Available online at www.sciencedirect.com

Fusion Engineering and Design 69 (2003) 281–287

www.elsevier.com/locate/fusengdes

Lay-out of the He-cooled solid breeder model B in the European power plant conceptual study

S. Hermsmeyer [a,*], S. Malang [a], U. Fischer [b], S. Gordeev [b]

[a] Forschungszentrum Karlsruhe, Institut für Kern-und Energietechnik, P.O. Box 3640, D-76021 Karlsruhe, Germany
[b] Forschungszentrum Karlsruhe, Institut für Reaktorsicherheit, P.O. Box 3640, D-76021 Karlsruhe, Germany

Abstract

The European helium cooled pebble bed (HCPB) blanket concept is the basis for one of two limited-extrapolation plant models that are being elaborated within the European power plant conceptual study (PPCS). In addition to addressing the case for fusion safety and environmental compatibility, following earlier studies like SEAFP or SEAL, this reactor study puts emphasis on plant availability and economic viability, which are closely related to specific plant models and require a detailed lay-out of the fusion power core and a consideration of the overall plant (balance of plant). Within the development of in-vessel components for the plant model, the major tasks to be carried out were: (i) adaptation of the HCPB concept—featuring separate pebble beds of ceramic breeder and Beryllium neutron multiplier and reduced-activation ferritic-martensitic steel EUROFER as structural material—to the large module segmentation chosen for reasons of plant availability in part II of the PPCS; (ii) proposal of a concept for a Helium cooled divertor compatible with a maximum of 10 MW/m^2 heat flux to satisfy the requirements of reasonably extrapolated plasma physics; (iii) lay-out of the major plant model components and integration into the in-vessel dimensions found from system code calculations for a power plant of 1500 MW electrical output and iterated data on the plant model performance. The paper defines all major in-vessel components of plant model B, as it is called in the PPCS, namely (i) the unit of FW, blanket and high temperature shield that is to be replaced regularly; (ii) the low temperature shield that is laid out as a lifetime component of the reactor; (iii) the divertor; and (iv) the in-vessel manifolding. Results are presented for the thermal-hydraulic performance of the components and for the thermal-mechanical behaviour of the blanket and the divertor target plate. These results suggest, together with results from the wider exploration of the plant model within the PPCS, that the He cooled solid breeder blanket is a credible concept. They stress the positive role that He cooling can play in economically attractive fusion power plants.

Keywords: Breeder; Model; Cooling

1. Introduction

The European power plant conceptual study 2000–2002 [1] was undertaken to demonstrate (i) the credibility of the power plant designs considered; (ii) the claims for the safety and environ-

---

* Corresponding author. Tel.: +49-7247-822047; fax: +49-7247-824837.

E-mail address: stephan.hermsmeyer@iket.fzk.de (S. Hermsmeyer).

0920-3796/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0920-3796(03)00355-7

mental advantages and for the economic viability of fusion power; and (iii) the robustness of the analyses and conclusions. Within a set of four plant models, the solid breeder concept is one of two concepts positioned as requiring limited technological extrapolation given the development state of the blanket, the materials and the manufacturing technology that have been subject of the long-standing EU HCPB blanket programme. Further characteristic properties of the model are (ii) the potential for high efficiency that is based upon gas cooling and a high energy multiplication in the blanket system and the absence of hot water/steam from the reactor core to prevent under all circumstances an exothermic chemical reaction with Beryllium.

The major challenge of the study beyond previous blanket development has been the requirement to produce a comprehensive plant model including a consistent design of plasma, blanket and divertor.

It was found that, despite the development status of the blanket, the task of developing a plant model was rather conceptual than detailed, mainly because (i) a credible divertor concept ($>$ 10 MW/m^2, He) needed to be put forward and (ii) systems around the blanket needed to be adapted to the large module segmentation that was chosen for reasons of plant availability. It has become clear that the segmentation brings new boundary conditions for the blanket and that a re-design of the blanket and a much more detailed integration into the machine is needed.

2. Conceptual design of in-vessel components

With the credibility and realistic evaluation of plant models one of the major tasks of the study it was important to (i) adapt the previous HCPB design to a power plant environment that is very different from the DEMO 95 [2] frame and to (ii) explore the potential of a Helium cooled divertor because of its great impact on plasma physics assumptions and thus on the credibility of the plant.

2.1. First wall, breeding zone and shield

First wall, breeding zone and shield are the functional layers that make up the blanket. The way of integrating them in a design characterises blanket concepts and gives spaces for the adaptation to plant requirements.

The characteristic features of the EU helium cooled pebble bed (HCPB) blanket have been kept since 1995: The strong RAFM steel box is well cooled by a dense pattern of parallel He channels. Beryllium and ceramic breeder are employed in the form of particles within alternating shallow beds, separated by steel cooling plates; Be is needed as neutron multiplier, while the ceramic breeder produces sufficient T to supply the fusion reaction. T is removed from the pebble beds by a slow purge flow of He at atmospheric pressure.

Recent changes to the concept were proposed in the preparatory phase of the PPCS where the flow path of He in the breeding zone cooling plates was changed to radial to shorten channels and reduce pressure drop [3]. A welcome side effect was a slight reduction in structural material and an improvement in T breeding that allowed the use of single-size Be pebble beds with $\approx 64\%$ packing fraction instead of binary beds at 80%.

Conceptual changes in the 2001/2002 phase III of the PPCS have become necessary to achieve the integration of the HCPB concept in the power reactor. The move to large-module segmentation (see Fig. 1 from neutronic modelling) from banana-shaped large inboard and outboard segments in DEMO 95, has important consequences for the design of the blanket box: (i) with a module handling concept of introducing the blanket through small equatorial ports, module size and weight becomes critical. That has led to the proposal of a blanket box that contains only the layers that see large neutron damage and require regular replacement—FW, BZ and a part of the shield that will be referred to as high temperature shield (HTS). The blanket box is mounted flexibly on the underlying structure with a radial gap of 20 mm. In this way, the box is allowed to expand when hot during operation, while underlying structures stay at the level of coolant inlet temperatures. Sizes, weights and power of the poloid-

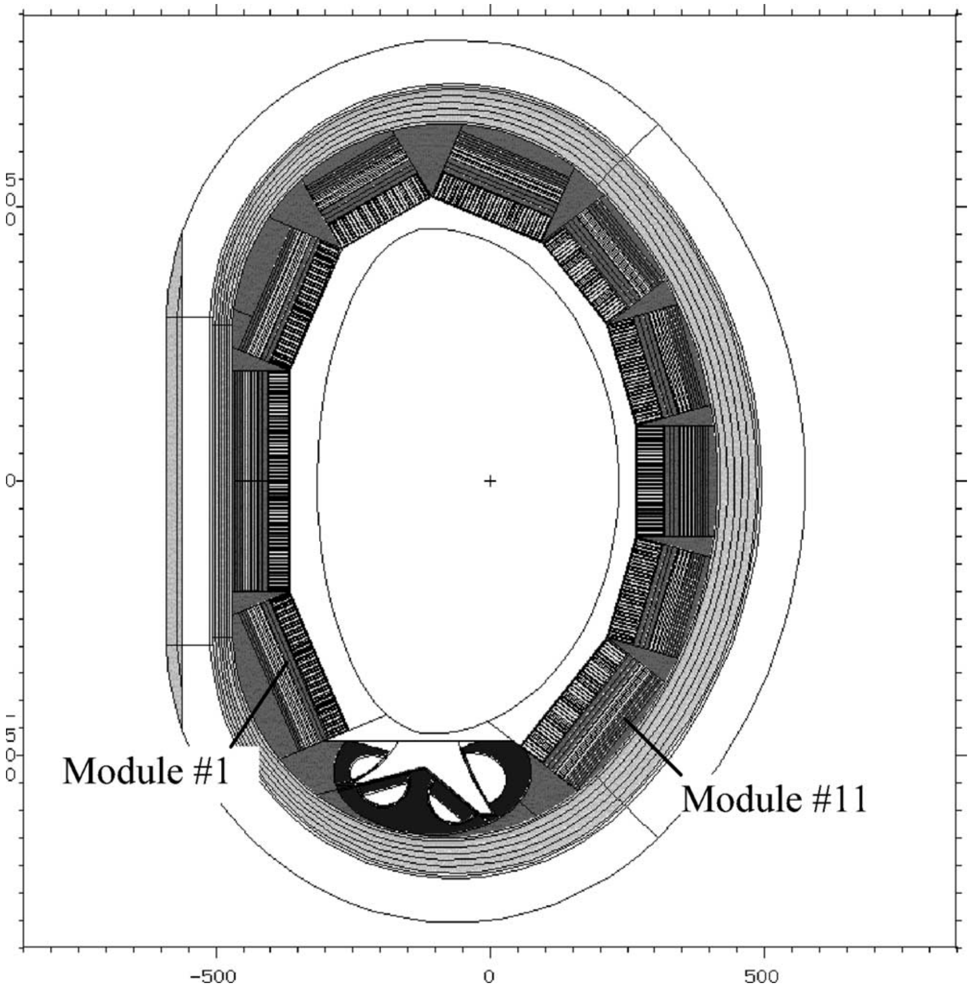

Fig. 1. Cross section through reactor core.

ally different modules, nine of Nos. 1–4 on the inboard blanket, 18 of Nos. 5–11 on the outboard, are displayed in Table 1.

The BZ is virtually identical to the preparatory phase [3], the only differences being (i) that bed heights have been adjusted to the neutron wall load in the plant model. Latest suggestions are that the explored Li_4SiO_4 ceramic breeder beds could be 12 mm high, the Be pebble beds about four times that value. (ii) Cooling plate channels are proposed to run forth and back in one cooling plate, with three channels in a pack to counter the heat exchange of hot and cold leg.

As stated above, a radially separated shield is proposed: (i) the manifold zone at the back of the blanket box has a steel content of $\approx 60\%$ and provides sufficient shielding to make structures behind the blanket box lifetime components. Part of this HTS are wedge-shaped shield plugs that close the gaps between modules. (ii) The second part of the shield, referred to as low-temperature shield (LTS), is a box of its own, ideally the same size as the blanket box and handled with the same tools. It contains 18 vol.% $ZrH_{1.7}$ as moderator contained in steel cylinders of 30 mm inner diameter and 3 mm wall thickness; the remains

Table 1
Replaceable module dimensions and power

Mod. No.	B (m)	H (m)	R (m)	Weight (t)	P (MW)
1	4.41	2.7	0.578	20.1	24.6
2	3.92	2	0.578	13.1	17.8
3	3.92	2	0.578	13.1	17.8
4	4.63	2.4	0.578	18.5	22.8
5	2.12	1.9	0.778	9.7	8.5
6	3.05	2.2	0.778	16.7	16.2
7	3.66	1.9	0.778	17.6	18
8	4.02	1.9	0.778	19.4	21.3
9	4.08	2	0.778	20.7	23.5
10	4.04	1.9	0.778	19.5	21.2
11	3.64	2.5	0.778	23.0	23.1

of the LTS is 72% steel and 10% He coolant. The LTS shielding efficiency is sufficient to ensure reweldability of the vacuum vessel (VV). The gap between HTS and LTS allows the latter to be operated under 300 °C, close enough to the VV temperature to prevent prohibitive stress in the fixed connection between LTS, in-vessel manifold and VV.

$ZrH_{1.7}$ can be safely operated up to slightly above 800 °C, where hydrogen partial pressure is ≈ 0.5 MPa, but rising steeply with increasing temperature. Plant safety demands measures that keep LTS temperatures below critical values under all circumstances. Good thermal contact with the vacuum vessel and a passive natural convection cooling loop using lead [4] have been proposed and analyses show that even in the most serious accident, assuming no operator intervention, LTS temperatures do not exceed 820 °C.

Neutronic analyses suggest that regarding shielding tungsten carbide is an alternative to $ZrH_{1.7}$.

2.2. *Divertor*

The divertor proposed for the plant model is mostly a scaled version of the ITER divertor, but consisting of 54 cassettes, six per sector.

The change brought about by employing He as coolant instead of water has been considered for the target plates that were designed to reach a performance of 10 MW/m^2 peak load that is needed to justify the assumption of ITER-like plasma physics for the limited-extrapolation plant model. Target plate design and performance have been detailed in Ref. [5]. Essentially, a large heat transfer coefficient of ≈ 50 kW/m^2 K together with a conductivity of 100 W/m K of the tungsten proposed as structural material allow a design where both maximum temperatures and structural stress become manageable. The coolant flow path is optimised to concentrate large pressure drop on a length of 5–10 mm where large heat transfer is needed.

2.3. *In-vessel manifolding*

In the reactor, the He manifolding is positioned behind the LTS (see Fig. 2). The concept proposed in the reactor study is a stiff connection between manifolding and VV: to keep thermal stress between the two entities limited, the manifold features concentric tubes, with the cold leg in the outer, square cross-section tube and the hot leg in the inner, circular one.

With plant cost highly sensitive to the radial extension of the inboard blanket, one of the main design goals was minimising manifold space requirements: (i) a scheme was proposed of branching the manifold into a divertor branch feeding the

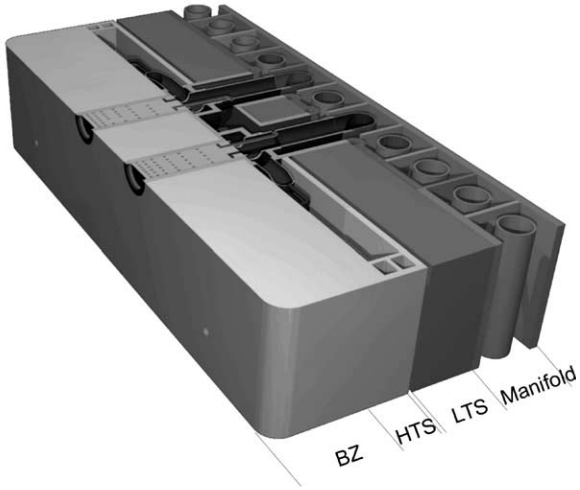

Fig. 2. HCPB blanket large module with shield and manifold.

lower modules, a top branch feeding modules at the top of the machine and an outboard branch. (ii) The cooling channel cross section required behind each module was established for a couple of alternative groupings of modules within these three branches and locations with space limitations identified. (iii) It was determined how many manifold channels, of square cross-section in order to fill the manifold space both in radial and in circumferential direction, were needed to feed each module, the figure of merit being pressure drop. Table 2 displays the final choices of manifold design.

Table 2
In-vessel manifolding of blanket modules

Mod. No.	Branch	R_{MF} (m)	MF/mod.	MF pipes
1	DIV	0.175	10	18
2	DIV	0.175	8	8
3	IB	0.175	8	8
4	IB	0.175	10	18
5	IB	0.25	2	20
6	IB	0.25	2	22
7	OB	0.25	2	14
8	OB	0.25	2	12
9	OB	0.25	3	10
10	OB	0.25	3	7
11	OB	0.25	4	4

3. Plant parameters and performance

The task of analysing the economic viability of plant models in the PPCS requires contributions from a number of different disciplines. The fusion reactor system code PROCESS [6] at UKAEA the main vehicle of integrating plant design and plasma physics for a plant of 1500 MW net electric output and providing key parameters of the machine (Tables 3 and 4). Estimates of blanket energy multiplication, net power conversion efficiency and admissible divertor peak load are the key plant characteristics entering the model.

Plasma parameters from the system code were fed into a neutronic MCNP model of the HCPB plant to provide information on the power distribution in all components, T breeding, shielding, etc. Table 3 contains a selection of the key parameters. The data confirm that functional requirements are reached. The energy multiplication implies that the power removed exceeds the fusion power by almost 40% due to nuclear processes in blanket, shield and divertor. This value is about twice that of alternative concepts; it implies a significant reduction in installed fusion power and plant size.

Power density distributions from neutronic analyses [7] are the input for a detailed thermal-hydraulic lay-out of reactor components. Table 3 displays blanket temperatures and pressure losses. The maximum structural temperatures of the cooling plate stay within the limit of 550 °C, which shows that the grouping of channels is

Table 3
System code data of the HCPB plant model

Parameter	Value
Blanket energy multiplication*	1.39
Net conversion efficiency* (%)	40.5
Divertor peak load* (MW/m^2)	10
Fusion power (GW)	3.6
Aspect ratio	3.0
Elongation (95% flux)	1.7
Triangularity (95% flux)	0.25
Major radius (m)	8.6
Average neutron wall load (MW/m^2)	2.0

* Input.

Table 4
Blanket system performance data

	Blanket	Divertor
Structural material	Eurofer	W/Eurofer
Inlet temperature (°C)	300	500
Outlet temperature (°C)	500	740
Helium pressure (MPa)	8	10
Pressure loss (MPa)	0.15	0.2
Overall power (MW)	3966	658

effective in reducing heat exchange between hot and cold leg. The limitation of the pressure drop in manifold and blanket to 0.15 MPa could be achieved by tailoring both manifold and first wall channel cross section to the module size; this became necessary by the significant increase in module width, from ≈ 2 m in DEMO to >4 m for some of the modules. The previous choice of one channel dimension for all modules had to be abandoned because of large differences in module sizes.

The overall energy balance of the plant is displayed in Fig. 3. Here, it has been assumed that all blanket heat and half of the divertor heat produce live steam for a h.p. turbine; the remaining half of the divertor heat is used for a re-heat between h.p. and i.p. turbine. The power conversion efficiency estimate of 40.5% for this scheme is thought to be conservative and needs to be verified.

4. Conclusions

The reactor study has been a much needed incentive to integrate blanket system and plasma physics in a plant. For the HCPB concept it confirms a potential for high efficiency subject to a He-cooled divertor capable of at least 10 MW/m^2. Positive results from conceptual studies within the plant model development indicate that this is feasible and have led to a new divertor development research.

The change to large module blanket segmentation and the explicit goal of estimating the cost of electricity production, have brought about a number of new design requirements, like module

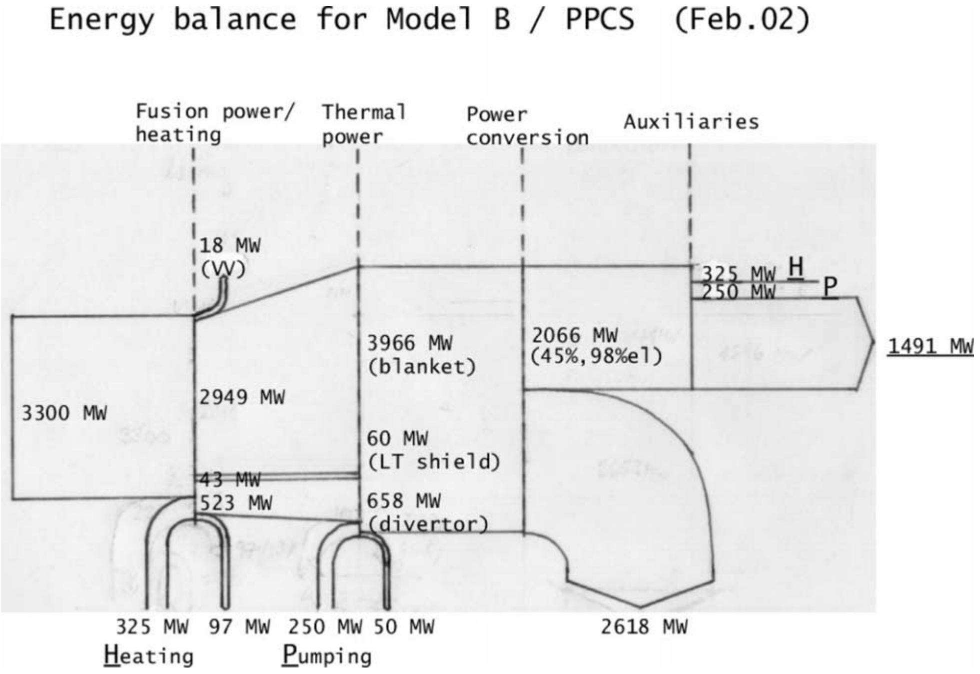

Fig. 3. Energy balance of HCPB plant model.

weight limitation, manifold space limitations, shielding etc., that were taken more care of than in the past. A number of conceptual developments have been proposed that point to the direction of an integrated reactor design. A process of further integration is now needed: the overall model has to be critically reviewed and a reactor core design developed that meets all design requirements necessary for a reactor to be entirely conclusive.

References

[1] D. Maisonnier et al., Power plant conceptual study, main technological issues, Third IAEA Tech. Comm. Meeting on Steady State Operation of Magnetic Fusion Devices, Greifswald, Germany, May 2002.

[2] M. Dalle Donne (Ed.), European DEMO BOT solid breeder blanket, KfK 5429, Forschungszentrum Karlsruhe, 1994.

[3] S. Hermsmeyer, et al., An improved European helium cooled pebble bed blanket, Fus. Eng. Des. 58–59 (2001) 689.

[4] L. Boccaccini et al., Passive system for cooling the inboard region in case of a severe accident, ISFNT-6, San Diego, CA, April 2002.

[5] S. Hermsmeyer et al., Gas-cooled high performance divertor for a power plant, ISFNT-6, San Diego, CA, April 2002.

[6] T.C. Hender et al., PROCESS code, UKAEA FUS 333, Culham, 1996.

[7] U. Fischer et al., Neutronics design issues of the WCLL and HCPB power plant models, SOFT-22, Helsinki, Finland, 2002.