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Investigations on Containment Structures in the Frame-Work of Risk-Studies

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Abstract

In the course of risk studies loadings beyond design loads have been investigated with respect to ultimate loading capacity and defined leakage path.

Loading conditions investigated were mainly pressure build-up due to core-meltdown and H_2-deflagration.

In addition to previous studies which concentrated more on the undisturbed steel shell structure, present investigations include also penetration areas and local restraints by the surrounding structures.

The detailed elasto-plastic calculations yielded results very similar to previous estimates, significant problems arise in the calculation of leak areas.

1. Introduction

The containment structures have always been regarded as an important engineered safeguard because it is the final barrier to avoid a release of radioactivity to the atmosphere in case of internal accidents. For light-water reactors the principle design basis - the maximum pressure-build-up due to a sudden release of the reactor coolant - is nearly unchanged over the last 20 years.

To protect the nuclear reactor against external events the structures have been enforced according to the specific requirements in each country. In the Federal Republic of Germany it is practice to decouple the containment concrete structure which protects the containment against the external loads.

For the design basis the specified leak-tightness is the dominant design goal. In the course of risk studies loadings beyond design loads have been investigated with respect to the topics:

- ultimate loading capacity,
- defined leakage path.

In phase A of the german risk study /1/ the estimated failure pressure was calculated for the global shell structure at static pressure conditions. The failure criteria were based on flow stress and linear elastic fracture mechanics (LEFM). Reference plant is a 1300 MWe pressurized water reactor (PWR). In the present work (Phase B of the risk study) more datailed analyses are performed to investigate the behaviour of the shell structure as well as the penetration areas under different loading conditions.

2. Loading Conditions

Loading conditions investigated were:

(a) static pressure build-up due to core-meltdown,

(b) dynamic exitation due to extreme seismic conditions,

(c) dynamic pressure build-up due to H_2-deflagration (global and local),

(d) local heat-up during pressure load.

The analyses of loading conditions (a) and (c) are contained in this paper. The results for loading condion (b) are contained in /2/ partly. The local heat-up effect was investigated at a different structure, the results are given in /3/.

A typical static pressure loading due to core-meltdown is shown in Fig. 1. For the dynamic pressure build-up due to H_2-deflagration or detonation (c) parametric studies are performed to analyse the structural response.

3. Structural Models

With respect to the topics to investigate

- ultimate loading condition and
- defined leakage path

it is necessary to perform an in-situ design review before the structure can be modeled for the analysis. In view of the large deformations to be expected special attention has to be given not only to the as-built penetration but also to the surrounding environment. For the reference plant the important areas to be analyzed are shown in Fig. 2. All the PWR-containments of the Kraftwerk-Union design are very similar. But minor differences in the design or as-built conditions can change the results quite drastically with respect to the leakage path.

In the finite-element idealization of the spherical shell structure rotational symmetric continuum-elements are used. In the areas where the membran stress is dominant one element coveres the whole wall thickness whereas in the areas of discontinuities (penetrations) a narrow mesh idealization is chosen. Because of the rotational symmetric model the penetration A is transfered to the zenith of the sphere.

The local behaviour of point E is investigated in the zenith position too. This can be done without losing accuracy because the influence of the bending disappeares after a short length in comparion to the length between the discontinuities. The nonlinear geometrical contact-problems (points A, B and E) are idealized by springs with bilinear stiffnes characteristic (gap trusses).

The bolted connection of the material hatch to the spherical shell (covered by on-welded sealing plate) has been analyzed by a separate analytical model.

The structural response in case of dynamic loadings have been analyzed using the finite-element model as well as an analytical approach which is described in /4/ and summerized below.

For spherical symmetry, there results an ordinary differential equation for the radial displacement in both the elastic and plastic region. The derivation of the equations is based on the equilibrium of forces and on a bilinear stress-strain relation. In the case of an elastic, ideal plastic stress-strain relationship and of impulsive loads, the energy balance between the initial kinetic and final plastic deformation energy results in a simple formula for the maximum strain as a function of the initial shell impulse. This formula can be shown to be approximately valid for local pressure loads, too.

4. Failure Criteria

In order to evaluate the range of possible failure pressures we have applied commonly used stress criteria as well as advanced strain criteria and fracture mechanics methods, shown together in Tab. I. The strain criteria used are based on a method shown in /5/ including defects using a triaxiality factor similar to /6/.

5. Results

The results of the calculations for the ultimate loading capacity are summerized in Tab. II. In addition to the failure pressures the equivalent stress, the radial displacement and the begin of yielding of the shell using minimum and median mechanical properties is indicated.

The large penetration, point A, shows the lowest failure pressure for the static pressure case because of the very high stress conditions.

In the dynamic loading case the failure pressure of the shell would be lower if no increase of material properties due to strain rate effects are assumed. The final dynamic loading case has not been specified yet.

The analyses of possible leakage paths have been concentrated first on the bolted connection of the materials hatch. Depending on the design of the area early leakage can be calculated for one case but not for all cases.

The possibilities of calculating leak cross sections by elasto-plastic fracture mechanics methods are under investigation.

6. Conclusions

In addition to previous studies which concentrated more on the undisturbed shell structure, present investigations include also penetration areas and local restraints by the surrounding structures.

Preliminary conclusion can be summarized as follows:

° ultimate loading capacity
  - present design requirements have provided a large margin of safety, so considerable loads beyond design basis can be taken,
  - datailed elasto-plastic calculations yielded results similar to previous estimates /1/ and studies in /7/,
  - failure criteria should be selected according to the local state of stress (strain),
  - the overall deformation behaviour is influenced by local heat-up for certain geometries.

° defined leakage path
  - the most probable leakage path is largely affected by local conditions of the structure under investigation,
  - significant problems arise in the calculation of leak cross sections.

7. References

/1/ Deutsche Risikostudie Kernkraftwerke, Gesellschaft für Reaktorsicherheit (GRS) mbH, Fachband 5, Verlag TÜV Rheinland, 1980

/2/ Deutsche Risikostudie Kernkraftwerke, Gesellschaft für Reaktorsicherheit (GRS) mbH, Fachband 4, Verlag TÜV Rheinland, 1980

/3/ Kuntze W.M. et.al., "Deformation of a Steel Containment Loaded by Pressure and Temperature" SMiRT 8, Brussels 1985, Paper 3/2.

/4/ W. Klassmann, Dynamische und elastoplastische Beanspruchung einer Kugelschale unter lokaler und globaler Innendruckbelastung. Ein Beitrag zur Deutschen Risikostudie (Phase B), GRS-A-910: Gesellschaft für Reaktorsicherheit (GRS) mbH, Köln, Dezember 1980.

/5/ Schulz H., Glahn M., "Requirements on the Mechanical Design of Reactor Systems Operating at Elevated Temperature" SMiRT 5, Berlin 1979, Paper L6/4.

/6/ Ju F.D., Butler T.A. "Review of Proposed Failure Criteria for Ductile Materials" NUREG/CR-3644 (April 1984).

/7/ Jeschke, J., "Limit Load Analysis of Actual Spherical Containments Subjected to Static Internal Pressure and Temperature" NUREG/CP-0056 (August 1984)

Table I: Failure Criteria

- Strain limit

$$\varepsilon_{se} = \varepsilon_u \times f_1 \times f_2 / TF \qquad TF = \sigma_1 + \sigma_2 + \sigma_3 / \sigma_v$$

ε_{se} = strain limit
ε_u = minimum uniform elongation
f_1 = size effect (plate thickness and weld)
f_2 crack influence (determined for a reference defect)

- engineering flow-stress

$$\sigma_v \leq \sigma_F \qquad \sigma_F = (R_{p0,2} + R_m) / 2 \cdots 2,4$$

- equivalent stress "v. Mises"

$$\sigma_v \leq R_m$$

- major prinziple stress

$$\sigma_i \leq R_m$$

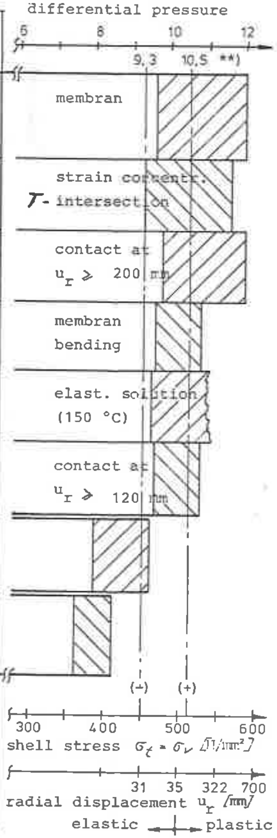
- linear elastic fracture mechanics

$$K_I \leq K_{Ic}$$

- elastoplastic fracture mechanics
  - J-Integral
  - plastic collapse

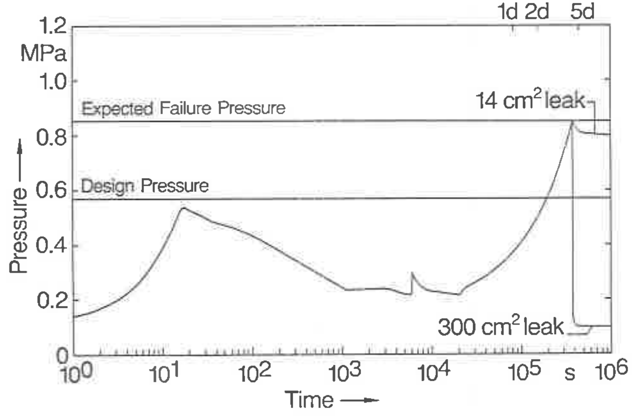
Table II: Differential Failure Pressures at varions locations

LOCATION	Fail. CRITERIA	P_{max} /bar/	Mate-rial
SHELL	ε_{sl} σ_F	12.0 9.6	+*) -
A	ε_{sl} σ_i	11.6 9.3	+ -
B	ε_{sl} σ_F	12.0 9.8	+ -
C	ε_{sl} ε_{sl}	10.8 9.6	+ -
D	no leak	9.5 9.5	+ -
E	ε_{sl} σ_F	10.8 9.6	+ -
H_2 loading	ε_{sl} σ_F	9.5 8.0	+ -
Risk.-Study Phase A	σ_F K_{IC}	8.5 7.5	- -



*) median mechanical properties: +
minimum mechanical properties: -

**) differential pressure at yield in the shell



CONTAINMENT PRESSURE TIME HISTORY
DUE TO LEAKS IN THE STEEL SHELL

FIG. 1: CONTAINMENT PRESSURE IN CASE OF CORE-MELTDOWN-ACCIDENT

A: Nozzle for Steam Line Penetration (Stress Concentration)
B: Annular Concrete Console(Gap ≈ 200 mm)
C: Embedding of Steel(Additional Bending)
D: Bolted Joint to Material Hatch(Distribution of Forces)
E: Single Steel Cantilever (Gap ≈ 120 mm ; Concentrated Force)

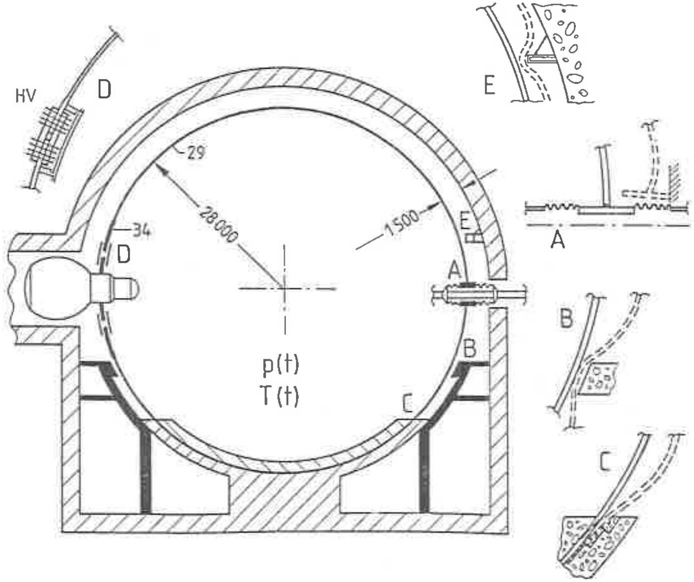


FIG. 2: STEEL CONTAINMENT LOCATIONS INVESTIGATED