Thermal and Structural Behaviour of a Double Containment Water Cooled BOT Ceramic Blanket for "NET"

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INTRODUCTION

The NET objectives and the European strategy towards fusion power demonstration are aimed at producing energy by a device which meets the basic design and operating requirements of a fusion reactor.

Design parameters and geometry have been selected in order to reproduce many of the features of future reactors but neglecting other features less relevant to the fixed goal. In particular the achievement of a high Tritium Breeding Ratio (TBR) has been sacrificated.

According to the previous considerations in its first operation phase the NET blanket will be mainly composed by shielding components even if locations for testing reactor relevant blankets have been foreseen. When the shielding function is considered as the principal one a TBR as high as possible is strongly recommended.

At the present design stage several blanket concepts are being considered, most of them being described elsewhere /1-2/. Many blankets were studied or optimized with reference to a reactor-like application. Besides, during the feasibility demonstration phase power generation is not requested and Tritium breeding is desirable but not specified. Moreover the NET will have a wider plasma chamber, i.e.: a thinner blanket.

Ansaldo Ricerche and the Universities of Genoa and Pisa began a joint study of a new concept of water cooled ceramic blanket, designed to met the requirements of this "extended plasma" phase and suitable to be fabricated and assembled on most part of the vacuum vessel by current materials and technologies.

Breeder water cooling is attractive for fusion reactors, since water is mainly considered for first wall cooling and involves proven technologies for power generation. Safety problems arise when a water reactive breeder is used (e.g.: LiO_2) so this design was developed aiming at obtaining both good safety characteristics and good Tritium Breeding Ratio (TBR).

The roots of this concept are in a blanket scheme designed by Ansaldo for its Hybrid Tokamak Reactor (HTMR) study /3/, a modified version of this scheme having been later developed for NET /4/ at the University of Pisa.

BLANKET DESCRIPTION

This blanket is based on the Breeder Out of Tube (BOT) concept and makes use of several rows of poloidal running, double walled water tubes passing through a

pebble-bed ceramic breeder material.
This latter is Litium Alluminate moderately enriched in ^6Li, which offers significant safety advantages with respect to water reactivity.
The main geometry boundary conditions, plasma and coolant flow data were given by the NET Team /1/. A continuous Tritium purge was also considered.
The blanket module illustrated in Fig.1 will fit into the middle ouboard part of one of the 16 segments corresponding to each toroidal field coil. It can be considered as a box that has to be put inside another, the latter consisting in the first wall (FW), the back plate and all the arrangements for upper coolant inlets and outlets, external constraints etc., which form the layout of the NET blanket segments. Its main characteristics are:
i - The ceramic breeder is composed by a sphere-pac of $LiAlO_2$ microspheres. It is contained into a AISI 316 poloidal module box stiffened by transversal and longitudinal bulkheads. The former are perforated and act also as spacing grids for the coolant tube rows.
ii - The breeding material is contained into several cells, which are kept at 0.2 MPa by a Helium flow passing through several Tritium purge tubes.
iii - An AISI 316 lobed shell like module design is used to get low stresses and to withstand moderate incidental overpressures.
iv - The module act as a single beam-like structure connected to the FW module back plate. The weight is transferred by an upper load attachment.
v - Poloidal, double walled AISI 316 tubes run from two upper collecting inlet/outlet drums to the bottom of the module where they form a U-bend.
vi - Double containment and almost free thermal expansion are assured.
The double containment concept offers the following advantages:
- it allows to keep the breeder at an optimum temperature range by properly dimensioning the gap between inner and outer tube, by this way allowing a good TBR and reducing the effects of the thermal gradients
- it is inherently reduntant, both in case of rupture of an inner tube and by putting multiple oxide layers between Tritium and coolant flow
- it allows to monitor water leakages in the gap between the tubes.
The manufacturing problems were checked with the cooperation of several firms (Breda, Belleli, Dalmine, CSC) and a preliminary fabrication, assembly and control plan was devised.

NEUTRONICS AND TRITIUM PROBLEMS

The neutronic performances of the blanket have been studied with XSDRN-PM-S /5/, a discrete ordinate monodimensional code, using a P-8/S-16 quadrature. A section of the blanket, extended from the FW to the back plate, and normal to the poloidal plane, has been represented in a slab geometry in order to perform parametric calculations aimed at reaching the optimum temperature for both Tritium breeding and breeder integrity.
The plasma has been simulated as a neutron source in vacuum and the blanket structure was accurately described in a slab geometry, taking into account the heterogenity of materials. This type of geometrical approach leads to results for TBR and temperature distribution calculation, which are more conservative than for the homogeneous model.
The blanket modeling, the total and the thermal neutron flux and the power density are shown in Fig.2. The data related to the power density will form the basis for further thermal and thermal-hydraulic calculations.
The shielding capability of this outboard blanket has been evaluated and it

seems to comply with present NET requirements.
The Tritium purge from the Litium Alluminate sphere-pac is performed by a Helium flow having 0.2 MPa pressure and a 0.15 cm^3/s flow rate.
Using Litium 30% enriched in Li6 a TBR of perhaps 0.67 with 70% coverage is obtained. This result is close to those obtained by other researchers /7/ with regard to similar NET blankets.

THERMAL AND THERMAL-HYDRAULIC ANALYSIS

The main aims of the thermal analysis is to control the power extraction, to map the temperatures for structural analysis, to evaluate the power output and to check that the breeder temperatures fall in the so called 'thermal window' for proper Tritium breeding.
Within these constraints it was verified if the requirements for proper reactor plant operations, structural and breeder integrity and Tritium extraction are met, assuming 400° and 850°C for the 'thermal window' limits and a upper limit of 550°C for the structural material.
The thermal analysis was performed by the HEATING 6 /6/ finite differences computer Code using both monodimensional (cylindrical) and bidimensional (x-y, $r\text{-}\theta$) geometries. The geometric modeling of the cylindrical cell and the optimized results, obtained by parametric calculations, are shown in Fig.3 for three power and water temperature values, using three different Helium gap sizes in the double containment tubes.
These calculations have been repeated for each of the chosen set of values, taking into account the neutronics data for the real blanket configuration. They demonstrate an asymmetric, peaked behaviour of the produced power. Accounting also for the irradiated heat, it was possible to get the optimum configuration, shown in Fig.1, which is characterized by the least severe working conditions.
During this optimization phase the use of ZrO_2 as thermal insulator in the tubes gap was also considered. The results were not acceptable and this solution was discarded.
As above indicated, no particular problem arises in performing the thermal-hydraulic calculations regarding normal reactor operations.

STRUCTURAL ANALYSIS

A three-dimensional elastic structural analysis of the blanket was performed with reference to the design conditions.
The thermal loads were evaluated by using the results of the thermal analysis with reference either to the start-up/shut-down cycle or to the start/end of a operating pulsed cycle. Cautelative assumptions were made everywhere (e.g.: rigid contraints at the back plate-blanket interfaces).
The finite element ANSYS code /8/ was used and the analysis was focused on:
i - overall behaviour of the module box and its poloidal tube rows; the structural weight, the radial thermal gradients, the weight of the the breeder and the coolant, the momentum and pressure loads were all modeled and the constraint loads were evaluated
ii - local behaviour of the module structure and of the double containment tubes, as the 'cold spot' effect due to the presence of tube spacers. The effect of the thermal loads and of the pressure loads acting on the lobed module walls, bulkheads and enclosures where analyzed.
The calculated primary and secondary stresses were checked with reference to the

ASME III /9/ criteria, using the AISI316 design curves at 500°C with fluence inferior to 10 dpa and duration 1.8 10^4 hours /10/.
The ASME criteria were almost everywhere met, the upper elastic peak stresses (about 160 MPa) being evaluated at the lobes of the module box and at the junction between outer tubes and U-bend enclosures.
At the 'cold spots' in the outer tube walls, near the spacers, the analysis shows that plasticity may be involved.
A further check was made with reference to the fatigue growth of an existing shallow crack in some of the tubes.

CONCLUSIONS

A water cooled ceramic breeder BOT blanket, based on the concept of double walled poloidal running cooling tubes was described.
This type of blanket, which provides a TBR of 0.67 with 70% coverage, without multiplier and with acceptable shielding performances, can be a viable design either for introducing Tritium technologies in the first NET phases or for further power reactor development.
The use in this blanket of the double containment concept allows both safety improvement and Tritium Breeding Ratio optimization.
In order to solve many other issues related to the present design concept, further analytical and experimental work is required.

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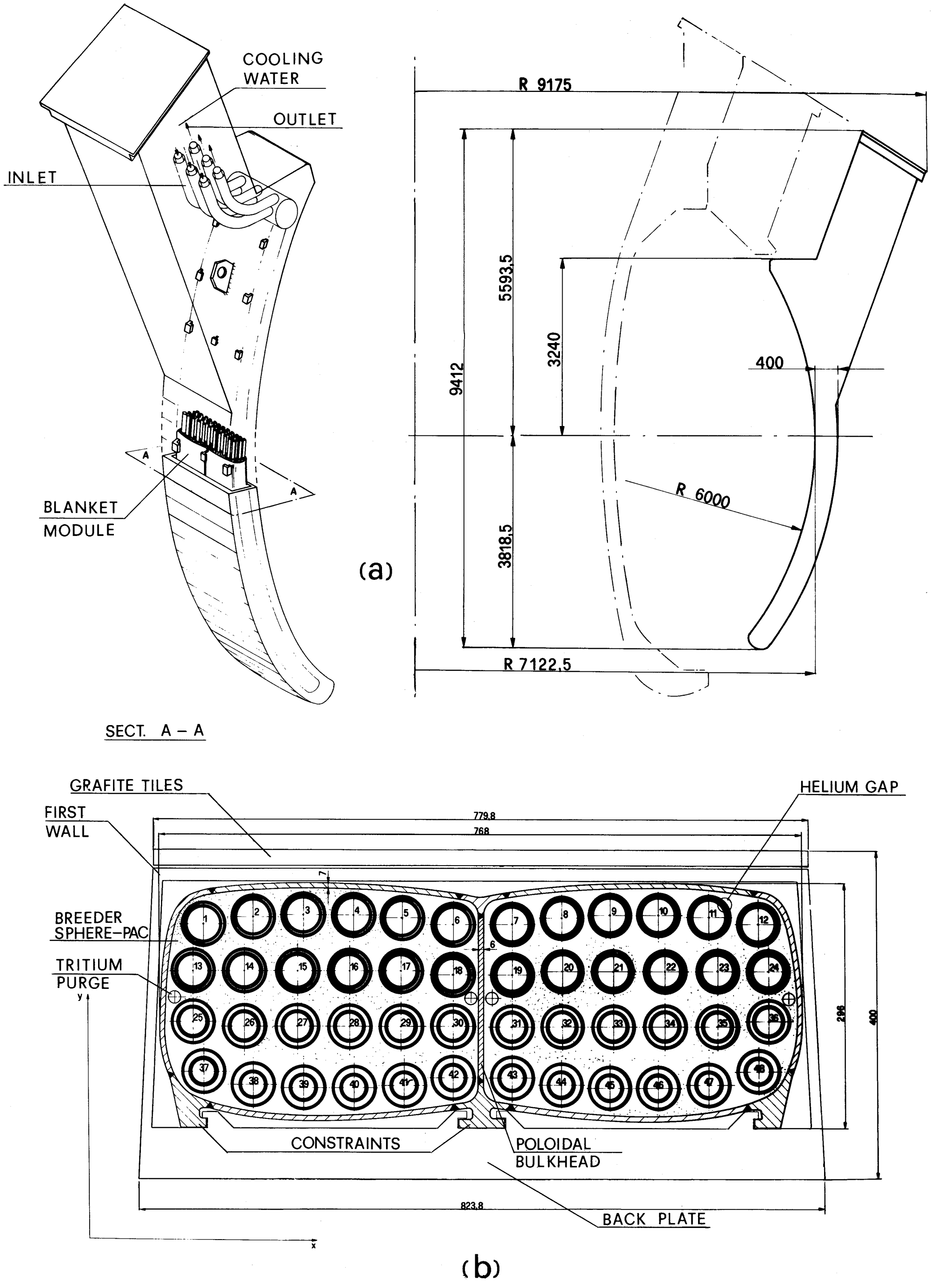

Fig.1 - Blanket module overall layout (a) and main cross section (b)

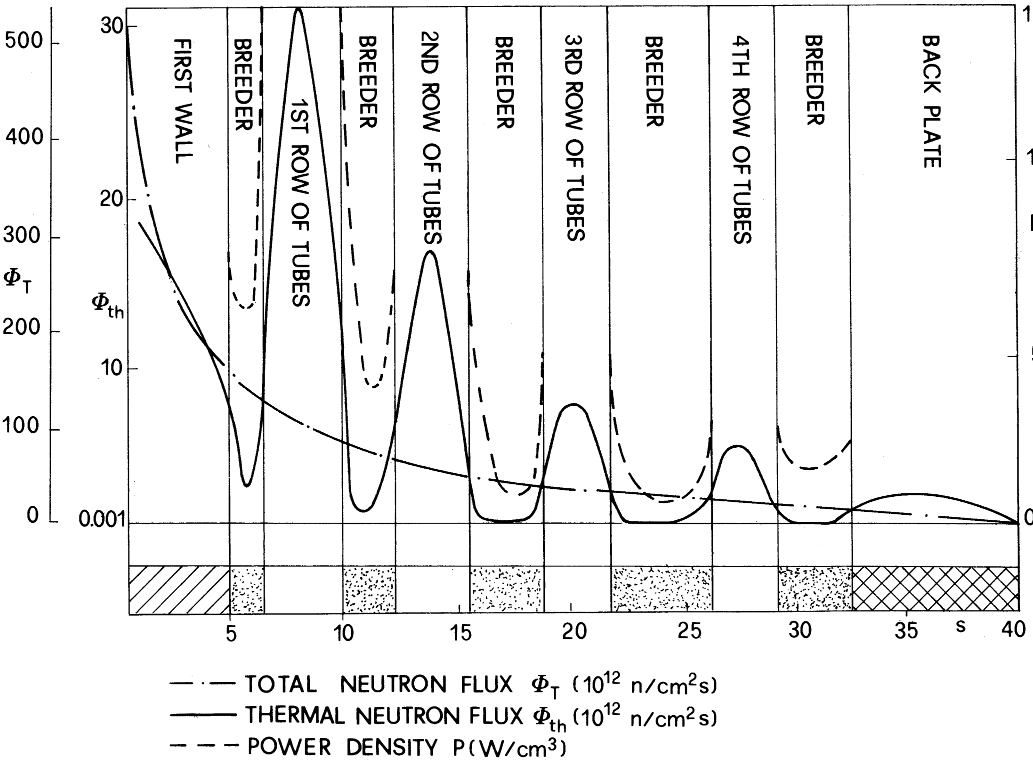

Fig.2 - Blanket modeling for neutronic calculations. Total and thermal neutron fluxes and power density behaviours are shown. The Tritium production is proportional to the thermal neutron flux

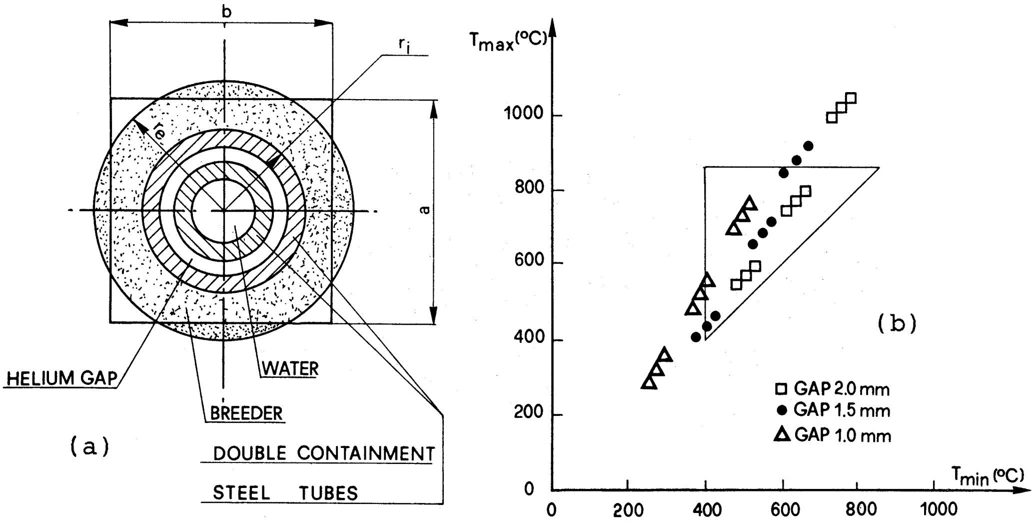

Fig.3 - Cell modeling adopted for thermal calculations (a) and plot of minimum and maximum breeder temperatures (b) obtained for various values of specific power (5 - 7.5 - 10 Wcm^{-3}), cooling water temperatures (60° 90°- 120°C) and Helium gap sizes (1 - 1.5 - 2 mm). The triangle defines the range of allowed breeder temperatures (thermal window).