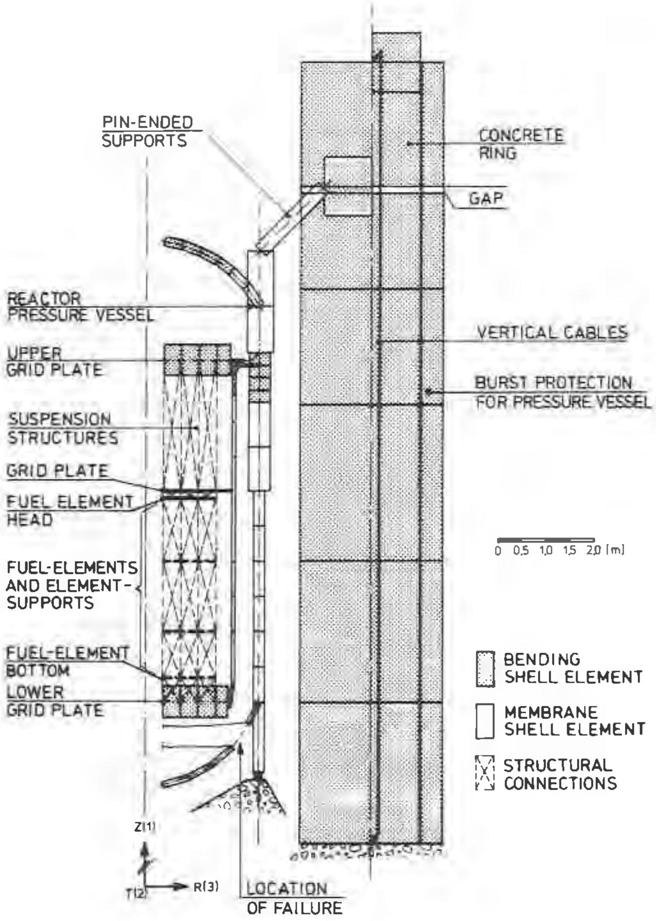


CIRCUMFERENTIAL DISTRIBUTION

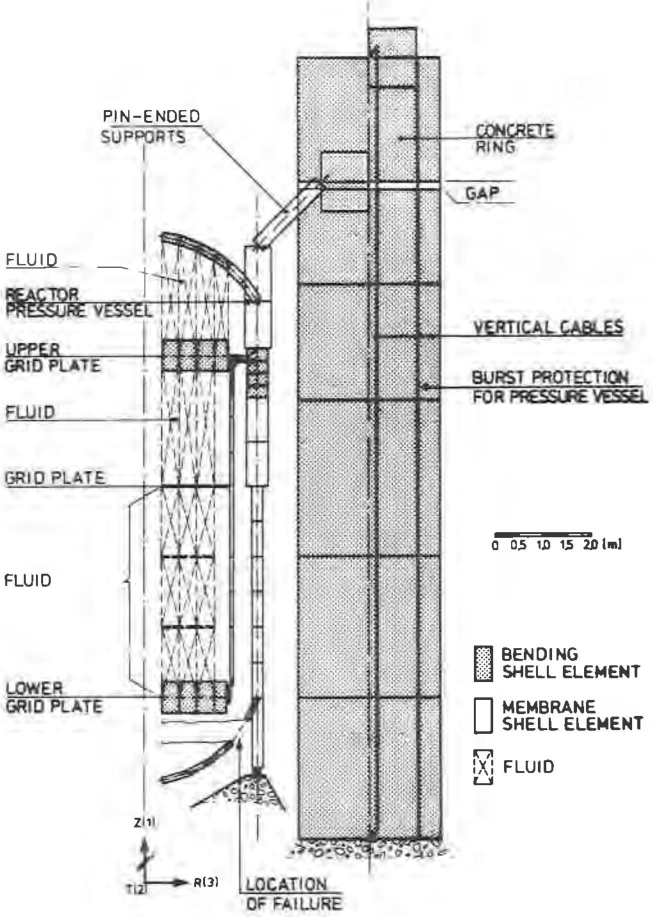
$\sigma_{22}(\varphi) = \sigma_{22}\cos(\varphi)$

VERTICAL FAILURE MODE
STRESSES AT CORE BARREL SUPPORT

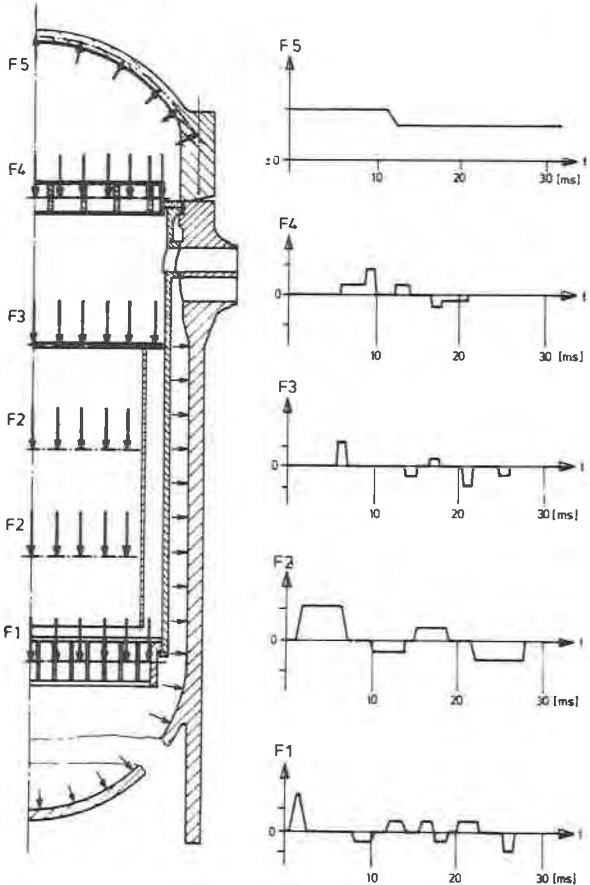
FIG.15



HORIZONTAL FAILURE MODE MODELLING OF STRUCTURES FIG.16

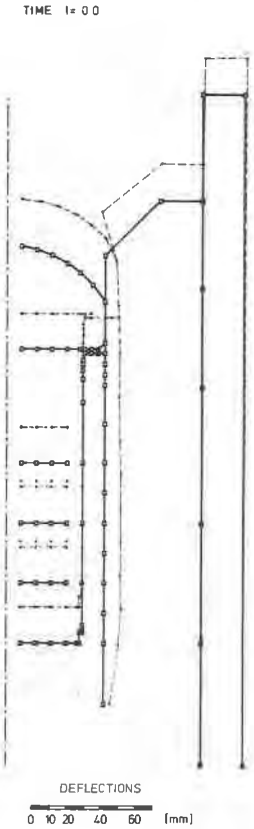


HORIZONTAL FAILURE MODE MODELLING OF FLUID FIG.17



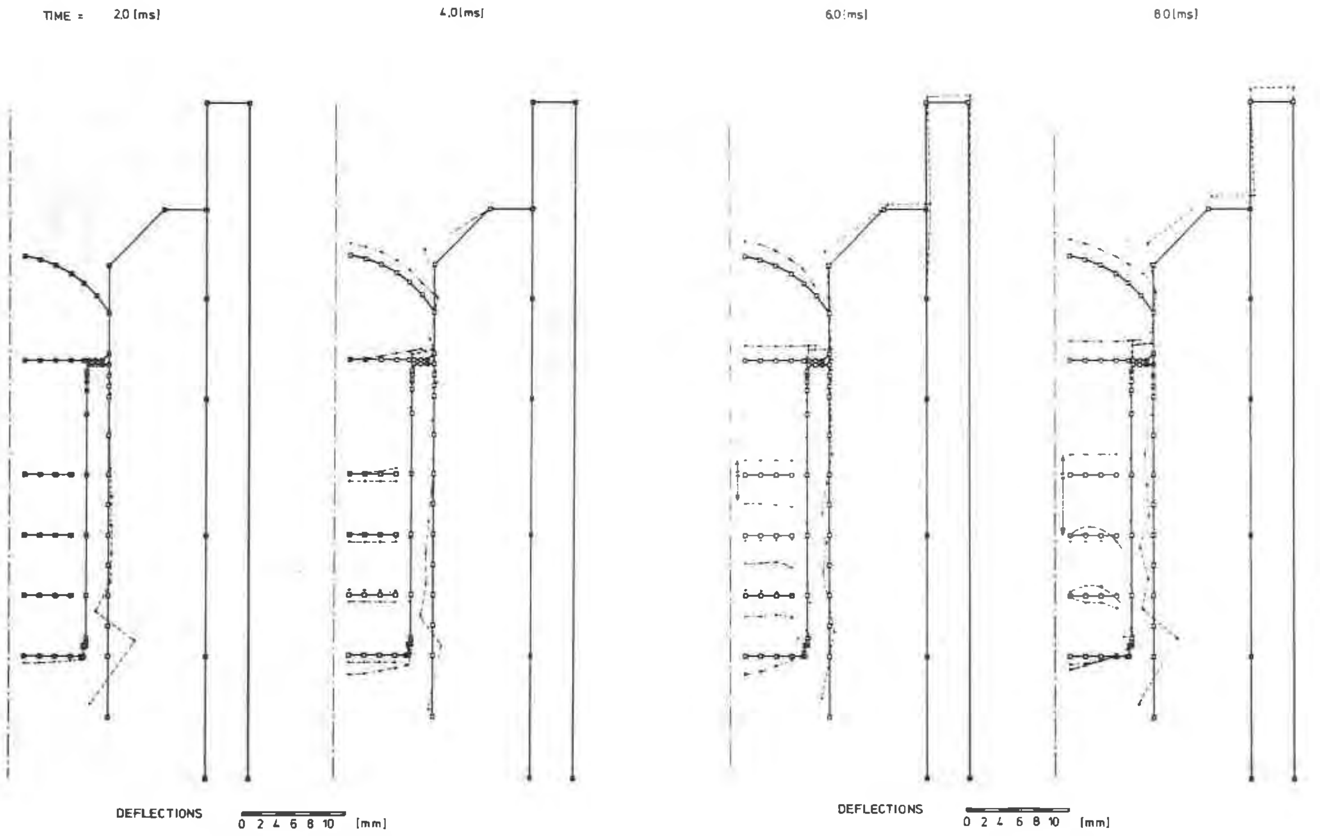
HORIZONTAL FAILURE MODE
FORCES RESULTING FROM PRESSURE DIFFERENCES
ON SRUCTURAL PARTS
(ONLY SOME FORCE TRANSIENT ARE PLOTTED)

FIG.18



HORIZONTAL FAILURE MODE
INITIAL DEFLECTIONS (BEFORE RUPTURE)

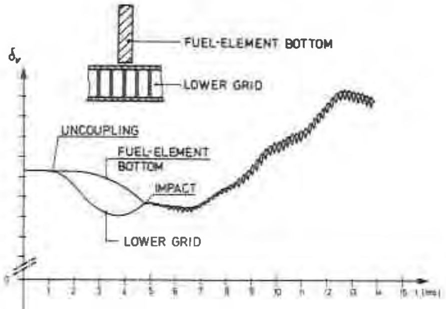
FIG.19



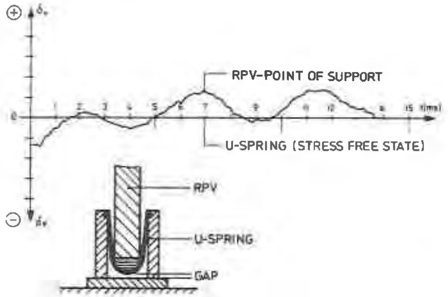
HORIZONTAL FAILURE MODE

CHANGE OF DEFLECTIONS RELATIVE TO INITIAL STATE

FIG.20



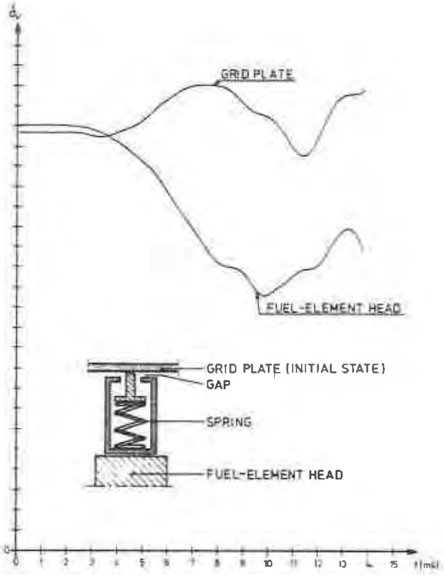
DEFLECTIONS OF LOWER GRID AND FUEL-ELEMENT BOTTOM



DEFLECTION AT POINT OF SUPPORT FOR RPV

HORIZONTAL FAILURE MODE

FIG. 21



DEFLECTIONS OF GRID PLATE AND FUEL-ELEMENT HEAD

HORIZONTAL FAILURE MODE

FIG. 22

HORIZONTAL FAILURE MODE
FORCE-DEFORMATION CHARACTERISTICS OF FUEL ELEMENTS

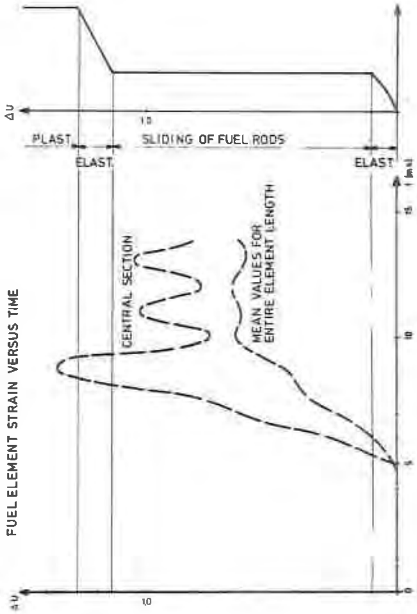
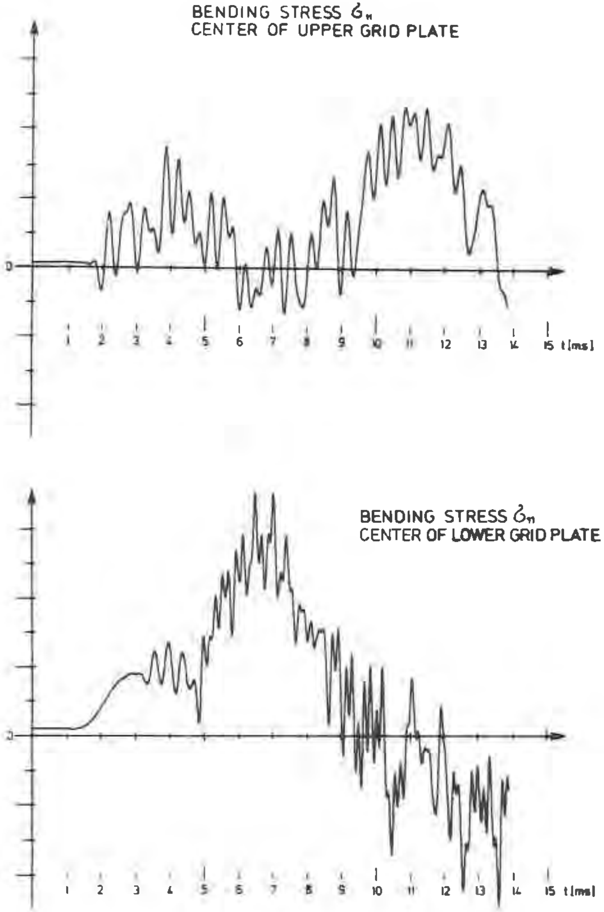
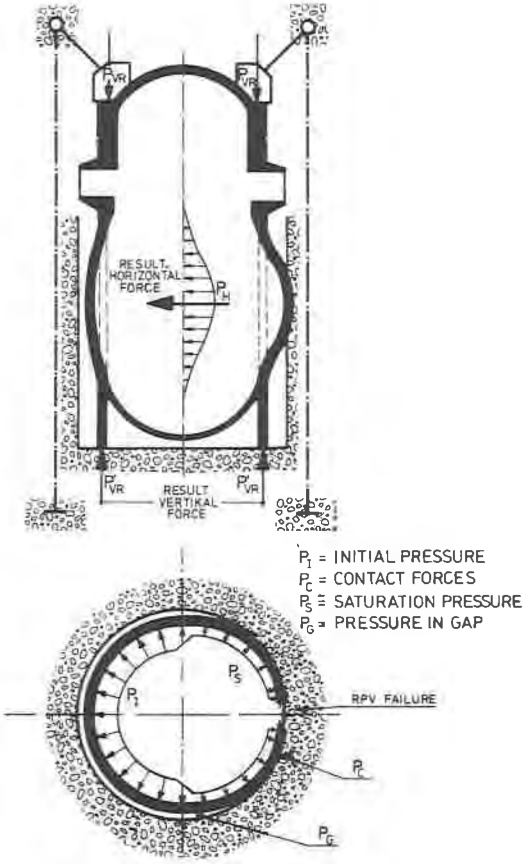


FIG. 23



HORIZONTAL FAILURE MODE
STRESSES IN GRID PLATES

FIG. 24



VERTICAL FAILURE MODE FORCES

FIG. 25