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Dynamic Response of INTOR/NET Blankets After Coolant Tube Rupture

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Abstract

The dynamic response of different water-cooled liquid $Li_{17}Pb_{83}$ breeder blanket modules has been calculated to study the potential of these modules in case of coolant tube rupture. Numerical calculations with the code PISCES have been carried out taking into account the fluid-structure interaction and the elasto-plastic behaviour of the structural material. The results show that for inert coolant characteristics the proposed conceptual designs for NET and INTOR have sufficient resistance against coolant tube rupture but when taking into account energy release due to chemical reaction of water with LiPb-alloy up to doubling of the wall thickness has to be envisaged to guarantee structural reliability.

1. Introduction

A sudden rupture of a high pressure coolant tube inside a liquid $Li_{17}Pb_{83}$ filled breeder-blanket module might be of serious concern, because the occurrence of a strong pressure shock loading on the module wall might result in rupture of the wall. Then considerable contamination of the plasma chamber with liquid breeder material and coolant would follow possibly accompanied with chemical reactions. Therefore one of the blanket-design objectives is, that failure of the wall should be avoided and that possible deformations lie within tolerable limits.

In the framework of a system and safety study for the Next European Fusion machine an analysis of liquid breeder blankets, cooled by pressurized water flowing through tubes inside the modules, has been performed to evaluate the structural integrity of the module in case of a coolant tube break. The transient numerical calculations of the pressure waves in the liquid LiPb and the dynamic response of the structural wall have been performed with the finite difference computer code PISCES /1/, taking into account the coupled fluid-structure interaction of the liquid with the flexible elasto-plastic wall. A comparison with a rigid wall and a purely elastic wall has also been made. A sudden rupture of a coolant pipe without and with the occurrence of additional water-liquid reactions has been looked at.

Three different types of geometry for the water-cooled liquid breeder-blanket module have been investigated:

a) A horizontally lying short cylindrical vessel (FINTOR-D like module /2/) with a length of 120 cm, a diameter of 40 cm and a wall thickness of 10 mm, at a nominal coolant pressure of 50 bar (this geometry served as proto-type for the computations).

b) The non-circular canister type INTOR/NET blanket module (vertically arranged in toroidal segments) /3/ of 120 cm length with flat and hemi-cylindrical walls of varying wall thickness, also cooled by pressurized water of 50 bar.

c) The currently proposed 5 m long vertically placed tubular NET II blanket module either with a diameter of 20 cm and a coolant pressure of 80 bar /4/ or with a diameter of 13.3 cm cooled by water at 50 bar /5/.

The hydrostatic pressure of the liquid LiPb eutectic is ca. 2 bar, the temperature of the liquid is ca. 300°C. The single-phase water temperature is about 280°C at the outlet and the maximum temperature of the stainless steel structure (type AISI-316) is 350°C. In all cases a separate first wall is envisaged to protect the modules from plasma radiation and erosion. Therefore the walls of the modules can be taken as thin as is mechanically acceptable.

The present paper summarizes the results of the short term response of the cylindrical blanket types a) and c) to a sudden, guillotine-like, coolant tube rupture. Results obtained for the non-cylindrical module b) are not described here because these are comparable with those discussed in the paper of V. Renda /6/.

2. Computational procedure and basic data

The finite difference computer program PISCES /1/ has been employed, as it is a very suitable code for analysing fast transient non-linear phenomena in the field of hydrodynamics, structure dynamics and coupled fluid-structure interaction problems. 2-Dimensional r-z axial-symmetric and x-y plane-symmetric options have been used for the present problem describing the mesh in Eulerian and/or Lagrangian frames using 4-node quadrilateral elements.

The liquid LiPb is assumed to be an acoustic compressible medium with equation of state $\dot{p} = K\dot{\rho}/\rho$, where the bulk compression modulus $K = 29.10^9$ N/m^2 and the density of the $Li_{17}Pb_{83}$ liquid $\rho = 9400$ kg/m^3. The sound velocity in the fluid is $c = \sqrt{K/\rho} = 1750$ m/s.

The coolant tube break is represented by a spherical- or line-pressure source located elsewhere in the vessel. In the model being used for the pipe break the break opening is represented by the rise time of the linear increasing pressure load up to the nominal coolant pressure (of 50 or 80 bar). Thereafter the pressure source is kept at constant value for inert coolant conditions or a triangular pressure spike is superimposed to represent the LiPb-water reaction. The minimum rise time considered is $t_r = 10$ µs, which represents a guillotine-like tube rupture.

For the elasto-plastic behaviour of the stainless-steel structure (AISI 316 at 350°C) a piece-wise linear stress-strain curve with isotropic strain-hardening (on the basis of equivalent values according to von Mises) has been used, based on data from /7/, taking as yield strength $S_y = 120$ MPa, and as ultimate tensile strength $S_u = 445$ MPa. Further the Young modules $E = 1.8\ 10^{11}$ N/m^2, the Poisson ratio $\nu = 0.3$, and the mass density $\rho_{ss} = 7800$ kg/m^3. For an assessment of the integrity of the structure the design limits for the primary stress intensity for fault condition according to the ASME rules /8/ have been used, where the maximum allowable membrane stress (in inelastic analysis) is the maximum of 0.7 S_u and $S_y + \frac{S_u - S_y}{3}$, which is 311 MPa.

3. Results for the short cylindrical vessel

The geometry and the axial-symmetric mesh of the simplified prototype is shown in fig. 1. Fig. 2 shows the pressure history at the inner side of an infinite cylinder with axially lying line pressure source of 50 bar (and $t_r = 10$ μs) for three different cases of the structural behaviour (rigid, pure elastic, and elasto-plastic). For a rigid wall as well as for a purely elastic wall the peak pressure is about 100 bar, being twice the pressure source as can be expected from linear elastic excitation theory. In case of elasto-plastic material behaviour the maximum peak pressure is limited to about 75 bar, being roughly the pressure where plastic deformation of the wall commences. The time dependent radial deflection of the flexible wall and the tangential stress in the wall are depicted in fig. 3. Plastic deformation starts about 0.8 ms after the onset of the pressure load, thereafter due to work hardening the wall behaves elastic. The periodic motion of the coupled liquid-wall system is about 10 times slower than for the excited empty cylinder (for which the fundamental period of axial-symmetric vibration is $T_o = 2\pi R\sqrt{\rho/E} = 250$ μs) in conformity with the added mass principle.

The same maximum values for pressure, stress and deformation, but initially on a somewhat slower time scale due to spherical wave propagation, have been found for the "point"-source model of fig. 1b. In fig. 4 is shown the pressure at the inner side of the elasto-plastic wall at different positions (as allocated in fig. 1) and in fig. 5 the dynamic response of the wall is given. In this short vessel where axial reflection on the flat rigid vessel heads has been assumed, the 1-dimensional "line"-source calculations give already rather good and only slightly conservative predictions of the arising pressure loads, stresses and strains.

A non-central lying peripheral axial line source (in 2-dim.plane geometry) gives nearly the same results as the central lying line source; the circumferential variation is within 10%.

4. Results for the NET-II cylindrical module

Fig. 6 shows the response of the liquid LiPb filled NET-II cylinder having a diameter D = 200 mm and a wall thickness d = 5 mm to a central axial line step source of 80 bar. This illustrates the response to a sudden pipe break without reactions of water with LiPb.
In fig. 7 is shown the peak values of the pressure load on the wall, of the tangential stress and of the tangential strain as function of wall thickness for both NET-II design proposals as obtained by 1-dimensional line source calculations.
It has also been shown that these results differ only within 5% from those for an excited empty cylinder. For a wall thickness of 5 mm for the 80 bar cooled cylinder with D = 200 mm and for a wall thickness of 3 mm for the 50 bar cooled option with D = 133 mm the maximum pressure peak is ca. 1.25 x nominal coolant pressure, the maximum arising tangential stress peak is ca. 200 MPa, and the maximum strain value is $\lesssim$ 0.5%. These values are far below the allowed design limits for fault condition.

Recent experiments /9/, however, have shown that due to the chemical reaction of water with LiPb pressure spikes lasting for a few ms have to be taken into account. For the present NET design conditions a conservative value for this pressure spike of 250 bar has been assumed. 1-Dimensional and 2-dimensional calculations have been performed for a step pressure source with superimposed pressure spike of 250 bar and pulse length 10 ms. In the 2-dimensional calculation a cylinder length of 50 cm has been taken instead of 5 m in order to take into account axial reflection against internal structures.

Results for the module with D = 133 mm and d = 5 mm! are given in fig. 8 and fig. 9. Also in this case the 1-dim. calculations give only slightly conservative results. The maximum arising stress of 405 MPa at time t = 5.7 ms is ca 30% beyond the value as predicted by the classical pressurization formula $\sigma = pR/d = 308$ MPa due to a pressure overshoot of 10% and an excessive plastic strain of 10%.
Relying on these dynamic calculations a first estimate of the minimum required wall thickness for a shock-resistant wall taking S = 300 MPa as allowed stress limit is made, giving d = 6 mm for the cylinder with D = 133 mm and d = 10 mm for the cylinder with D = 200 mm, i.e. the ratio $d/D \approx 0.05$ should be twice that required in case of inert coolant condition. For the latter case (D = 200 mm, d = 10 mm) the effect of pulse length on wall response is depicted in fig. 10, which shows how shorter pulse lengths are less worse than longer pulse lengths.

5. Conclusions

- The results of the transient calculations show that the pressure-shock waves in the liquid breeder material and the dynamic response of the structure that follow a coolant tube rupture, depend largely on geometry and wall thickness of the module and on the break opening time. The tube break location seems to be of minor importance.
- Particularly for the cylindrical modules the maximum overpressure and structural stress achieved depend on the plastic behaviour of the structure. The fluid-structure interaction mitigates the structural response.
- Comparison of 1-dimensional and 2-dimensional axial-symmetric calculations shows that for a general evaluation 1-dimensional or plane-geometry calculations, in which the pipe break is simulated by a line pressure source, already give rather good and only slightly conservative predictions for the pressure-shock loading and the arising stresses and strains.
- From a parametric variation study, assuming no chemical reaction of water with LiPb, it follows that a wall thickness of 5 mm for the 80 bar cooled tubular NET-II module and a wall thickness of 3 mm for the 50 bar cooled tubular module are acceptable choices from the dynamic point of view even for guillotine-like coolant tube rupture conditions. The maximum pressure load is 1.25 x nominal coolant pressure and the maximum value for stress and strain (200 MPa and 0.5% resp.) are far below the allowed design limits for fault conditions according to ASME-III criteria.
- Calculations on the NET-II cylinder taking additional pressure pulses into account that result from chemical reaction of water with LiPb, show that relative to inert coolant conditions a doubling of the wall thickness has probably to be envisaged ($d/D \approx 0.05$) to ensure wall integrity. Pulse height and pulse length are important parameters for which a reliable data base is still lacking.

References

/1/ "PISCES-2DELK, User manual to solve dynamic structural fluid-flow and fluid-solid interaction problems", PISCES International Corp.
/2/ "FINTOR-D, A Demonstration Tokamak Power Reactor", EUR-7322, 1981.
/3/ "INTOR, International Tokamak Reactor, Phase IIA, Part I", IAEA, 1983.
/4/ G. Vieider, "Design concepts for NET first wall and blanket", 13th SOFT, Varese, Sept. '84.
/5/ M. Biggio et al., "Progress in Blanket Designs with $Li_{17}Pb_{83}$ Liquid Breeder", 13th SOFT, Varese, Sept. '84.

/6/ V. Renda, "Mechanical analysis of a module of the breeding blanket of NET in faulted condition", this conference (N6/6).

/7/ ASME boiler and pressure vessel code, section III, N47 (1980), Fig. T-1800-B1.

/8/ ASME boiler and pressure vessel code, section III, app. F, 1980.

/9/ H.M. Kottowski, "Interaction of Eutectic LiPb and water with respect to safety aspects in the fusion reactor blanket", 13th SOFT, Varese, Sept. '84.

Fig. 1 a. simplified blanket module geometry for investigating fluid–structure interaction

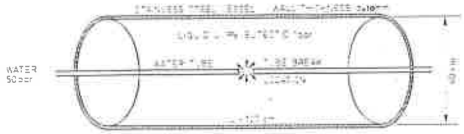

Fig. 1b. mesh layout PISCES (Lagrange r–z frame) for cylindrical vessel with point pressure source.

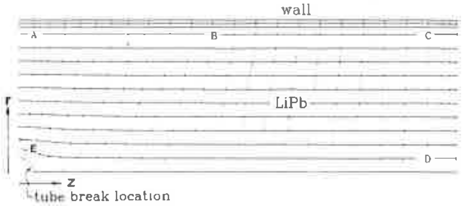

Fig. 2. pressure response on the inside of a cylinder filled with LiPb subjected to an axial line source of 50 bar. (fluid and structure in Lagrange mesh)

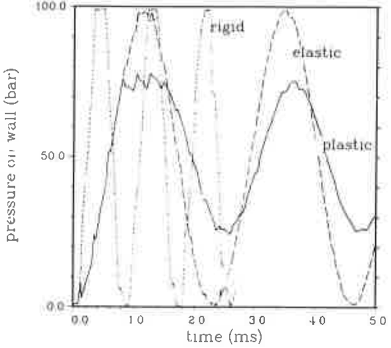

Fig. 3. radial vibration and hoop stress in cylinder filled with LiPb subjected to an axial line source of 50 bar. (fluid and structure in Lagrange mesh)

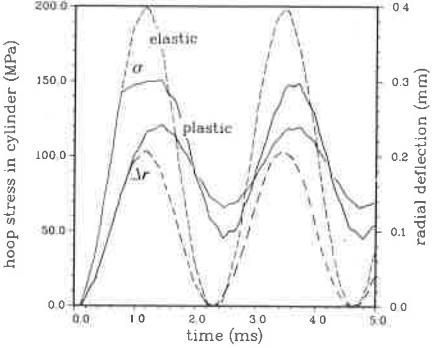

Fig. 4. pressure response on the inside of a cylinder filled with LiPb subjected to a central point source of 50 bar. (elasto-plastic wall)

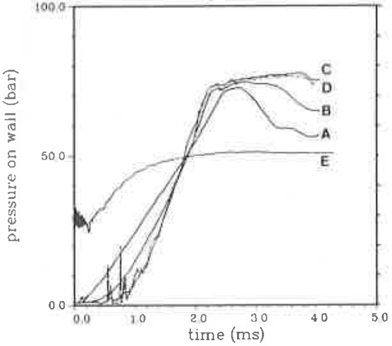

Fig. 5. maximum hoop stress in wallstructure of cylinder filled with LiPb subjected to a central point source of 50 bar (elasto-plastic wall)

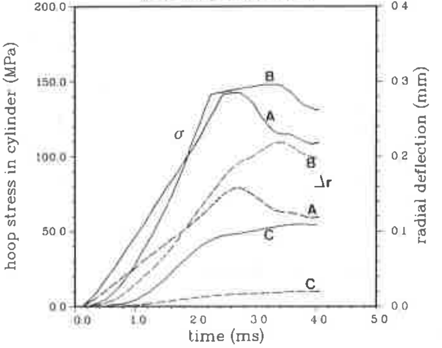

Fig.6 response of elasto–plastic cylinder filled with LiPb subjected to an axial line source of 80 bar (diameter 20 cm, wallthickness 5 mm)

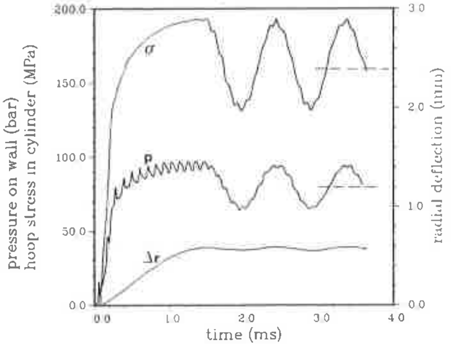

Fig 7 peak values of p,σ,and ε in LiPb filled module

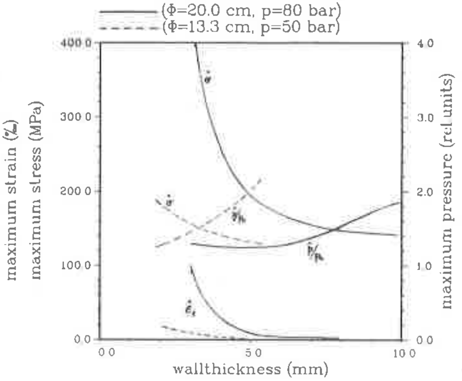

Fig 8 response of elasto plastic cylinder filled with LiPb subjected to an axial line source of 50/250 bar (diameter 13 cm, wallthickness 5 mm)

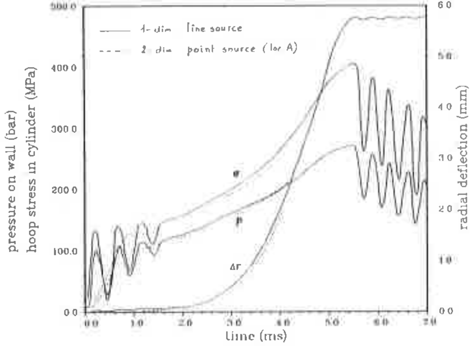

Fig.9 a pressure on elasto–plastic cylinder filled with LiPb subjected to an central point source of 50/250 bar (diameter 13 cm, wallthickness 5 mm)

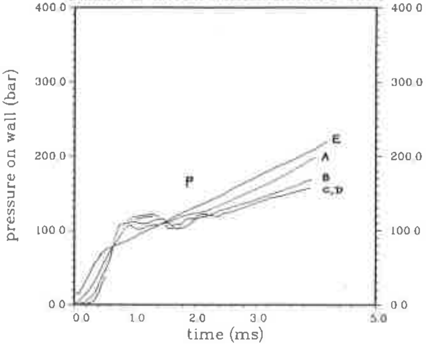

Fig.9 b response of elasto–plastic cylinder filled with LiPb subjected to an central point source of 50/250 bar. (diameter 13 cm, wallthickness 5 mm)

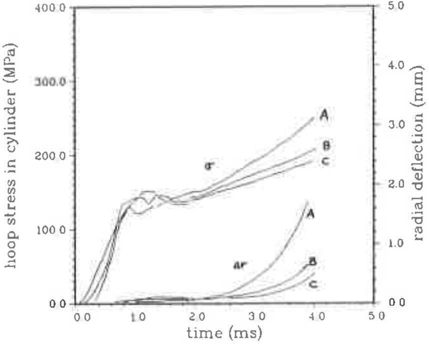

Fig.10 maximum values of p,σ,Δr,and t̂ in LiPb filled module (Φ=200mm,d=10mm) for triangular pressure pulse source with peakpressure of 250 bar.