IT9700087

ISSN/1120-5563

ENTE PER LE NUOVE TECNOLOGIE,
L'ENERGIA E L'AMBIENTE

Associazione EURATOM-ENEA sulla Fusione

IT9700087

EVALUATION OF THE EUROPEAN BLANKET CONCEPTS FOR DEMO FROM THE AVAILABILITY AND RELIABILITY POINT OF VIEW

CLAUDIO NARDI
ENEA - Dipartimento Energia
Centro Ricerche Frascati, Roma

2

RT/ERG/FUS/95/26

Paper received in december 1995

This report has been prepared and distributed by: Servizio Edizioni Scientifiche - ENEA
Centro Ricerche Frascati, C.P. 65 - 00044 Frascati, Rome, Italy

SUMMARY

This technical report is concerned with the ENEA activities relating to reliability and availability for the selection among two of the four European blanket concepts for the DEMO reactor. The activities on the BIT concept, the one proposed by ENEA, are emphasized. In spite of the lack of data relating to the behaviour of structures in an environment similar to that of a fusion reactor, it is evidenced that the available data are relevant to the BIT concept geometry. Moreover, it is evidenced that the qualitative reliability evaluations, compared to the quantitative ones, can lead to a better understanding of the typical problems of a structure to be used in a fusion reactor.

(RELIABILITY, AVAILABILITY, BLANKET, FUSION)

RIASSUNTO

In questo rapporto tecnico vengono presentate le attività ENEA relative ad affidabilità e disponibilità (reliability e availability) per la selezione di due fra i quattro concetti di blanket proposti nell'ambito delle attività europee per il reattore DEMO. Viene dato particolare rilievo alle attività svolte sul concetto BIT, proposto dall'ENEA. Nonostante l'assenza di dati relativi al comportamento di strutture in un ambiente simile a quello di un rettore a fusione, si mostra come i dati utilizzati siano applicabili alla geometria del concetto BIT. Inoltre si mostra come valutazioni qualitative possano portare ad una migliore comprensione dei problemi tipici di una struttura da utilizzare in un reattore a fusione, rispetto alle valutazioni quantitative.

INDICE

ENEA CONTRIBUTION TO EVALUATION OF THE EUROPEAN BLANKET CONCEPTS FOR DEMO FROM THE AVAILABILITY AND RELIABILITY POINT OF VIEW

1. NOTE

This report presents the work carried out by ENEA in the framework of the Blanket Comparison and Selection Exercise (BCSE) and specifically in the Working Group (WG) 6b - Reliability and Availability, relating to reliability and availability of the proposed blanket concepts. The positions reflected in this document are the ones of ENEA experts, not the ones of the whole WG 6b, mainly because a common position on the conclusion has not been agreed in the WG 6b.

2. INTRODUCTION

The BCSE was aimed to select the most "attractive" blanket concepts to be developed for the DEMO reactor. As the DEMO reactor will be the essential step in the development of an industrial fusion power reactor, the selection must take into account also the needs of a future utility.

One of such needs is the reliability/availability of the plant. As the blanket is a relevant component for the power generation of the plant, its availability greatly influences the overall plant availability. Having recognized this need, the Blanket Coordination Group (BCG) settled down an ad hoc working group (WG 6b - Reliability and Availability) with the representatives of the Associations that are developing designs for the BCSE (ENEA, CEA, FZK). This report presents the viewpoints of ENEA experts regarding the problems of reliability and availability of the four blanket concepts. In the WG 6b also external circuits have been evaluated, however no statements on this regard are referred in this report.

3. GENERAL DESCRIPTION OF THE BLANKET CONCEPTS

Four concepts for a DEMO blanket have been proposed, differing for a main choice: liquid breeder or solid (ceramic) breeder and for secondary ones (multiplier and coolant). The four concepts are schematized in Table I. The differences in breeder and multiplier gave rise to very different designs.

Because of the evident differences in the designs, explained in the next paragraphs, a single common indicator cannot be taken as a reference in order to compare the reliability of the different blankets, but an as complete as possible reliability analysis has to be carried out.

Table I - Schematization of the four blanket concepts

	Concept	Breeder	Multiplier	Form	Coolant	Ref.
WCD	Water Cooled	Li	Pb	Liquid	Water	[1]
DC	Dual Coolant	Li	Pb	Liquid	LiPb/He	[2]
BIT	Breeder in Tubes	$LiAlO_2$	Be	Solid	He	[3]
BOT	Breeder outside Tubes	Li_4SiO_4	Be	Solid	He	[5]

3.1 - Water Cooled Design (WCD)

This design uses an eutectic Pb17Li as breeder and multiplier, while water is used as coolant. The sketch of a blanket outboard module is reported in Figs. 1 and 2 [1]. As the chemical reactions between Li and water can lead to dangerous situations (overpressure in the containment box), the water containment is assured by a double walled pipe. These double pipes are brazed together using a soft brazing technology in order to avoid the possibility of common mode failures due to the crack propagation along the brazing filler material.

The whole exchange surface between Pb17Li and water needs to be coated, as the steel at the foreseen temperatures is permeable to the tritium generated in the Pb17Li, and the presence of remarkable quantities of tritium in the cooling water would lead to problems for the radioactive exposure of personnel and for safety issues in a possible accident.

3.2 - Dual Coolant (DC)

This design uses the same eutectic Pb17Li as breeder and multiplier, and uses He as coolant for the first wall, while the blanket (breeding volume) is cooled by the Pb17Li itself. This arrangement requires that the Pb17Li will move at velocities of the order of a few m/s (in the WCD the Pb17Li moves at velocities of few mm/s). In this way the problem arises of the MHD phenomena, which are due to the interaction between the moving Pb17Li (electrically conducting material) and the magnetic field present in the blanket region of a tokamak reactor. The problem can be limited reducing the length of electrical closed loops, and the reference solution

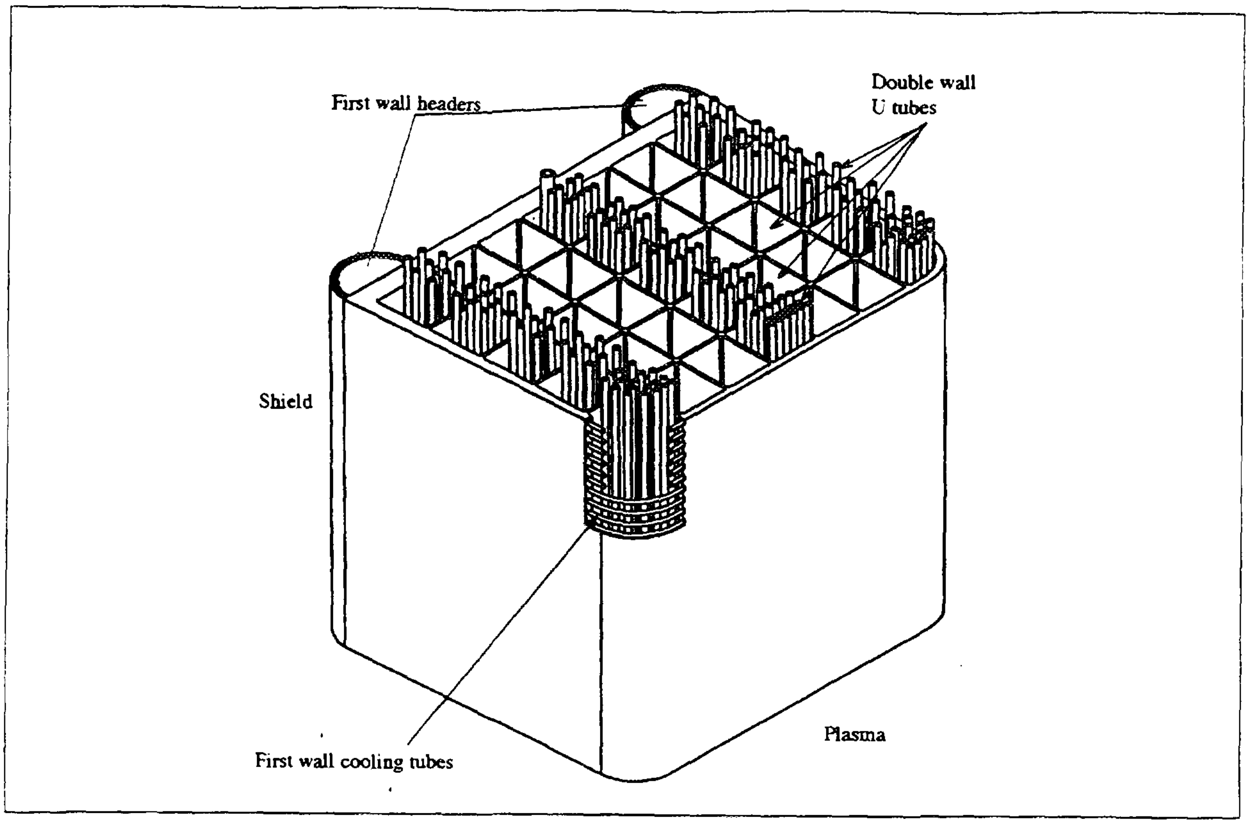


Fig. 1 - Isometric view of the outboard segment of the WCD concept (from [1])

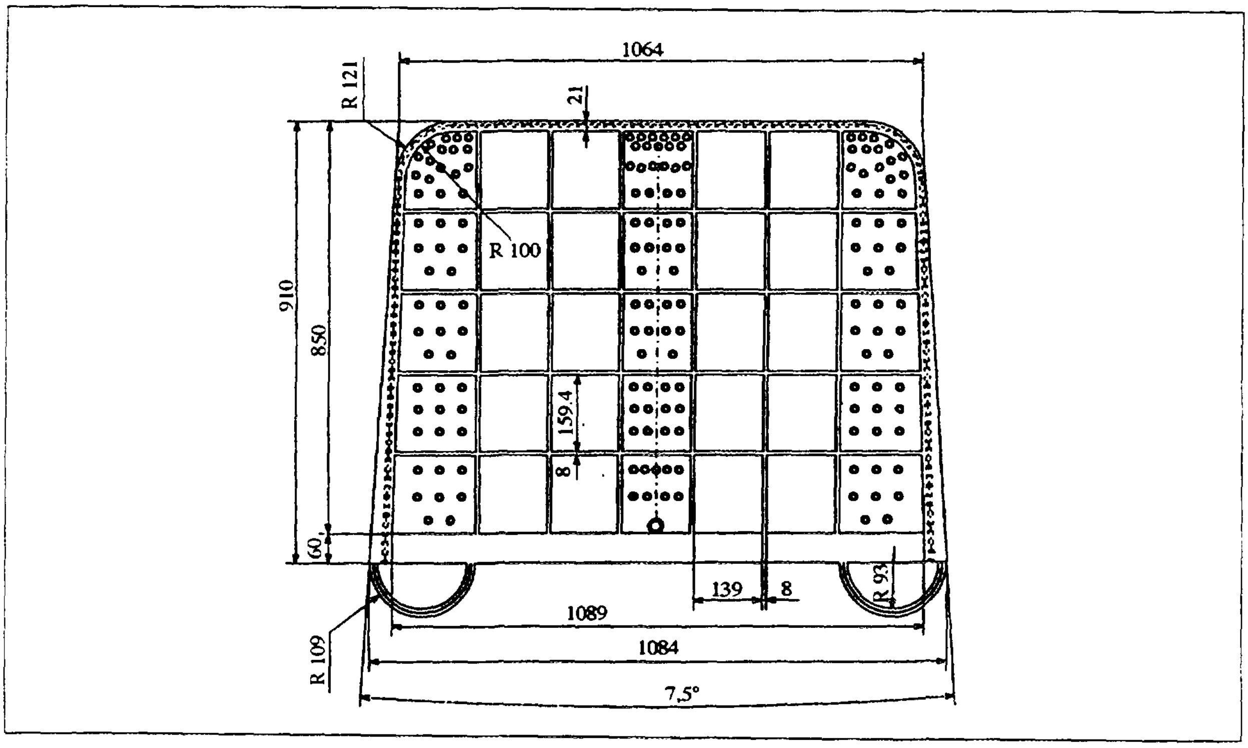


Fig. 2 - Horizontal mid-plane cross section for an outboard segment in the WCD concept (from [1])

was to coat the whole inner surface with an insulating layer. In this coating the presence of a single crack of limited length does not lead to significative problems, however two cracks, also of very little length, in the same segment lead to an unacceptable loss of cooling power into the segment itself. The sketch of a blanket outboard module is reported in Figs. 3 and 4 [2].

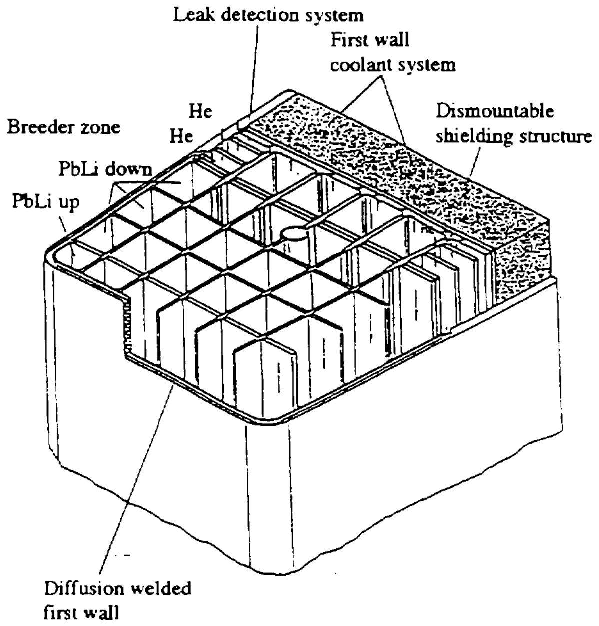


Fig. 3 - Perspective view of an outboard segment in the DC concept (from [2])

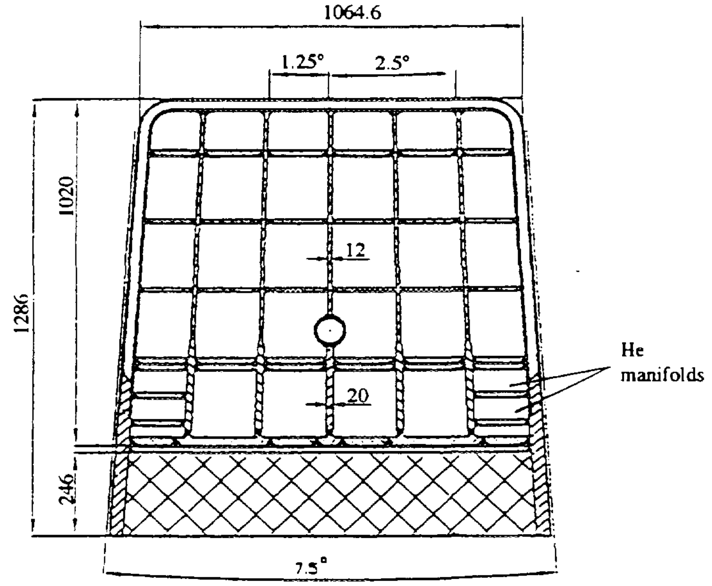


Fig. 4 - Horizontal cross section of an outboard blanket segment in the DC concept (from [2])

The He is collected in headers in the back of the blanket segment (see Fig. 4) and is sent to the steam generators. The Pb17Li is collected and sent to double fluid steam generators, having also the function of extracting the tritium from the Pb17Li. The proposed intermediate fluid is an NaK alloy.

3.3 - Breeder In Tubes (BIT)

This design uses $LiAlO_2$ (ceramic) as breeder and Be as multiplier. The breeder is in the form of annular pellets, while the multiplier is in the form of compact bricks. The cooling of the breeder is performed using high pressure He, while the tritium removal from the breeder (purging) is performed using low pressure He. The containment of the cooling gas is assured by seamless pipes, containing also the breeder pellets. The segment is composed of 83 modules (outboard) or 57 modules (inboard). The arrangement of an outboard segment and of a module are reported in Figs. 5 and 6 [3]. The first wall (mechanically and functionally independent from the breeding volume) is cooled by high pressure He, collected in separate manifolds.

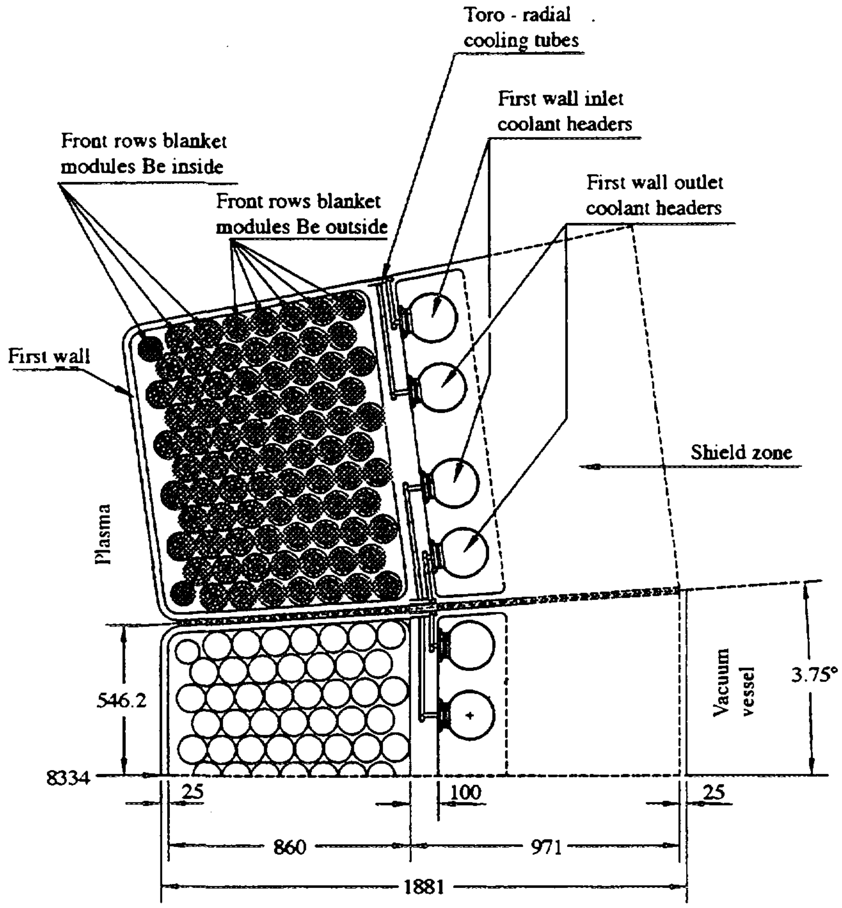
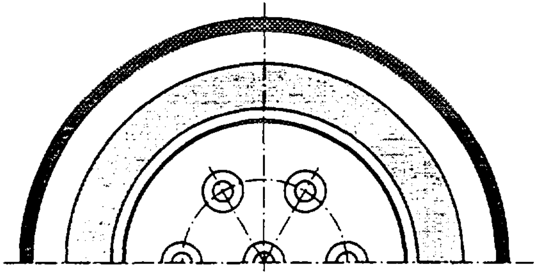
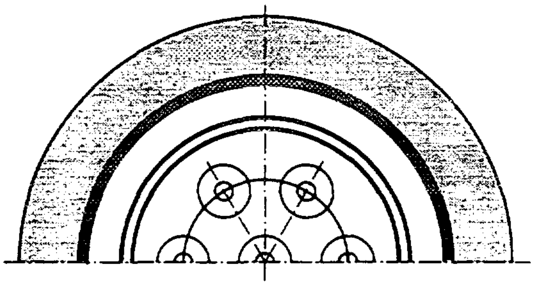


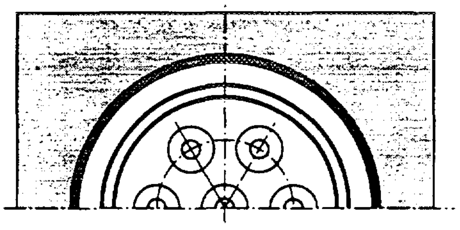
Fig. 5 - Layout of an outboard module for the BIT concept (from [3])



Berylium inside, circular section



Berylium outside, circular section



Berylium outside, square section

Fig. 6 Internal layouts of blanket modules in the BIT concept (from [3])

In order to avoid the tritium permeation into the cooling He the surfaces separating the breeder form the coolant need the presence of coatings [4].

The cooling He and the purge He are collected in separate manifolds at the top of the segment.

3.4 - Breeder Outside of Tubes (BOT)

This design uses Li_4SiO_4 as breeder and Be as multiplier. Both are in form of pebbles (0.08 - 2.3 mm in diameter) and low pressure He moves through the pebble beds purging both Li_4SiO_4 and Be [5]. The separating plates are manufactured by diffusion welding, in order to have channels in the thickness of the plate. High pressure He flows in these channels, performing the cooling of the breeder. The arrangement of an outboard segment and of the connections to the first wall are reported in Figs 7 and 8 [5].

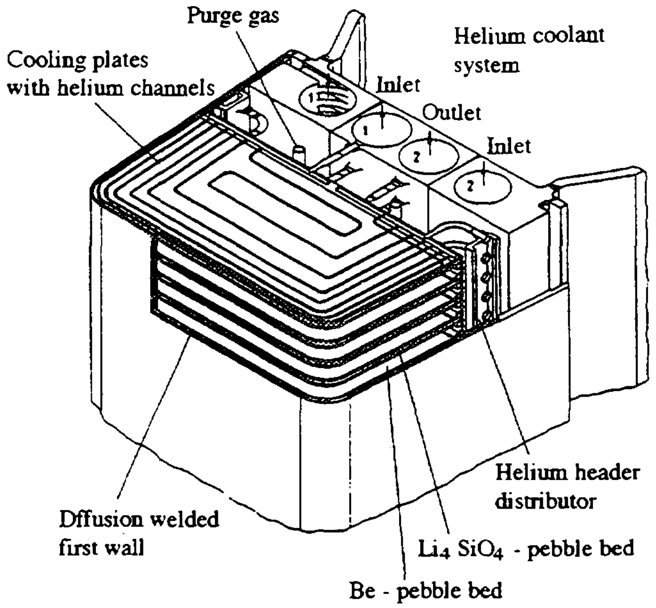


Fig. 7 - Isometric view of a poloidal part of the outboard blanket segment in the BOT concept (from [5])

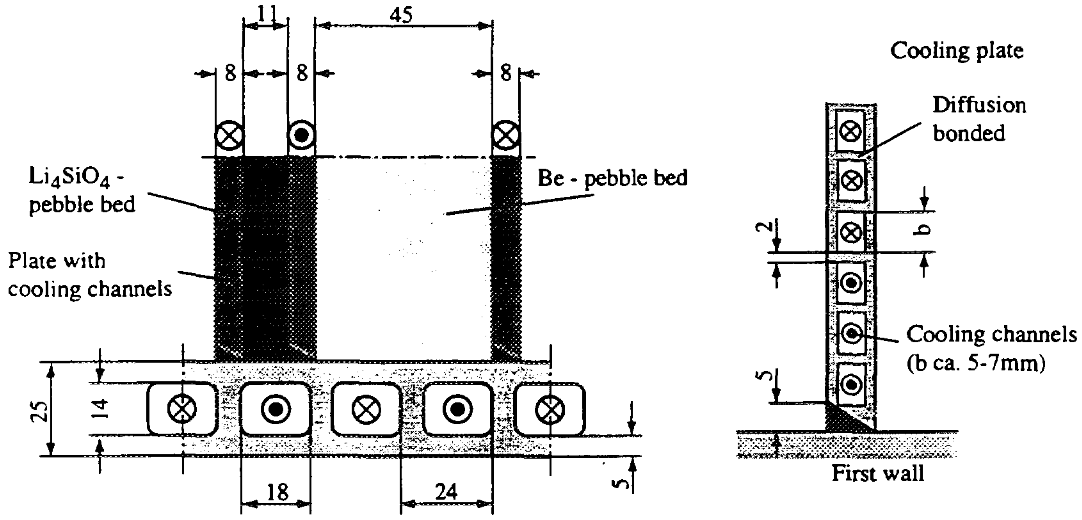


Fig 8 - Poloidal-radial cross section of a blanket module in the BOT concept: detail showing the arrangement of the He cooling channels in the first wall and in the cooling plates (From [5])

Also this design needs coatings in order to avoid the tritium permeation into the coolant. However studies are in progress in order to evaluate the real need of such a coatings.

The coolant is collected in cylindrical manifolds at the back of the segment, while the purge He is collected in a rectangular manifold in the back of the segment (Fig. 7).

4. FAILURES DATABASE

Experience of the behaviour of complex structures in a fusion-like environment is not available, so the value of the reliability of the blanket must be assessed in an analytical way [**6**]. The analysis has been carried out using the failure rates of basic items, obtained in a different environment. These conditions frustrate any effort to get a quantitative evaluation of the real reliability of the blanket segments, allowing only to get comparative statements on the relative reliability or availability for the four concepts.

To get estimates of quantitative values a series of parametric analyses would be necessary. However the WG 6b agreed to avoid as possible this tool, as it would generate uncertainties on the results. Moreover the parameters needed for such an analysis would be a great number, leading to too high uncertainties.

In order to reduce the uncertainties in the BCSE, the members of the WG 6b agreed to use a common failure rates and repair rates database. This need arises from the fact that, because of the already mentioned relative nature of the work, introducing different evaluations for the failure rates or repair rates of the same item would lead to very different results. The main sources for this database can be found in Refs. [7-8].

The failure rates of "new" components and technologies have been evaluated to be one order of magnitude greater than those of the corresponding "consolidated" technology (in agreement with the practice proposed in [8]). A "new" technology (component) is considered a technology (component) having an operating experience, reported in qualified databases, too limited to do not allow for a statistics with error margins comparable with those of the corresponding "consolidated" technology (component). This statement has not been agreed in the WG 6b, however it is the basis for the calculations carried out in this paper.

Moreover, for the weld failure rates, the probability of a weld global loss of integrity is supposed to be one order of magnitude lower than the weld failure rate referred to the weld leak (tearing) failure mode, that is reported into the database (Table II).

The wear ageing due to the neutron induced damage has not been evaluated, because of the lack of basic data on failure rates for most of the proposed concepts. However see paragraph 7. for further discussion on this point.

The proposed values of failure rate, **M**ean **T**ime **T**o **R**epair (MTTR) and **M**ean **T**ime **T**o r**E**place (MTTE) are reported in Table II. The Table II, as presented in this paper, has been the subject of much controversy and a certain number of items were not accepted by all the members of WG 6b. These items are reported here only in order to give a guideline for further deepeing of the open problems.

Table II - Values for failure rates and mean times to repair for the basic items proposed in the reliability and availability evaluations in the BCSE

Component	Env.	Proposed Values		
		Failure Rate (1/h)	MTTR (h)	MTTE (h)
OUT OF BLANKET COMPONENTS				
Pipe	He	3×10^{-9}	-	100
Pipe	LiPb	3×10^{-9}	-	200
Pipe	Water	3×10^{-9}	-	100
Steam Generator 80 MW	He	4.4×10^{-5}	-	1000
Steam Generator 116 MW	He	4×10^{-5}	500	1200
Steam Generator 140 MW	LiPb/NaK	2×10^{-6}	-	1200
Steam Generator 180 MW	He	1.2×10^{-5}	400	1000
Steam Generator 280 MW	LiPb/NaK	4×10^{-5}	500	1200
Steam Generator 300 MW	Water	1.5×10^{-5}	400	1000
Steam Generator 322 MW	He	7.9×10^{-6}	-	1000
Steam Generator 350 MW	He	2.5×10^{-5}	400	1000
Steam Generator 450 MW	Water	2.3×10^{-5}	400	1000
Steam Generator 550 MW	He	3.6×10^{-5}	400	1000
Valve	Water	1×10^{-6}	-	100
Valve	He	1×10^{-6}	-	100
Valve	LiPb	3×10^{-6}	-	200
Pump	LiPb	5.6×10^{-6}	100	200
Pump	Water	1×10^{-6}	50	100
Blower	He	1×10^{-5}	50	100
Header	Water	1×10^{-8}	-	100
Header	He	1×10^{-8}	-	100
IN BLANKET COMPONENTS				
Weld EB (1/m)	-	1×10^{-9}	-	-
Weld diffusion (1/m)	-	1×10^{-8}	-	-
Weld - Long. (1/m) (*)	-	1×10^{-9}	-	-
Weld - Girth (1/weld) (*)	-	1×10^{-9}	-	-
Brazed fillet joints (1/weld) (*) (**)	-	1×10^{-9}	-	-
Elbow (180°)	-	1×10^{-8}	-	-
Pipe bend (90°)	-	5×10^{-9}	-	-
Straight pipe (1/m)	-	1×10^{-10}	-	-
Breeder rod (1/rod)	-	1×10^{-9}	-	-

(*) Conventional technology, nuclear quality

(**) This value has been agreed by the WG 6b members. Further investigations will be carried

5. ISSUES

The evaluation of the concepts has been carried out on the basis of "issues", each of them evidencing a particular aspect of the problem. In this paper all the more relevant issues are listed. These issues are divided in quantitative and qualitative ones. The first group is concerned the reliability issues that can be calculated using the data in Table II. The qualitative issues, being related to parametric evaluations or to indicators not directly transferable as reliability values, need an evaluation based on the general experience.

It is opportune to remark, at this point, that a segment box /first wall equal for all the concepts was assumed. This is the reason why no issues related directly to the first wall are considered. In any case the reliability of the segment box is included in the evaluation of the availability of the segments, using a common value for all the four concepts ($\lambda = 4.4 \times 10^{-5}\ h^{-1}$ for the global failure rate of the first wall-segment box system).

5.1 - Quantitative issues

5.1.1 - Segments unavailability (breeding volume)

This issue takes into account the contribution of the segments (breeding volume) to the total blanket unavailability. Although the reliability is a more sensitive indicator, WG 6b took the availability as the main reference value because

- the availability is directly related to the reliability, as the value of the downtime has been assumed equal for each failure in a blanket segment for each concept (90 d)
- the availability is a more interesting feature for the utility

5.1.2 - Primary circuits unavailability

This issue is very different (as far as consequences are concerned) from the previous one, because, as the circuits are external to the vacuum chamber, a reduced basic availability can be managed with a greater redundancy of critical components and circuits. On the contrary, obviously, it is not possible to insert redundant components into the vacuum chamber.

5.2. Qualitative Issues

A consolidated statistic experience on the behaviour of components in the fusion environment obviously is not available, so the need arises of relying on a parametric analysis or on indirect indicators. This is the reason why the relevant considered issues are referred as "qualitative" ones, not because they could not be evaluated quantitatively.

The main new aspects of the fusion blanket that are out of the conventional operating experience are concerned with:

- coatings used as tritium permeation barriers or as electric insulators to control the MHD interaction
- high irradiation fluence of high energy neutrons

These aspects are, of course, interconnected, as the behaviour of the coatings is strongly influenced by the neutron irradiation.

5.2.1 - Coatings

As the coatings are a peculiar component of the fusion blankets, no data can be found for their failure rate. A parametric analysis has been carried out [9] in order to understand their influence on the global reliability and availability of the blanket. This analysis is based on the following assumptions:

- coating failure rates of the same order for all the four concepts (no influence of the crack size on the failure rate)
- no self-healing effect (repair rate=0)
- immediate operation stop at the build-up of the failure.

5.2.2 - Welds

It is well known that the welds are subject to the neutron damage more than the base material. This is because the material lattice in the **M**elted **Z**one (MZ) and in the **H**eat **A**ffected **Z**one (HAZ) presents a higher quantity and a more severe typology of defects than those found in the base material. So the indicators that could be envisaged for the material degradation due to the neutron fluence must be related to the presence of welds. The most significative ones are related to the volume or to the length of the welds and to the fluence on the welds at **E**nd **O**f **L**ife (EOL).

6. EVALUATION OF THE SEGMENTS UNAVAILABILITY

The evaluation of the blanket segments unavailability in the WG 6b initially has been carried out in two different ways, the first one analyzing four series of event sets leading to undesired situations (system shut down). The second one used a functional approach in order to understand in deep the behaviour of the various functional components of the blanket segment. As the two approaches led to very different results, the first one was selected for the final evaluations, as it allows an easier interaction with the other WG's for the BCSE.

The agreed events sets for the evaluation of the unavailability of the segments are reported in Tables III-VI.

The calculations for the blanket unavailability are reported in Tables VII - X. The summary of the availability and reliability values for the four blanket concepts is reported in Table XI.

The evaluations by FZK and by CEA-ENEA related to the WCD (Table VII) were slightly different. The difference arose form the different evaluation of the failure rates of the double walled tubes and bends for the cooling water. The FZK position was to use a value of the failure rate one tenth of the failure rate of single walled tubes and bends. Instead the position ofÊCEA-ENEA was based on a mathematical evaluation of the probability of a failure in both walls of the tubes or of the bends [10]. In spite of the very different values that could be assessed for the failure rates of the two items (the FZK values were $1x10^{-11}$ $h^{-1}m^{-1}$ for tubes and $1x10^{-9}$ h^{-1} per elbow, while the estimated values of CEA-ENEA were $8x10^{-14}$ $h^{-1}m^{-1}$ for

Table III - Agreed Events Set for the WCD concept

Id.	Description	Reliability Indicators	Reference f.r.
FWS	Damage of the FW structure. Leakage of water into the vacuum chamber	L of DW	$1x10^{-8}$/m/h
CTF	Cooling tube failure for the whole blanket	L of cooling tubes	1 $x10^{-10}$ /m/h
BFA	Bend 180° for the whole blanket	N of elbows	$1x10^{-8}$ /h
BPF	Back-plate failure per segment	L of EB welds	Values get directly from [11]
MAF	Manifold failure per segment	L of welds	Values get directly from [11]
FCH	Damage of the FW structure caused by vertical box stiffeners plates per segment	L of welds	Values get directly from [11]
FLH	Damage of the flow leading system outside of the blanket segment box per segment (segment top triple header)	L of pipes L of welds N of bends (45°) N of bends (90°) N of bends (135°)	Values get directly from [11]

NOTE

The reliability indicator for the **FWS** event in the FZK evaluation has been reported, however it must be clarified that in the WCD designof the FW the reference solution does not use diffusion welds [1]. The numerical value of the indicator is that reported from the FZK calculations.

The events **BPF**, **MAF**, **FCH** and **FLH** [11] have a limited effect on the overall availability of the blanket, so the reference values have been transcribed directly form the quoted report.

Table IV - Agreed Events Set for the DC concept

Id.	Description	Reliability Indicators	Reference f.r.
FDD	Damage of the FW structure. Leakage of He, Pb17Li or both into the vacuum chamber (Diffusion welds)	L of DW	$1x10^{-8}$ /m/h
DWD	Damage of the FW structure caused by a EB double-weld damage. Leakage of Pb17Li into the vacuum chamber	L of EB welds	Spatial average among OR and AND values $MTTRx(x\lambda^{3}xMTTR^{3})^{1/2}$
FCD	Damage of the FW structure caused by a damage of the connection between the FW and the vertical flow leading plates	L of welds	$1x10^{-10}$ /m/h
FLD	Damage of the flow leading system outside of the blanket main structure	L of piping N of girth butt-welds N of bends (90°)	$1x10^{-10}$ /m/h $1x10^{-9}$ /h $5x10^{-9}$ /h
LDD	Leak detection in detection chamber either in the FW or in the back of the segment box	L of EB welds	$1x10^{-9}$ /m/h

Table V - Agreed Events Set for the BIT concept

Id.	Description	Reliability Indicators	Reference f.r.
FWS	Damage of the FW structure. Leakage of He into the vacuum chamber (Diffusion Welds)	L of DW	$1x10^{-8}$ /h/m
PRF	Pressure rod failure in a blanket segment (outboard or inboard)	L of pressure rods N of g. butt-welds	$1x10^{-10}$ /m/h $1x10^{-9}$ /h
PVR	Pressure vessel (seamless pipe) failure	L of pressure pipes L of welds (girth)	$1x10^{-10}$ /m/h $1x10^{-9}$ /m/h
PVUO	Pressure vessel upper head failure per outboard blanket (tubes and longitudinal welds)	L of tubes L of welds (girth) N of bends (45°)	$1x10^{-10}$ /m /h $1x10^{-9}$ /m/h $2.5x10^{-9}$ /h
IOMO	Inlet or outlet He manifold failure per outboard blanket	L of tubes L of welds (girth) N of bends (45°) N of bends (90°)	$1x10^{-10}$ /m /h $1x10^{-9}$ /m/h $2.5x10^{-9}$ /h $5x10^{-9}$ /h
PVUI	Pressure vessel upper head failure per inboard blanket		Evaluated by formula
IOMI	Inlet or outlet He manifold failure per inboard blanket		Evaluated by formula

Table VI - Agreed Events Set for the BOT concept

Id.	Description	Reliability Indicators	Reference f.r.
FDH	Damage of the FW structure. Leakage of He into the vacuum chamber (Diffusion welds)	L of DW	1×10^{-8} /h/m
DWH	Damage of the FW structure caused by an Electron Beam (EB) double-weld damage. Leakage of He into the vacuum chamber	L of EB welds	Spatial average among OR and AND values $MTTR\times(2\times\lambda^3\times MTTR^3)^{1/2}$
FCH	Damage of the FW structure caused by a damage of the connection between the FW and the horizontal cooling cassette	L of welds	1×10^{-10} /m/h
FLHO	Damage of the flow leading system outside of the blanket main structure (outboard blanket)	L of pipes N of bends (90°) N of elbows (180°) L of butt-welds (girth)	1×10^{-10} /m/h 5×10^{-9} /h 1×10^{-8} /h 1×10^{-9} /m/h
FLHI	Damage of the flow leading system outside of the blanket main structure (inboard blanket)	L of girth butt-welds L of tubes N of bends (90°)	1×10^{-9} /m/h 1×10^{-10} /m/h 5×10^{-9} /h
FIHO	Damage of the flow leading system inside the main blanket structure. Reduction of the cooling ability of the blanket segment (outboard blanket)	L of tubes N of bends (90°) N of girth butt-welds L of welds	1×10^{-11} /m/h 5×10^{-10} /h 1×10^{-10} /h 1×10^{-10} /m/h
FIHI	Damage of the flow leading system inside the main blanket structure. Reduction of the cooling ability of the blanket segment (inboard blanket)	N of girth butt-welds N of bends (90°) L of l. welds (headers)	1×10^{-11} /h 5×10^{-9} /h 1×10^{-9} /m/h

NOTE:
The diffusion weld blow up has been evaluated as a not relevant event [12]

tubes and 2×10^{-12} h^{-1} per elbow) the influence of these differences where not relevant for the global availability of the blanket (Fig. 9).

In the case of double welds, the value assumed for the failure rates was been the spatial average between the values of the failure rate of a single weld and that of two fully independent welds [11]

$$\bar{\lambda} = \sqrt{2\lambda^3/\mu}$$

where μ is the repair rate (1/MTTR) and λ is the failure rate of a single weld.

In the Tables VII-X the event FWF (First Wall Failure) encloses all the first wall related events.

In the BOT design the estimated value for the failure rate associated with the blow up of a diffusion weld was evaluated taking into account the conclusions from [12]. In the reference is

Table VII - Availability evaluations for the WCD concept

		Evaluations for the WCD blanket		
MTTR	2160	R. rate	4.63x10^{-4}	
Event	**Rel. Indicator**	**Unitary f.r.**	**Global f.r.**	**Remarks**
FWF			4.4x10^{-5}	FW failure rate
CTF	254400	1.0x10^{-12}	2.5x10^{-7}	
BFA	12720	1.0x10^{-11}	1.3x10^{-7}	elbows
	12720	1.0x10^{-09}	1.3x10^{-5}	girth buttwelds
BPF	960	2.1x10^{-12}	2.0x10^{-9}	
MAF	1920	2.1x10^{-12}	4.0x10^{-9}	
FCH	48	9.6x10^{-9}	4.6x10^{-7}	The unitary failure rates and
FLH	48	1.5x10^{-7}	7.2x10^{-6}	values have been evaluated
OTH			5.1x10^{-6}	directly from [11]
Total Failure rate			**7.0x10^{-5}**	
Total Unavailability			**13.1%**	

Table VIII - Reliability evaluations for the DC concept

		Evaluations for the DC blanket		
MTTR	2160	R. rate	4.63x10^{-4}	
Event	**Rel. Indicator**	**Unitary f.r.**	**Global f.r.**	**Remarks**
FWF			4.5x10^{-5}	FW failure rate
DWD	2074	6.6x10^{-11}	1.4x10^{-7}	frl
	858	6.6x10^{-11}	5.6x10^{-8}	
FCD	12672	1.0x10^{-10}	1.3x10^{-6}	
	6336	1.0x10^{-10}	6.3x10^{-7}	
FLD	2909	1.0x10^{-10}		Tubes
	2576	1.0x10^{-9}		Long. W
	1152	5.0x10^{-9}		Bends (90°)
			8.6x10^{-6}	Total
LDD	4800	1.0x10^{-9}		Long. welds
	1817	1.0x10^{-9}		EB welds
Total Failure rate			**5.6x10^{-5}**	
Total Unavailability			**10.7%**	

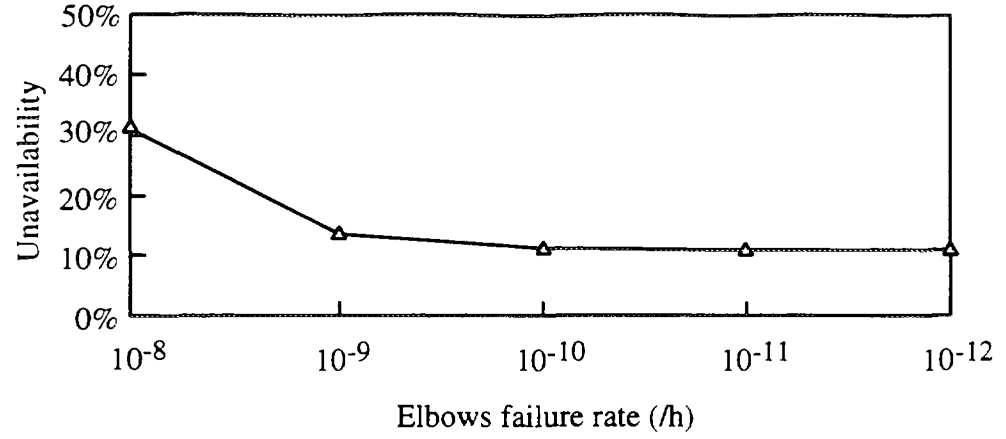


Fig. 9 - Unavailability of the WCD blanket vs failure rate of double walled elbows and tubes

Table IX - Reliability evaluations for the BIT concept

			Evaluations for the BIT blanket		
MTTR	2160	R. rate	$4.63x10^{-4}$		
Event	**Rel. Indicator**	**Unitary f.r.**	**Global f.r.**	**Remarks**	
FWF			$4.5x10^{-5}$	FW failure rate	
PRF	105000	$1.0x10^{-10}$		Tubes	$1.1x10^{-5}$
	21000	$1.0x10^{-9}$		Girth B. welds	$2.1x10^{-5}$
			$4.0x10^{-6}$	Total (1)	
PVR	60000	$1.0x10^{-10}$		Tubes (seamless)	$6.0x10^{-6}$
	12799	$1.0x10^{-9}$		L. Welds	$1.3x10^{-5}$
			$1.9x10^{-5}$	Total	
PVUO	2909	$1.0x10^{-10}$		Tubes	$2.9x10^{-7}$
	1251	$1.0x10^{-9}$		L. Welds	$1.3x10^{-6}$
	480	$2.5x10^{-9}$		Bends	$1.2x10^{-6}$
			$2.7x10^{-6}$	Total	
IOMO	1267	$1.0x10^{-10}$		Tubes	$1.3x10^{-7}$
	640	$1.0x10^{-9}$		L. Welds	$6.4x10^{-7}$
	3840	$1.0x10^{-10}$		Double welds	$3.8x10^{-7}$
	192	$2.5x10^{-9}$		Bends (45°)	$4.8x10^{-7}$
	192	$5.0x10^{-9}$		Bends (90°)	$9.6x10^{-7}$
			$2.6x10^{-6}$	Total	
PVUI	32	$5.7x10^{-8}$	$1.8x10^{-6}$	Values obtained directly from the corresponding	
IOMI	32	$5.4x10^{-8}$	$1.7x10^{-6}$	values for the outboard blanket	
Total Failure rate			**$7.7x10^{-5}$**		
Total Unavailability			**14.2%**		

NOTE: (1) As 4 rod failures are tolerated, the evaluation is carried as in [14]

Table X - Reliability evaluations for the BOT concept

Evaluations for the BOT blanket

MTTR 2160 R. rate 4.63×10^{-4}

Event	**Rel. Indicator**	**Unitary f.r.**	**Global f.r.**	**Remarks**	
FWF			4.5×10^{-5}	FW failure rate	
FCH	39424	1.0×10^{-10}	3.9×10^{-6}		
FLHO	51	1.0×10^{-10}		Tubes	5.1×10^{-9}
	6	5.0×10^{-9}		Bends (90°)	3.0×10^{-8}
	6	1.0×10^{-8}		Elbows (180°)	6.0×10^{-8}
	31	1.0×10^{-9}		Length of welds	3.1×10^{-8}
	48	1.3×10^{-7}	6.0×10^{-6}	Total	
FIHO	97	1.0×10^{-11}		Tubes	9.7×10^{-10}
	0	5.0×10^{-9}		Bends (90°)	
	48	9.7×10^{-10}	4.6×10^{-8}	Total	
FLHI	19	1.0×10^{-10}		Tubes	1.9×10^{-9}
	16	5.0×10^{-9}		Bends (90°)	8.0×10^{-8}
	16	1.0×10^{-9}		Length of welds	1.6×10^{-8}
	32	$9.8,\times10^{-8}$	3.1×10^{-6}	Total	
FIHI	59	1.0×10^{-11}		Tubes	5.9×10^{-10}
	0	5.0×10^{-9}		Bends (90°)	
	0	1.0×10^{-9}		Length of welds	
	32	2.6×10^{-7}	5.9×10^{-10}	Total	
	192000	1.0×10^{-12}	1.9×10^{-7}	DW blow up	
	153600	1.0×10^{-10}	1.5×10^{-5}	Girth failure (guillottine)	
	19200	5.0×10^{-10}	9.6×10^{-6}	Bend failure (guillottine)	
Total Failure rate			$\mathbf{8.3\times10^{-5}}$		
Total Unavailability			**15.3%**		

Table XI - Summary of the reliability and availability evaluations for the four blanket concepts

Concept	**WCD**	**DC**	**BIT**	**BOT**
Reliability (breeding zone excluding FW) (h^{-1})	2.6×10^{-5}	1.1×10^{-5}	3.2×10^{-5}	3.8×10^{-5}
Reliability (whole blanket)(h^{-1})	7.0×10^{-5}	5.6×10^{-5}	7.7×10^{-5}	8.3×10^{-5}
Availability (%)	86.9	89.3	85.8	84.7

shown that a single failure in a diffusion weld in cooling plates of the BOT design does not lead to a loss of cooling of the plate itself. So at least a double failure must be hypothesized in order to have an undesired event (system shutdown).

7. EVALUATIONS BASED ON NUCLEAR DATA

The preceding estimates are related to the behaviour of a full scale mock-up in conventional environment, not to the operation of a true blanket in fusion environment. In order to take into account the differences in the environment among the evaluated reliability and the correct one, the need arises of evaluating other issues related to the behaviour under fusion relevant operating conditions that cannot be quantified with the same accuracy as those considered for the "conventional" blanket reliability. Therefore these issues have been defined as "qualitative" ones by the WG 6b.

The main nuclear data applicable to fusion are those obtained from the **F**ast **B**reeder **R**eactors (FBR), and the only component sustaining a neutron fluence comparable to that of a fusion blanket is the cladding of the fuel elements (pins). From the operating experience gained on these nuclear components, it results that the failure rate is roughly one pin per reactor per year [13] neglecting the fabrication related failures. The failure rates of FBR pins are evaluated [13] to be about $2x10^{-5}$/pin due to fabrication defects and about $1.5x10^{-4}$/pin after neutron irradiation. Considering the PHENIX FBR data on pin failures, pin number and irradiation time, the global λ can be evaluated as $1.5x10^{-9}$/h/pin. To have a comparison between the behaviour of a pin (PHENIX) and the data used for the evaluation, the pin has been modeled as a pipe (seamless) 1 m long with two girth butt-welds. Using the data from Table II, the calculated λ would be $2.1x10^{-9}$/h/pin, showing a very good agreement between the PHENIX nuclear data and the conventional ones.

Because of the geometry, these data can be directly applied to the BIT concept only, since this is the only one having a tube based geometry [3]. The structural resistance of the other three EU concepts rely on longitudinal welds stiffening the blanket box [1,2,4]. As in nuclear fission plants the structural welds are strictly avoided in the high fluence areas, no data from nuclear fission plants are available for structures similar to those used in the other concepts (BOT, DC, WCD). This means that the availability values, obtained for non nuclear environment (Table II), are much more representative of the real performance of the BIT blanket, under DEMO operation, than for the BOT, DC and WCD blankets.

8. QUALITATIVE ISSUES EVALUATION

The calculations for the contribution of the coatings to the reliability have been carried out in [9], and the results are reported in Table XII and Fig. 10. In order to get a picture of the relevance of the coatings in the whole behaviour of the blanket, these results have been combined with

Table XII - Coating failure contribution to the reactor overall failure rate (h^{-1}) as a function of the coating specific failure rate (m^{-2} h^{-1}) (from [9])

	Coating failure rate (/m^2/h)				
Concept	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}
WCD	1.91×10^{-2}	2.22×10^{-4}	2.26×10^{-6}	2.26×10^{-8}	2.26×10^{-10}
DC	1.17×10^{-1}	9.33×10^{-3}	2.78×10^{-4}	3.49×10^{-6}	3.59×10^{-8}
BIT	1.11×10^{-2}	1.18×10^{-4}	1.19×10^{-6}	1.19×10^{-8}	1.19×10^{-10}
BOT	7.57×10^{-3}	8.22×10^{-5}	8.30×10^{-7}	8.30×10^{-9}	8.30×10^{-11}

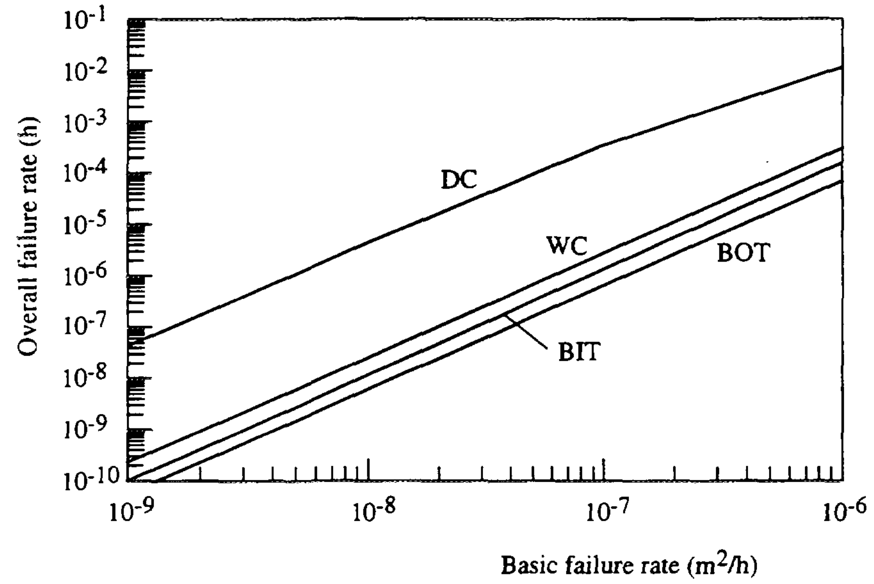


Fig. 10 - Coating failure rates as a function of the coating basic failure rate (from [9])

those already obtained to get the global failure rate and the global unavailability of the blankets, including the coatings. The results are reported in Figs. 11 and 12. It is interesting to evaluate how much of the total number of failures is related to the coatings. In Table XIII the coating failure rates are reported that lead to a given percentage of failures related to the coatings in comparison with the global number of failures.

In order to evaluate the risk of material degradation related to the presence of welds, different indicators can be envisaged, the most significative being:

- total length of welds in the blanket
- length of welds in the high fluence zone
- percentage of welds in the high fluence zone.

The high fluence zone is defined as the front zone of the blanket where the neutron flux is greater than its overall blanket volume averaged value. These three indicators are reported for the four blanket concepts in Table XIV. In Fig. 13 the influence of the various items on the reliability of solid breeder blankets in the high fluence zone is reported.

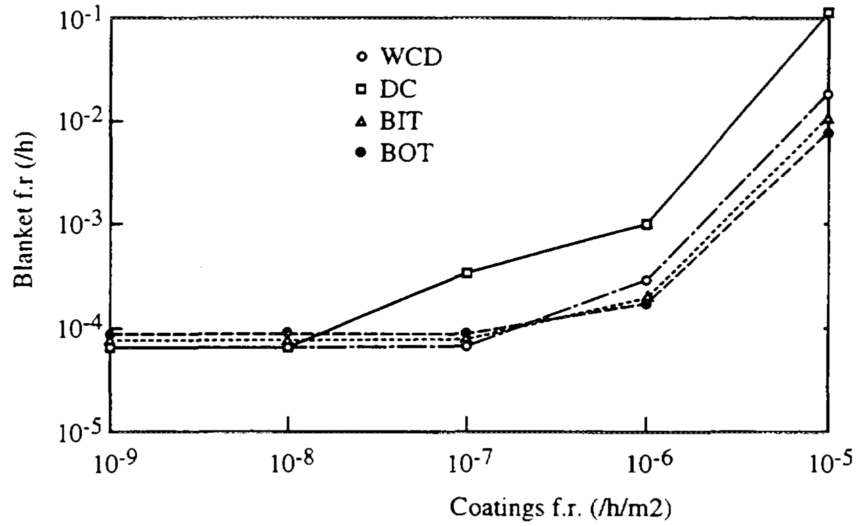


Fig. 11 - Blanket Failure Rate including Coatings Contribution

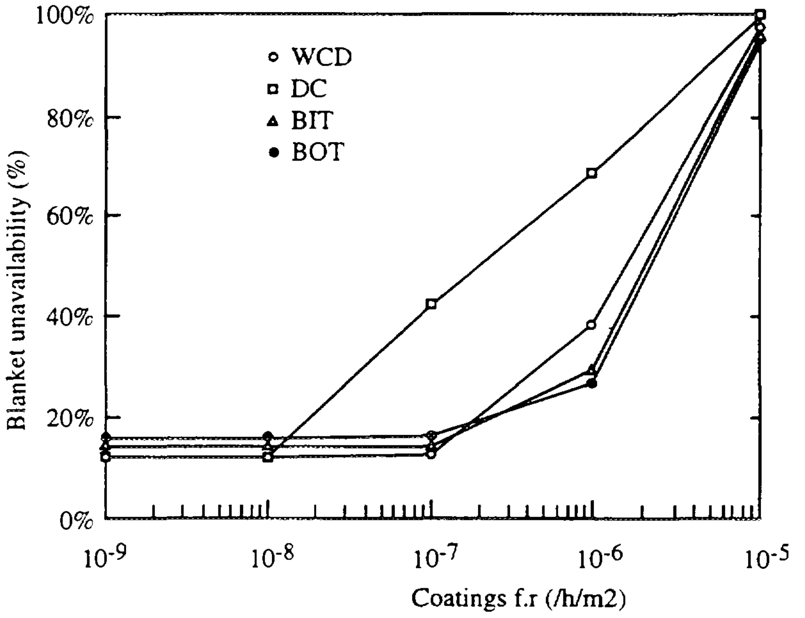


Fig. 12 - Blanket Unavailability (MTTR 2160 h) including Coatings

Table XIII - Failure rates of the coating ($m^{-2}h^{-1}$) leading to a given percentage of failures related to the coatings themselves (Out R. = Out of the range of the parametric analysis)

Coating failure percentage				
% of failure due to the coatings	**WCD**	**DC**	**BIT**	**BOT**
50.0	5.38×10^{-7}	4.51×10^{-8}	8.00×10^{-7}	1.03×10^{-6}
90.0	1.75×10^{-6}	3.66×10^{-7}	2.43×10^{-6}	3.16×10^{-6}
95.0	2.69×10^{-6}	1.11×10^{-6}	3.55×10^{-6}	4.62×10^{-6}
99.0	6.99×10^{-6}	2.44×10^{-6}	8.19×10^{-6}	Out R.
99.9	Out R.	7.34×10^{-6}	Out R.	Out R.

Table XIV - Welds prominence in the four blanket concepts

Welds in the four blanket concepts				
	WCD	**DC**	**BIT**	**BOT**
Total length of welds (km)	37	43	6	98
Length of welds in the high fluence zone (km)	13	11	0	47
Percentage of welds in the high fluence zone	36%	25%	0%	48%

NOTE

- The length of welds is for the whole blanket
- In the BOT length of welds the diffusion welds have not been included (180 km)

The high fluence zone has been considered as the front volume of the blanket (9 m vertical height, 0.25 radial depth), where the neutron flux is above its averaged value over the whole blanket volume

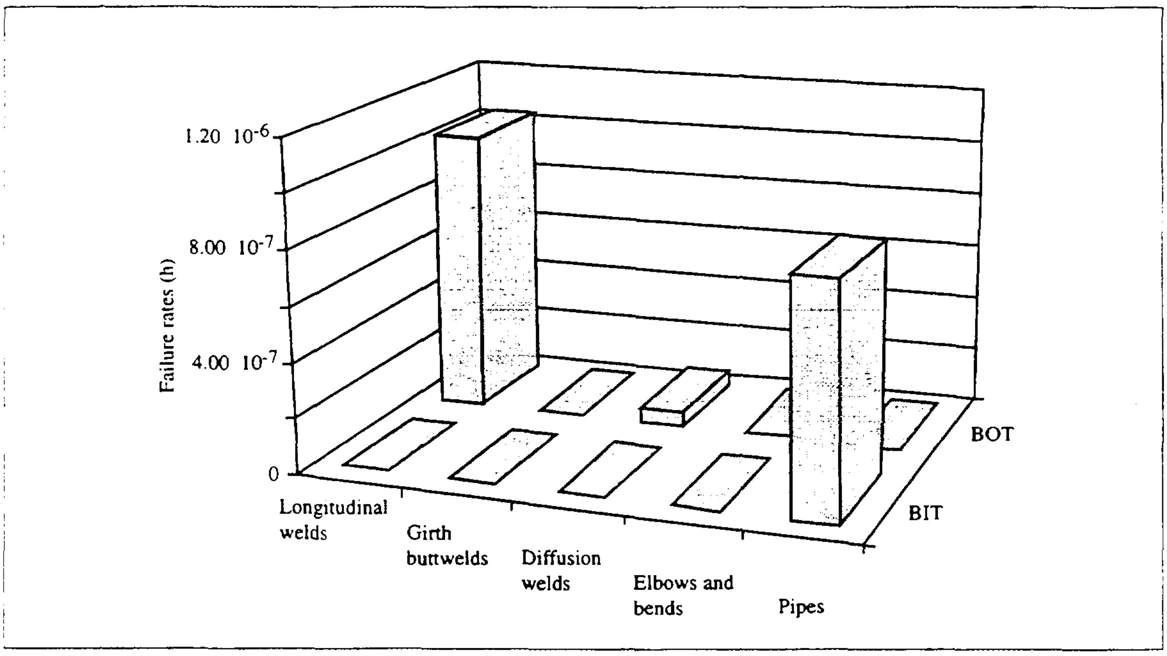


Fig. 13 - Influence of items in the high fluence zone on the reliability for solid breeder blankets. The influence of the first wall is not reported

9. CONCLUSIONS

The analysis carried in the present report shows that values for reliability and availability can be obtained for the four European blanket concepts proposed for DEMO. However these values are liable to a basic uncertainty, because they are not evaluated from data obtained in a fusion reactor environment. The importance of this uncertainty is not the same for the four concepts, as both the evaluation of available nuclear data and the evaluation of "qualitative" indicators lead to suppose the uncertainty lower for the BIT than for the other concepts (DC, WCD, BOT).

This conclusion relays on these two facts:

- the data obtained from FBR's, which are in good agreement with those used in the present analysis, can be extrapolated only to tube-like geometry, *i.e.* that of the BIT.
- the qualitative evaluations carried out on coatings and on welds that are located in the high fluence zone show a fair behaviour in the BIT, while they indicate a marked degradation of reliability factors of the other concepts.

REFERENCES

[1] L. Giancarli et al., 'Water Cooled Pb-17Li DEMO Blanket Line EU reference conceptual Design and Performance Presentation" *Report DMT 94/538 (SERMA/LCA/1678) (1994)*

[2] S. Malang, K. Schleisiek et al., "Dual Coolant Blanket Concept" *Report KfK 5424 (1994)*

[3] M. Eid, M. Ferrari et al., "Helium Cooled Ceramic Breeder In Tube Blanket Line" *Report DMT 94/576 SERMA 1682/RI-RCT 94/2 (1994)*

[4] C. Alvani et al., "Effect of purge gas oxidizing potential on tritium release from Li-ceramics and on its permeation through 316L SS clads under irradiation (TRINE experiment)" *Fusion Reactor Materials (25-29/9/95 - Obninsk)*

[5] M. Dalle Donne et al., "European DEMO BOT Solid Breeder Blanket" *Report KfK 5429 (1994)*

[6] M. Eid, W. Kramer, C. Nardi, "WG 6b - Reliability/Availability" *(Feb. 93)*

[7] L.C. Cadwallader, S.J. Piet, "1989 Failure Rate Screening Data for Fusion Reliability and Risk Analysis" *EGG-FSP-8709-INEL (Sep. 1989)*

[8] R. Bunde, S. Fabritsiev, V. Rybin, "Reliability of Welds and Brazed Joints in Blankets and its Influence on Availability" *Fusion Engineering and Design 16 (1991) 59-72*

[9] M. Eid, "A Comparative Study Availability/Reliability of the EU Blanket Conceptual Design Lines" *Report DMT 95/271 - SERMA/LCA/1756 (July 1995)*

[10] M. Eid et al., "On the use of double-walled tubes as a means to improve safety and availability of the EU-DEMO Water Cooled Pb-17Li Blanket" *18th Symposium on Fusion Technology (22-26 August 1994 - Karlsruhe)*

[11] Technical report by H. Schnauder, "Evaluation results of Blanket Selection Exercise: the availability of different blanket concepts" *(Jul. 1995)*

[12] P. Norajitra, "BOT Helium Cooled Solid Breeder Blanket for DEMO - Local Stress Analysis of the Cooling Plates" *FZK- Internal Beriocht 31.06.20/07A (July 1995)*

[13] P. Cecchi, S. Tirini, "Experimental Data on Cladding Failure Rate in FBR: Extrapolation to Fusion Reactors" *ENEA Report CT.WCH.00011 (1990)*

[14] M. Eid" "Availability and Reliability Consideration for the He cooled ceramic BIT blanket concept" *Report DMT 94/635 - SERMA/LCA/1687 (Rev. 1 - Sept. 95)*

Edito dall' ENEA
Funzione Centrale Relazioni
Lungotevere Grande Ammiraglio Thaon di Revel, 76 - 00196 Roma
Stampa: RES-Centro Stampa Tecnografico - C. R. Frascati

Finito di stampare nel mese di settembre 1996