Mechanical Analysis of a Model of the Breeding Blanket of NET in Faulted Conditions

V. Renda, L. Papa
Commission of the European Communities, J.R.C. Ispra Establishment, Applied Mechanics Division, I-21020 Ispra, Italy

Abstract

This paper has been prepared in the framework of the safety analysis of blanket designs proposed for NET (Next European Torus). Two different concepts of blanket using 17Li83Pb as breeder and pressurized water as coolant have been developed with a "modular" and a "tubular" configuration, respectively. In both concepts the shell of the vessel containing the breeder represents the first barrier against accident propagation in case of coolant pipe break (LOCA). A mechanical analysis of the "modular concept" is presented where the vessel shell is subjected to the pressure transient due to a LOCA. The mechanical behaviour, evaluated in dynamic conditions taking into account non-linearities and fluid-structure interaction, shows that the structural reliability cannot be guaranteed, and suggests to continue the development of the "tubular concept" for which a much better mechanical behaviour is expected.

1. Introduction

The 17Li83Pb/H_2O NET blanket of "modular concept" is placed in the outward zone of the 24 segments placed around the plasma chamber. The first wall which also consists of 24 independent systems, is extended on the segment sides and is welded to the rear zone of each segment, so as to afford a supplementary containment. Each blanket segment is composed of 20 stainless steel (AISI 316) vessels (modules) containing the breeder material. They are arranged in the toroidal (five rows) and poloidal (4 vessels for each row) directions without being welded together (Fig. 1).

Cooling is achieved by pressurized light water (5 MPa) circulating in tubes embedded in the breeder region (Figs. 1 and 3). The presence of the pressurized water in the toroidal region gives origin to the problem of the mechanical behaviour of the vessel in the case of break of the tubes of the coolant, defined in the following as a LOCA. In this case, a pressure wave is generated near the break and reaches the wall of the vessel containing the breeder. This phenomenon is complicated by the fact that the transient is affected by a chemical interaction between the water and 17Li83Pb. Besides the blanket design indicated above a new one called "tubular concept" has been developed (Fig. 2). Aim of the present work is to evaluate the resistance of a shell module in case of LOCA and to make some preliminary assessments on the "tubular concept" behaviour in the same accident.

2. Basic Data

2.1 Geometry

The geometry of the component and the thickness of the vessel are defined in Figs. 3 and 5, while the position of the modules in the blanket is shown in Fig. 1. For the purpose of this note, the geometry is considered as a 2-D plane one, and the analysis is made with the plane strain option, because of the continuity of the material of the vessel in the direction normal to the analysed cross section.

2.2 Standard and quality class

In this phase of feasibility studies of fusion reactor components there are no data available on standards and quality-class of the vessel. The following hypotheses have been made:

- Standards:

The rules and the allowable limits for the verifications are those of the ASME-III code and the associated CASE: the justification for this choice is that the component is assimilated to a nuclear one (fission);

- Quality class:

The quality class of the component for the design is the: /CLASS ONE/ of the standards, the justification being that the component has a remarkable importance from the safety point of view (first barrier against radioactive materials propagation). As a consequence, the design is verified in agreement with the ASME-III/NB + APPENDIX [1] and the CODE CASE n° 47/17 [2]. The reference version is that of 1977.

2.3 Materials

The unit's vessel is made of stainless steel SA 240 type 316, as defined in ASME-III - APPENDIX I.

The main characteristics of the materials at the temperature of 673 K are the following:

Temperature: 673 K	*Stainless steel*	
	- allowable stress intensity S_m	111 MPa
	- yield strength Sy	123 MPa
	- ultimate strength Su	492 MPa
	- Young modulus	$1.7 \cdot 10^5$ MPa
	- Poisson modulus	0.3
	- density	7500 kg/m^3
	17Li83Pb	
	- density	9500 kg/m^3
	- sound speed	1890 m/s

The elastoplastic calculations have been performed using a trilinear traction curve derived from [2] and defined by the following values of stresses and hardening slopes:

σ [MPa]	146	193
E [MPa]	$2.45 \cdot 10^3$	$7.5 \cdot 10^2$

2.4 Loads

The load taken into account is that generated by a pipe break of the cooling circuit inside the module. The phenomenon is not well known; the assumptions made in the following are based on some experimental data obtained from experiments performed at the JRC-Ispra.

The assumed phenomenon evolution can be described in three steps with a different time scale:

- *Step No. 1*: Pipe break in the module cooling circuit followed by an instantaneous rise of the pressure from zero to 5 MPa (pressure of the primary circuit) around the tube;
- *Step No. 2*: Energy release due to the chemical interaction between water and 17Li83Pb and to the thermodynamic equilibrium between the fluids (with possible vaporization of the water). This transient has been investigated in a simple geometry in an experiment performed at JRC-Ispra, and represented by a triangular pulse with a peak of 25 MPa and a duration of 10 ms.
- *Step No. 3*: The whole primary circuit and the vessel module are in equilibrium at the steady state pressure of 5 MPa. In this case the pressure can be considered as statically applied to the vessel wall.

The pressure evolution with time, as described above, is shown in Fig. 4.

3. Models and Codes

The calculations are performed using the Finite Element Method (FEM) with the following model

- plane geometry
- plane strain option
- fluid-structure interaction
- non-linear behaviour of the material.

The computer code utilized is EURDYN-1M developed at JRC-Ispra [3]. The mesh of 4-node fluid elements and conical shell elements is shown in Fig. 5, where capital letters indicate selected elements for the presentation of time histories (pressure, stress and strain).

4. Results

The most interesting results are presented in the form of time histories, at different points of the module, of the following parameters:

- pressure (elements A,B,C in Fig. 5)
- stresses and strains (shell elements D,E,F in Fig. 5).

4.1 Pressures

The pressures acting on the vessel wall are shown in Fig. 6 for three locations (inward zone, flat side and outward zone) of the module shell. The analysis of pressure versus time shows that the pressure histories are complicated by oscillations, due to inertia of the fluid and vibration of the vessel wall, particularly in the rear zone of the module, and by a time delay at the beginning of the transient. At the final part of the analysed transient, the pressure evolutions are comparable to the input pressure transient and maintain the same order of magnitude.

4.2 Stresses and strains

The membrane stresses are shown in Fig. 7. The important difference in stress between the inward zone (element D) of the module and the side and the rear zones is due to the difference in thickness (8 mm in the inward zone against 20 ÷ 30 mm in the other parts). The membrane strains, associated to the membrane stresses, are presented in Fig. 8. The stress and strain histories show that the dynamic effects of the pressure peak are not yet terminated, but the stress and strain in the inward zone of the vessel are so high that there is no reason to continue the computation.

The total (membrane plus bending) stresses and strains have also been calculated; they show that the vessel geometry gives origin to very high bending stresses and strains due to congruence between flat and curved parts of the wall.

5. Verifications by Standards

The pipe break is a dangerous enough accident to oblige to change the blanket segment. This means that there is not more than one LOCA in a module's life. The LOCA accident has been considered as a "LEVEL D SERVICE LOAD" (FAULTED CONDITION) and the verification has been done according to the ASME-III - NB/3200 and Appendix-F.

5.1 Stresses classification

According to ASME-III - NB-3217-1, the membrane stresses must be considered as primary while the bending stresses can be considered as secondary.

5.2 Verifications

According to ASME-III - APPENDIX-F the verification is required only for the primary stresses and the allowable limits are listed in APPENDIX-F, Table F-1322.2-1. The stresses have been calculated considering all the non-linearities of the system (fluid structure - interaction) and of the component (elastoplastic behaviour of the vessel) so that the allowable limit for stresses is stated as follows: $Sm = \text{Maximum} \left| \begin{array}{l} 0.7\ Su \\ Sy + (S_u - S_y)/3 \end{array} \right.$.

This formula leads to the following value: $Sm = 344$ MPa.

It is evident that this limit is largely exceeded in the inward zone of the vessel where one has: $\sigma m \sim 600\ \text{MPa} > 344\ \text{MPa} = Sm$ and that the verification is not achieved.

5.3 Critical parameters for the design

The plastic collapse of the structure could be avoided by changing the thickness of the inward part of the vessel, but also in that case it is not possible to avoid the very large bending stresses due to congruence between flat and curved parts. Another failure mechanism that must be taken into account is the instantaneous crack propagation in the wall thickness. In that case the bending stresses must be taken into account and a preliminary evaluation shows that the allowable flaw depth is so small that it cannot be obtained from the technological point of view. As a consequence of these last considerations about the crack propagation failure mechanism, it seems necessary to find a geometry where the bending stresses are reduced.

An alternative breeding blanket design named "tubular concept" is under examination at present. This concept has many advantages in what concerns the technological feasibility and, at the same time, it seems the best one to resist both plastic collapse and crack propagation failure mechanisms.

6. Conclusion

A non-linear analysis of the "modular concept" breeding blanket of NET has been performed to assess the feasibility of the design. The results have shown that with the present geometry it is not possible to guarantee the structural reliability of the vessel in case of an accident due to a pipe break in the module. Also if the plastic collapse of the module could be controlled by changing the thickness in the inward part of the vessel, the proposed configuration - because of the large secondary bending stresses - could break due to crack propagation mechanisms.

The alternative "tubular concept" breeding blanket, presently under development, minimizes the bending stresses and seems able to verify the allowable limit stated to avoid the plastic collapse and the crack propagation failure mechanisms.

References

[1] ANSI/ASME, BPV-III-NCA, ASME, Boiler and Pressure Vessel Code, 1977.

[2] CASE N-47-17 of ASME BPV Code, 1977.

[3] GIULIANI, S., "The computer code EURDYN-1M", CEC - JRC Ispra Establishment, EUR 8220EN (1982).

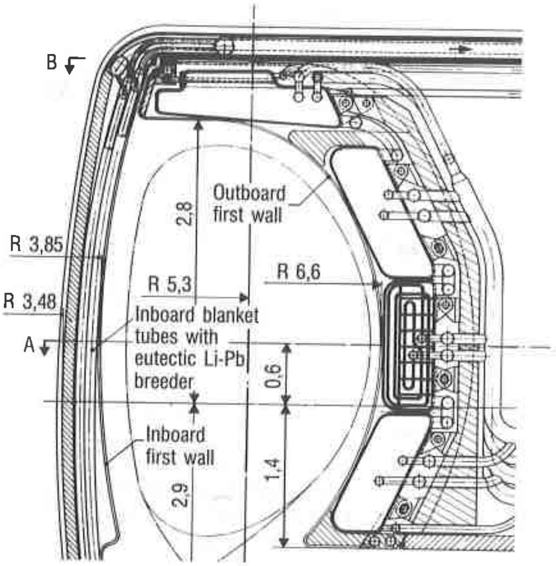

Fig. 1 - NET configuration (modular concept)

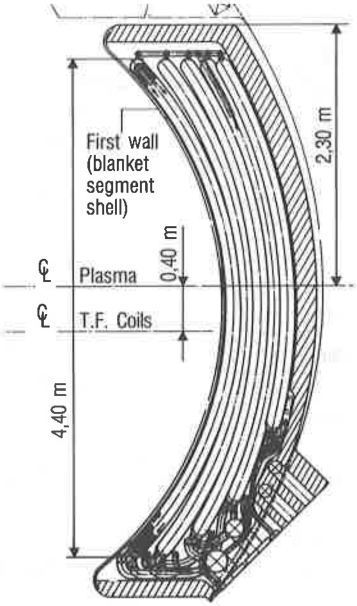

Fig. 2 - NET configuration (tubular concept)

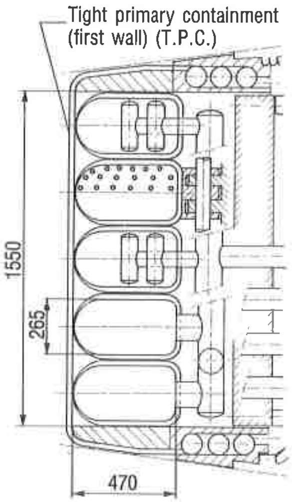

Fig. 3 - Breeding blanket modules detail

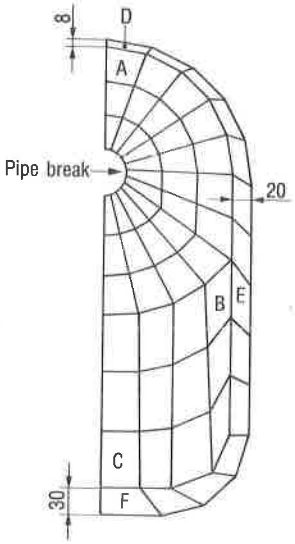

Fig. 5 - Mesh and selected elements

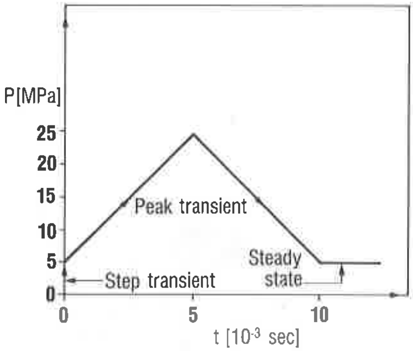

Fig. 4 - Pressure transient

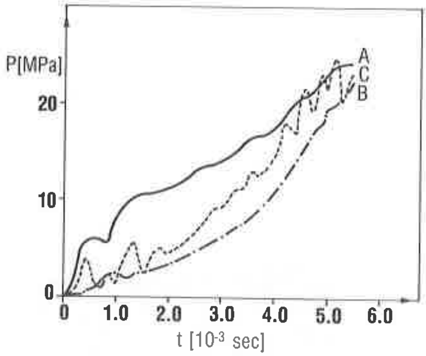

Fig. 6 - Pressures on the vessel wall

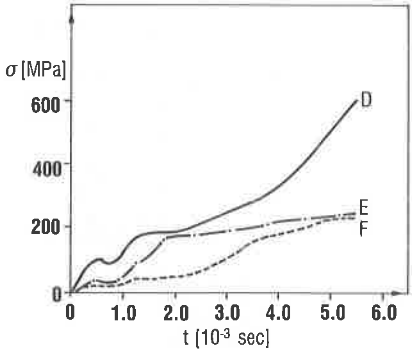

Fig. 7 - Membrane stresses in the module vessel

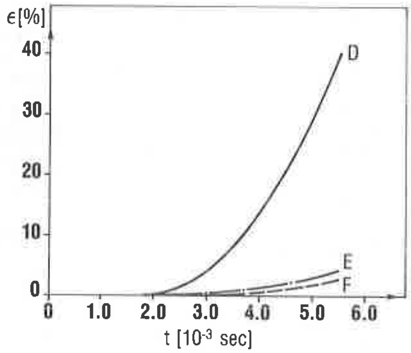

Fig. 8 - Membrane strains in the module vessel