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STRESS ASSESSMENTS FOR AN IMPROVED PWR CONTAINMENT DESIGNED AGAINST CORE-MELT ACCIDENTS

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ABSTRACT

The improved containment consists of an inner spherical steel shell and a surrounding thick concrete shell. Both shells are separated by a gap, through which environmental air can circulate for passive decay heat removal in case of a severe accident. Under normal operating conditions and during a LOCA both shells are freestanding structures. However, under excessive internal pressure the steel shell will deform until it is finally supported by ribs, which are attached to the concrete shell. Under the dynamic pressure loading of a postulated hydrogen detonation the steel shell is accelerated to a high velocity until it impacts the ribs. These are designed to act nearly as a homogenous crash material in order to limit the resulting strains in the steel shell. Thus, containment tightness will be maintained under these extreme loading conditions.

1. INTRODUCTION

For future PWR new containments are under discussion, which should be able to withstand also severe accidents without significant offsite releases. Eibl [1,2,3] proposed an appropriate containment concept, consisting of an inner steel shell, surrounded by an external concrete shell. Environmental air can flow through the gap between both shells and thus can remove heat from the inner steel shell, similar as in the AP600 concept [4]. In order to improve the heat transfer, the annular gap contains many ribs, which are attached to the concrete shell (fig. 1a). Under normal operating conditions the heads of the ribs have a certain distance from the steel containment shell.

According to preliminary thermodynamic calculations [5] it is likely that with the gap geometry of fig. 1a the decay heat of a 1300 MW_{el} plant can be removed at a shell temperature of 200 °C. It leads to an overpressure in the steam saturated containment atmosphere of up to 15 bar. This loading is far beyond the actual design pressure of about 5 bar, so that the steel shell will deform until it is finally supported by the ribs, which then prevent additional deformations. Steel shell, ribs and concrete shell then act as a composite structure.

Additionally, during a severe accident a hydrogen detonation might occur with peak pressures of about 100 bar acting for a duration of 5 ms [6]. In case of a hydrogen deflagration, a quasistatic pressure increase to a maximum of 15 bar has to be expected.

It should be mentioned, that these extreme loadings can be reduced significantly by appropriate accident management measures, e.g. by cooling the external shell surface with water and by burning the hydrogen before explosion conditions are reached. However, it is the aim of this concept to guarantee containment tightness even if no such measures are taken.

In [7] some structural mechanics investigations were performed for the concept of the composite containment proposed by Eibl. In this paper the essential results will be presented, leading to an optimized design shown in fig. 2. The integrity and the tightness of this containment under severe accident conditions will be discussed.

2. DISTANCE BETWEEN RIBS AND STEEL SHELL

According to the actual licensing procedures the stresses and strains in the steel containment shell must remain in the elastic region during a LOCA. For a containment building with a radius of 30 m this would correspond to an allowed radial deformation of about 40 mm. If the external ribs would already be required to carry the overpressure during a LOCA, then the distance between steel shell and ribs must not exceed this value of 40 mm. Three severe problems would then result:
In the finished plant the deviations of this distance from its nominal value must not be larger than a fraction of this value, i.e. some millimeters. Such a manufacturing precision is hardly achievable for the dimensions of the building under discussion.
During the required pressure test of the finished steel shell with an overpressure of 6 or 7 bar - as well as during a LOCA - contact between ribs and shell would occur and damage the corrosion protection of the shell. A repair would hardly be possible because of the reduced accessibility of the outer shell surface.
The small distance between steel shell and ribs would hinder thermal expansion of the steel shell caused by temperature increases up to 145 °C during a LOCA. This would lead to high compressive stresses in the shell causing buckling problems [7].

For a satisfaction of the actual licensing rules and avoiding the structural problems just discussed, it is necessary that the inner steel containment shell does not come into contact with external structures during a LOCA - and during all the other design basis accidents. Rather it is necessary that it carries the corresponding loadings alone as a free standing structure.

For such a steel containment shell designed primarily as a pressure vessel the most suitable shape is of course the spherical one. The required wall thickness for a design pressure of $p = 5$ bar, a shell radius of $r = 30$ m and an allowed stress of $\sigma = 200$ MPa is $h = p \cdot r/(2 \cdot \sigma) = 40$ mm. It is state of the art to manufacture containment shells with such dimensions. Of course, also other containment shapes are possible, but then the wall thicknesses have to be increased, what leads to severe problems during welding the steel shell on the site.

A free standing containment shell under a LOCA means, that the distance between shell and surrounding structures must be sufficiently large. Taking into account the largest deformation during a LOCA of about 100 mm (75 mm due to thermal expansion, 21 mm due to pressurisation), and taking into account some additional manufacturing tolerances, a distance of at least 150 mm is proposed (see fig. 2).

If, however, in case of a core melt accident, pressure loadings far beyond the design pressure of 5 bar occur, the steel shell will undergo slight plastic deformations. With the proposed distance of 150 mm between shell and supporting ribs, the shell will suffer moderate strains of 0.5 % until it is supported by the ribs. Deviations in the real distance of about ± 40 mm will induce deviations in the strains in the order of ± 0.1 %.

This design concept yields a definite separation of the state of stresses and strains in the steel containment shell due to a LOCA (and all other design basis accidents), where restrictive limits with high safety margins have to be considered, and due to rare severe accidents, where also plastic deformations are allowed to occur, what is acceptable as long as containment tightness can be guaranteed.

3. HYDROGEN DETONATION

During a hydrogen detonation with a peak pressure of 100 bar the steel shell is accelerated until it impacts the ribs with a velocity of about 70 m/s. After the impact the stresses and strains in the shell must remain acceptably low, so that failure of the shell can be surely excluded.

The influence of several rib designs was investigated numerically [7]. Only the most favorable concept will be presented here. It is shown in fig. 1b. The distance between neighboring ribs is 250 mm, their thickness is 5 mm. The material assumed for ribs and shell is the containment steel 15MnNi63 shown in fig. 3. Results for an impact computed with ABAQUS are shown in fig. 4. Only one rib with the corresponding section of the shell was modeled. The pressure loading accelerates the shell until it impacts the ribs after 3.6 ms with a velocity of 69 m/s. The largest deformations occur 2 ms later with maximal strains of about 2 % in the shell (membrane strain $\varepsilon_m \leq 1$ %, bending strain $\varepsilon_b \leq 1$%). The rib is compressed axially by 66 mm.

Additional computations were performed for thinner ribs, which, however, yielded similar results for the shell. This means, that the presented design is nearly an optimum. The ribs are so close to each other that significant bending of the shell between the ribs cannot occur, and the ribs are so thin that they cannot do any harm to the much thicker containment shell. In this design the ribs nearly act as a homogenous crash material for the shell under a detonation load.

In the computations performed, buckling of the thin ribs was suppressed. In order to avoid buckling in reality the ribs will be corrugated (detail in fig. 2). The final design, taking into account dynamic crumpling phenomena, has still to be done. Assembly of the ribs on the site can be facilitated by combining several ribs to prefabricated blocks, the base plate of which can be used to form the inner surface of the external concrete shell.

4. CONTAINMENT TIGHTNESS

It is hardly possible to prevent any leakage in a real containment under overpressure. But not the least leakage from inside the spherical steel containment must escape into the gap between the steel shell and the concrete shell, where the environmental air is flowing. This problem is solved by design measures: leakages cannot occur in welded shell domains, but rather only at valves, electrical penetrations, sealed hatches, damaged bellows and so on. Therefore, the penetrations are grouped together in a separate, closed part of the annulus between steel and conrete shell as shown in fig. 2. This is similar as in the AP600 concept. The atmosphere of this space is controled and can only escape to the environment via filters. In the remaining larger part of the annulus, in which the environmental air is flowing, the steel containment shell is perfectly tight. Of course, the tightness must be maintained under all circumstances also in case of plastic deformations of the shell due to severe accidents. But this is no serious problem as can be demonstrated by many tests including the bulge tests described in [8].

These tests were performed with the containment steel 15MnNi63. Circular membranes with a diameter of 860 mm and a thickness of 2 mm were machined from plates having an original thickness of 38 mm. The initially completely plane membranes were clamped at their outer boundary and then inflated with oil until failure occured. Fig. 5 shows the experimental set-up, fig. 6 a membrane after failure, and fig. 7 some measured and computed strains for the center of the membrane. It turned out that the membrane failed due to plastic instability after material strains of about 50 % had occured. Eight burst experiments were performed without any unexpected leakage having occured.

The weldings in the steel containment shell do not represent a weak point. In [9] wide plate tensile tests were performed with specimens of 500 mm width and 38 mm thickness, which contained weldings in axial and perpendicular direction. In the experiments uniaxial strains up to 19 % occured before failure. Additionally, bending tests were performed, in which a 38 mm thick plate with a welding was bent around a bolt with 90 mm diameter without surface cracks being detected.

Similar considerations can be found in [10], where proposals are made to accept global plastic membrane strains up to 25 % of the ultimate strain and plastic surface strains up to 40 % of the ultimate strain under severe accident conditions. Using the ultimate strain of the considered containment steel of 12 % (fig. 3), a membrane strain of 3 % and a surface strain of 5 % would be acceptable. These values are more than twice as high as the strains expected in the steel containment shell under discussion.

5. CONCLUSIONS

The investigations show, that the composite containment discussed above can withstand excessive loadings expected during a core-melt accident. However, slight plastic deformations of the containment shell have to be taken into account under these extreme conditions, which is acceptable as long as containment tightness can be guarantied. Due to an appropriate design of the external ribs, which act as nearly homogeneous crash material in case of a hydrogen detonation, it is possible to limit the largest strains in the shell to about 2%. It was demonstrated, that containment tightness is in deed not endangered by such moderate deformations.

Thus the presented design fulfills essential requirements of a core melt resisting containment. Active measures would no longer be necessary during coping with a core melt accident.

6. REFERENCES

[1] J. Eibl: A new Containment Design for PWR's. 3-rd International Seminar on Containment of Nuclear Reactors, Aug 1989, California, Los Angeles, in Conjunction with SMIRT 10.

[2] B. Kuczera, H. Alsmeyer, R. Krieg, J. Eibl: Considerations on Alternative Containment Concepts for Future PWRs, The Second International Conference on Containment Design and Operation, toronto, Ontario, Oct. 1990.

[3] H. H. Hennies, G. Kessler, J. Eibl: Sicherheitsumschliessungen in künftigen Reaktoren, Atomwirtschaft, Vol 37, Mai 1992, 238-247.

[4] R. Orr, J. Scobel, T. Ahl: AP600 Containment Design for Severe Accidents, Fourth Symposium on Current Issues related to Nuclear Power Plant Structures, Equipment and Piping, Orlando, Florida, Dec 1992.

[5] F. J. Erbacher, H. J. Neitzel: Passive Containment Cooling by Natural Air Convection for Next Generation Light Water Reactors, NURETH-5, Sept 1992, Salt-Lake-City, Utah, USA.

[6] W. Breitung: Wasserstoffverbrennung und Gebäudelasten bei schweren Kernreaktorunfällen, KfK-Nachrichten, Vol 24, No 4, (1992), 192-211.

[7] B. Göller, B. Dolensky, R. Krieg: Mechanische Auslegung eines kernschmelzenfesten Druckwasserreaktor-Sicherheitsbehaelters, KfK-Nachrichten, Vol 24, No 4, (1992), 183-191.

[8] B. Goeller, R. Krieg, G. Messemer, E. Wolf: On the Failure of Spherical Steel Containments under Excessive Internal Pressure, Nuclear Engineering and Design, Vol 100, 1987, 205-219.

[9] Staatliche Materialprüfungsanstalt an der Universität Stuttgart: Zugversuche mit geschweißten Großplatten aus dem Werkstoff TSB370 (15MnNi63), 1978, unveröffentlichter Bericht.

[10] R. F. Sammataro, W. R. Solonick, N. W. Edwards: Generic Approach for Containment Success Criteria under Severe Accident Loads, Fifth Workshop on Containment Integrity, Washington DC, May 1992.

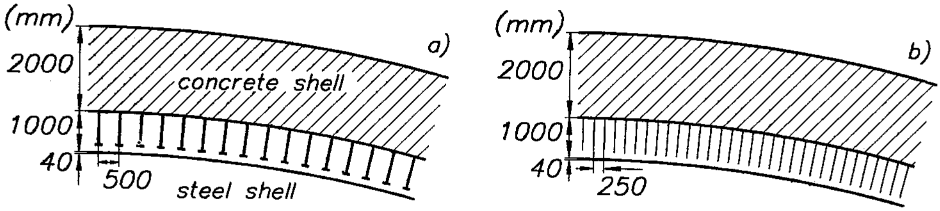

Fig. 1: Setup of the walls of the improved containment.
a) initial design, b) final design.

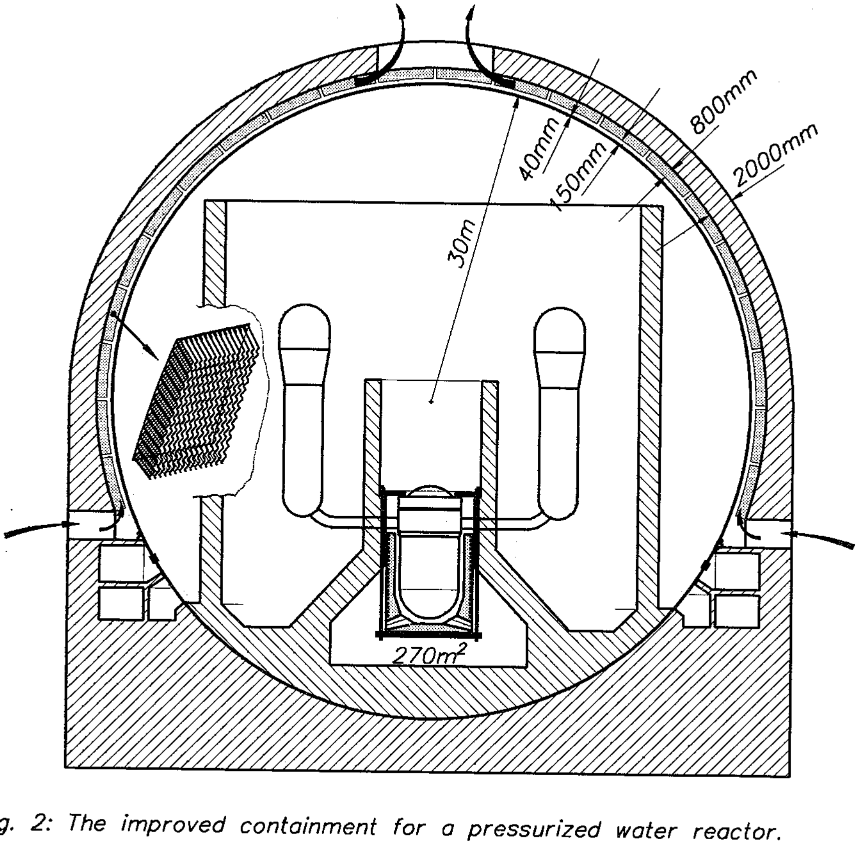

Fig. 2: The improved containment for a pressurized water reactor.

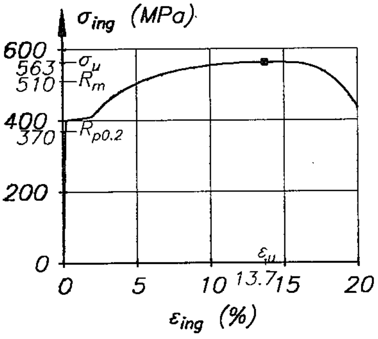

Fig. 3: Stress strain relation of the containment steel 15MnNi63.

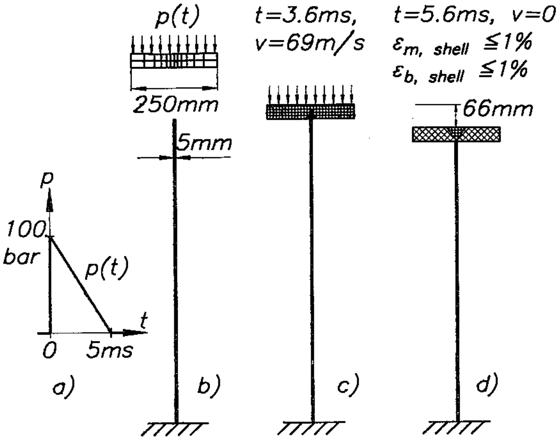

Fig. 4: Section of the containment shell under a hydrogen detonation loading.
a) pressure time history,
b) discretisation,
c) during impact,
d) state of maximal deformation.

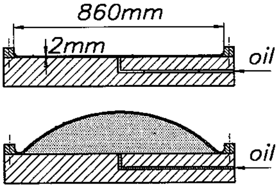

Fig. 5: Experimental set-up for the bulge tests.

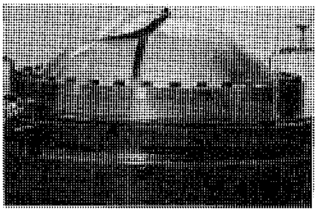

Fig. 6: Pressurized membrane after failure.

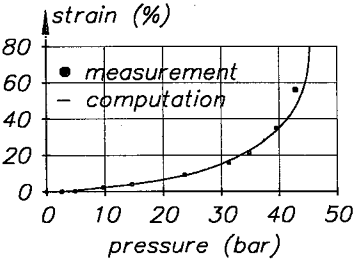

Fig. 7: Strains in the center of the membrane.