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Abstract

The European Union has been engaged since 1989 in a programme to develop tritium breeding blankets for application in a fusion power reactor. There are four blanket concepts under development. Two of them use lithium ceramics, the other two concepts employ an eutectic lead-lithium alloy (Pb-17Li) as breeder material. The two most promising concepts were to select in 1995 for further development.

In order to prepare the selection, a Blanket Concept Selection Exercise (BCSE) has been initiated by the participating associations under the auspices of the European Commission. This BCSE has been performed in 14 working groups which, in a comparative evaluation of the four blanket concepts, addressed specific fields. The working group safety addressed the safety implications.

This report describes the methodology adopted, the safety issues identified, their comparative evaluation for the four concepts, and the results and conclusions of the working group to be entered into the overall evaluation. There, the results from all 14 working groups have been combined to yield a final ranking as a basis for the selection. In summary, the safety assessment showed that the four European blanket concepts can be considered as equivalent in terms of the safety rating adopted, each concept, however, rendering safety concerns of different quality in different areas which are substantiated in this report.

Ein Sicherheitsvergleich der europäischen Blanketkonzepte für einen DEMO Fusionsreaktor

Kurzfassung

Im Fusionsprogramm der Europäischen Union werden seit 1989 tritiumbrütende Blankets für den Einsatz in Fusionsreaktoren entwickelt. Bislang befanden sich vier Varianten in der näheren Untersuchung, nämlich je zwei Varianten mit festem keramischem Brutstoff und zwei mit flüssigem Brutstoff, der eutektischen Blei-Lithium-Verbindung Pb-17Li. Aus den vier Konzepten wurden im Jahre 1995 zwei Varianten für die weitere Entwicklung ausgewählt.

Die Auswahl wurde in einer Studie vorbereitet, dem sogenannten Blanket-Auswahlverfahren (englisch: Blanket Concept Selection Exercise, BCSE), an der die in der Blanketentwicklung beteiligten Assoziationen und Industriegruppen sowie die Europäische Kommission mitwirkten. Die BCSE wurde in vierzehn Arbeitsgruppen durchgeführt, in denen die vier Konzepte nach vorgegebenen Themen und Kriterien bewertet wurden. Die Arbeitsgruppe Sicherheit behandelte die Sicherheitsaspekte.

In diesem Bericht werden die angewandte Methode, die identifizierten Sicherheits-Schwerpunkte, der Vergleich der vier Blanketkonzepte bezüglich dieser Schwerpunkte, sowie die Ergebnisse und Schlußfolgerungen der Arbeitsgruppe Sicherheit beschrieben. Die Ergebnisse gingen in die Endbewertung ein, in der die Resultate aller vierzehn Arbeitsgruppen zu einer gesamten Rangfolge zusammengefaßt wurden. In der Summe ergab die sicherheitstechnische Bewertung der vier europäischen Blanketkonzepte keine erheblichen Unterschiede. Die Konzepte zeigen jedoch unterschiedliche Qualität in der Einzelbewertung der Sicherheitsaspekte, die im Bericht herausgestellt werden.

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1. Introduction

The European Union (EU) has been engaged since 1989 in a programme to develop tritium breeding blankets for application in a fusion power reactor. There are four concepts under development [1], [2], [3], [4]. Two of these blanket concepts use lithium ceramics as breeder material, helium as coolant, and beryllium as neutron multiplier. The other two concepts employ an eutectic lead-lithium alloy (Pb-17Li) as breeder material, cooled either by circulating the liquid breeder material itself to external heat exchangers or by an extra water system.

A common basis for the DEMO blankets has been specified by the Test blanket Advisory Group (TAG) [5] with the aim to select the two most promising concepts in 1995 for further development. In order to prepare the selection, a Blanket Concept Selection Exercise (BCSE) has been initiated by the participating associations under the auspices of the European Commission. This BCSE has been performed in 14 working groups which, in a comparative evaluation of the four blanket concepts, addressed specific fields, i.e., design, neutronics, tritium, loops, maintenance, safety, reliability, MHD, coatings, breeders, beryllium, development risk, compatibility with ITER, and costs.

The working group 6a (WG6a) assessed the safety implications and this report documents the methodology adopted and the results of WG6a to be entered into the overall evaluation. There, the results from all 14 working groups were combined by the Blanket Co-ordination Group (BCG) to yield a final ranking of the concepts as a basis for the selection.

In this report a brief characterisation of the four blanket concepts under consideration is given in Chapter 2 with background information collected in Appendix B. The applied methodology in the safety assessment, which was set by the BCG to be used by any working group, is outlined in Chapter 3. According to these rules safety issues and their relative importance were identified (Chapter 4 and Appendix A), against which the four concepts could be evaluated (Chapter 5). The results and future developments (areas requiring further R&D) are reported in Chapter 6 with conclusions summarised in Chapter 7.

2. Brief Description of Blanket Concepts

The four European blanket concepts under consideration are named throughout this report as follows.

Blanket Concept Acronyms

BIT	Breeder inside tube (helium cooled solid breeder blanket)
BOT	Breeder outside tube (helium cooled solid breeder blanket)
DC	Dual coolant (self-cooled liquid metal breeder blanket with helium cooled first wall)
WC	Water cooled (water cooled liquid breeder blanket)

The concepts are characterised by the type of materials employed as breeder, coolant, and multiplier as indicated in Table 1 on page 4 and their principal design is summarised below. Specific background information relevant to evaluating the different issues is also provided in the issues evaluation tables in chapter 5 on page 21 and in the data sheets in Appendix B on page 65. Please refer to the original reports [1], [2], [3], and [4] for further details, in particular for the rationale of the different choices made by the concept designers.

BIT The **breeder inside tube** concept is characterised by longitudinal (poloidal) modules arranged in a hexagonal array inside the blanket box (Figure 1 on page 79 and Figure 2 on page 80). The modules in turn consist of several staggered tubes and rods serving as coolant confinement (high-pressure helium), as coolant flow channels, and as breeder ($Li\mathrm{Al}O_2$ or, alternatively, Li_2ZrO_3 pellets) and multiplier (beryllium blocks) cladding. The first wall is cooled by a separate helium cooling system. The major safety concern is the large beryllium inventory.

BOT In the **breeder outside tube** concept both the breeder (Li_4SiO_4) and multiplier (beryllium) materials are used in form of small pebbles, arranged in radial-toroidal layers, separated by cooling plates (Figure 3 on page 81 and Figure 4 on page 82). The coolant is high-pressure helium which is circulated in series, at first through the channels of the first wall structure and subsequently through the cooling plates. The major safety concern is, as with BIT, the large beryllium inventory.

DC In the **dual coolant** concept the liquid metal breeder material (Pb-17Li) is cooling and tritium transport system at the same time. For this purpose it is circulated at a sufficient flow rate to carry away the bulk of the generated heat and to extract the tritium in special triple fluid (Pb-17Li/NaK/water) steam generators. For reasons of MHD effects the heavily loaded first wall is cooled by an extra high-pressure helium cooling system. The use of two coolants gave the concept the name. Safety concerns are the chemical activity of the liquid metals. On the other hand, the design (Figure 5 on page 83 and Figure 6 on page 84) is comparably simple.

WC The configuration of the **water cooled** liquid metal breeder blanket concept (Figure 7 on page 85 and Figure 8 on page 86) resembles in the midplane cross section the layout of the DC concept. It circumvents the MHD problems by introducing an array of longitudinal (poloidal) coolant tubes in which high-pressure water removes the bulk of the generated heat. Likewise, the first wall is cooled by a separate water cooling system. The liquid metal is circulated at very low flow rates, sufficient for tritium extraction in external units. Safety concerns are associated with the combination of water and liquid metal in the same component.

Table 1. Materials used in the four EU DEMO blanket concepts

Breeder	Coolant		Multiplier	Type	Association
	for Breeder	for First Wall			
$LiAlO_2$ (Li_2ZrO_3)	helium	helium	Be blocks	BIT	CEA/ ENEA
Li_4SiO_4	helium	helium	Be pebbles	BOT	FZK
Pb-17Li	Pb-17Li	helium	Pb-17Li	DC	FZK
Pb-17Li	water	water	Pb-17Li	WC	CEA

3. Safety Assessment Methodology

The procedure for the concept evaluation methodology was established by the Blanket Co-ordination Group, derived from a number of proposals discussed in the different working groups. This scheme was meant to be used for the overall evaluation but it was recommended to also be used by the individual working groups. The safety group (WG6a) employed the proposed scheme (with minor modifications as indicated), which consists of the following six steps in the safety assessment:

STEP 1

In the first step all safety issues that are relevant to the assessment of the four blanket concepts have been identified (Table 4 on page 19). For details see Chapter 4 on page 9.

STEP 2

In the second step, the scale has been defined to be used in the evaluation of the concepts for each issue. The scale running from -2 to 0 has been selected with the rating interpretation as illustrated in the right column of Table 2.

Table 2. Proposed and chosen rating scale and interpretation for the evaluation of each concept

Rating Scale	Proposed rating interpretation		Chosen interpretation in WG6a
	1. Option	2. Option	
+2	much better than average	no problems or very well suited	not used
+1	better than average	well suited	not used
0	average	not relevant or not applicable	no problems
-0.5	-	-	minor problems
-1	worse than average	some problems	some problems
-1.5	-	-	substantial problems
-2	much worse than average	considerable problems or not suitable	considerable problems or not suitable

Note: The chosen scale and interpretation differ from the proposal made by the BCG which uses the range from -2 to +2 and, hence, includes positive interpretations. It was felt that the safety issues, by definition, cause more or less severe concerns in all of the concepts and should, therefore, not be rated positive. Furthermore, the chosen range from -2 to 0 has the advantage over the symmetric range from -2 to +2 in that positive and negative ratings of individual issues don't cancel out. Thus, the absolute values of the sum of the weighted ratings pertaining to each concept (steps 4 and 6) become larger, thereby avoiding a scatter of these sums (the overall safety ratings) around the null line. The symmetric range from -2 to +2, on the other hand, would have suggested a clear (but yet artificial) distinction between good and bad.

STEP 3

The third step was the definition of the scale to be used for the weighting of each issue. The weighting factors on a scale from 0 to 10 with the following interpretation were used, in agreement with the BCG proposal.

Table 3. Safety issues weighting factor interpretation

Weighting Factor	Interpretation
10	extremely important
8	very important
6	above average importance
5	average importance
4	below average importance
2	of minor importance
0	no importance

STEP 4

In the fourth step the weighting factors, F_i, were determined to be applied to each of the issues identified in step 1 (for details see Chapter 4 on page 9).

STEP 5

The fifth step was the evaluation of the concepts against each of the issues, using the rating scale established in step 2. This is described in detail in Chapter 5 on page 21.

STEP 6

This step involves the arithmetic procedure to arrive at an overall safety rating (OSR) for each concept (j). The following equation is used:

$$OSR_j = \sum_i R_{i,j} F_i \qquad (1)$$

where

OSR_j = overall safety rating for concept j (j = 1, 2, 3, 4)
$R_{i,j}$ = rating of concept j against issue i according to step 5
F_i = weighting factor of issue i according to step 4 (i = 1, 2, ..., 23)

The overall safety ratings, OSR_j are, by definition, negative values. They can be normalised to give positive values on a scale from 0 to +1 using equation 2.

$$osr_j = 1 - \frac{OSR_j}{(-2)\sum_i F_i} \qquad (2)$$

where

osr_j = normalised overall safety rating for concept j (j = 1, 2, 3, 4)
$(-2)\sum_i F_i$ = theoretically worst rating the concept could obtain on the chosen scale from -2 to 0.

4. Safety Issues Identification and Weighting Factors

The list of safety issues and the application of weighting factors presented in this Chapter (Table 4 on page 19) have been arrived at by consensus in the first meeting of working group 6a with participation of the three working group members (authors of this report) and specialists from other working groups [6]. 23 issues were finally formulated with the weighting factors of between 4 and 10 (and an average of 6.6) as described in 4.1 and 4.2 below.

4.1 Identification of safety issues

The governing safety objective is to protect humans and environment from hazards arising primarily from radioactive material. This means in practical terms: controlling the power (e.g., overpower, disruptions), cooling in-vessel components (afterheat removal from structures, breeder and multiplier materials), confining the radioactive material (tritium and other activation products in normal and abnormal situations), and minimising radioactive waste (especially high-level and long-term waste).

In order to achieve this goal, a series of physical barriers and several strategic levels of protection will have to be implemented in a fusion plant. Generally three physical barriers are envisaged: (1) the vacuum vessel or coolant boundary confining most of the radioactivity in first wall surface materials (including sputtered particles and dust) and fluids, (2) the secondary confinement enveloping all components that establish the first barrier, and (3) the outer building as third barrier providing controlled atmosphere in rooms located between the second and third boundary. (4) In addition, for the radioactivity contained in solid materials, like in in-vessel component structures, breeding materials and multiplier materials (if solid), the matrix of these structures can be viewed as a fourth barrier (or innermost barrier if seen from the origin) in analogy to fission reactors, where the fuel matrix is often regarded as first barrier.

Concerning the blanket safety, clearly only the aspects associated with the first barrier (vacuum vessel or coolant boundary) and the fourth barrier (matrix of solid blanket materials) can be regarded at present, whereas important safety aspects related to the second and third barriers (protecting personnel in normal operation and maintenance, managing internal accidents, mobilisation and transport of radioactivity in confinement rooms, leakage through confinement barriers, release to the environment, hazards to the public) are out of the scope of this work. Also excluded are, by the terms of reference, all aspects associated with potential chemical reactions of blanket media with the first wall protection material. Thus, DEMO blanket safety, in the frame of the blanket concept selection exercise, was essentially restricted to assessing the following topics:

- type and amount of radioactive inventory in components of the blanket system including the cooling systems
- energy sources which can trigger the dispersion of radioactive material
- tolerance of the blanket system to abnormal conditions in terms of reaching design limits and releasing radionuclides
- type and amount of radioactive waste.

The above mentioned qualities had to be cast into a set of assessable safety issues, against which the four DEMO blanket concepts could be evaluated on a comparative basis. As a goal, they should be generic, decisive, and comprehensive to the largest extent possible. In an attempt to find the most appropriate way to define and structure the set of safety issues, a scheme employed by Fiorini [7] was adopted in a modified form which is outlined in Appendix A. It is based on the defence-in-depth strategy according to the International Nuclear Safety Advisory Group of the IAEA [8], rendering a total of approximately 135 safety objectives which are listed in Table 10 on page 60. These objectives are structured at five levels of defence, i.e.,

1. Prevention (by conservative design, quality assurance, safety culture)
2. Control (of abnormal operation and detection of failures)
3. Protection (by extra safety systems and protection systems)
4. Accident management (by means of confinement protection)
5. Consequence mitigation (through off-site emergency response).

In establishing the safety issues the list of objectives has been used as a checking list, asking which of the objectives constitutes a safety issue and should be treated in working group 6a. It was found that many of the objectives listed in Table 10 (about 20) had to be assessed by other working groups, and that the majority of the remaining issues needs to be addressed in a later stage (those labelled ″beyond BCSE″), as the plant design advances, or is not specific to the blanket. For example, most of the objectives listed in block 1.2 of Table 10 (minimise the frequency for abnormal situations) are related to initiators resulting from non-blanket components, the behaviour of which is not known at present. Hence, a number of 23 issues has been selected for treatment by the safety group. These 23 issues are listed in Table 4 on page 19 in the sequence of their appearance in the original list, and are described in the next section.

Please note that in some cases an overlapping among safety issues, or a duplication with issues from other working groups, could not be avoided. This has been accounted for in the weighting factor by engineering judgement.

4.2 Description of safety issues and weighting factors

A description of the safety issues from Table 4 on page 19 is given below, in addition to their role in the defence-in-depth strategy, and the rationale for assigning a weighting factor to measure the issues relative importance in the context of the safety assessment. The weighting factor ranges in principle from 0 (no importance) to 10 (extremely important) as defined in Chapter 3 on page 5, step 3. Most of the issues originate from the highest level of the defence-in-depth concept (prevention) deserving a high weighting factor. In a number of cases, however, the weighting factor was substantially reduced due to the fact that the same concern was assumed to be addressed also by other working groups or because the information was felt to be too immature as to yield a clear judgement. Prominent examples for the first category are issues No. 3, 9, 16, 18, 21, and 22 and, for the second group, the issues No. 10, 11, 17. The following rationale applies to the 23 issues selected for evaluation in working group 6a, safety:

Issue 1: Minimise the fluids internal energy (system pressure)

The stored energy is the driving source for mobilising radioactivity within the confinement, associated with work potential, giving rise to severe accident scenarios, including confinement damage or bypass. Minimisation of the stored energy is, therefore, a principal design objective on the prevention level (level 1) in regard to extreme (hypothetical) accidents including those triggered by impacts generated external to the plant. Thus, the issue is judged extremely important with a weighting factor of 10.

Issue 2: Minimise the amount of chemically reactive materials

Fires can cause common mode failures jeopardising the plant control in case of leaks of combustible fluids, destroying cables, instrumentation equipment, isolation material, etc. Potential fires call for cost effective protection provisions, especially if radioactive material is involved (requiring, for instance, the dispersion of inventories into small subsystems, providing containment barriers with liners and cooling capabilities, ventilation and filter systems, etc.). Of particular concern are radioactive fluids rendering violent chemical reactions with water, air, and concrete in case of large LOCAs. Also solids can react violently or in a self-sustaining manner in abnormal situations. Avoidance or minimisation of chemically reactive materials is, therefore, a first level prevention type objective and is ranked extremely important (weighting factor of 10), even though the consequences can at present only be qualitatively assessed.

Issue 3: Minimise the frequency of occurrence of LOCA due to extreme disruptions

Plasma disruptions are phenomena which are not sufficiently understood as to be ruled out for a DEMO plant and, hence, their potential consequences will be classified as design basis accident (DBA). In the worst case a heavy disruption may lead to (and is perhaps the major initiating event for) a multi-segment blanket damage with subsequent large LOCA, implying all kinds of consequence analyses in the licensing process. Since the magnitude of forces and their impact location are highly uncertain, adequate mechanical design in terms of strength (embrittlement) and rigidity of blanket segment supports and pipe connections is hard to guaranty at the present state of knowledge. This situation is expected to be improved at the time a DEMO plant will be built. In general, the issue would nowadays be ranked as extremely important. However, this issue will also be addressed by WG1 (design) with view to capital investment. Furthermore, the consequences of LOCAs are treated in separate issues (e.g., No. 5 - 9). Therefore it is weighted by a factor of only 5, i.e., average importance.

Issue 4: Minimise the mechanical energy release upon flushing of primary coolant

In order to minimise the inherent potential consequences for the primary initiating event (PIE), the mechanical energy released in case of a pipe rupture should be kept small. This aids in simplifying the design of the blanket support structure, of the vacuum vessel, cryostat, expansion volumes, and of the second confinement barrier in terms of maximum loads and pressure. In principle, the mechanical energy released upon flushing can be kept low for single pipe ruptures by choosing small circuits. This, however, violates the design and cost goal of elaborating a simplified heat removal systems architecture (point 1.5 in Table 10 on page 60). In general the issue is extremely important. Due to the fact that the heat removal system architectures for the DEMO blanket concepts are preliminary, and less concept immanent, a weighting factor of 6 is considered adequate (also in conjunction with issue No. 23).

Issue 5: Minimise the activation products in solid blanket materials

The general safety objectives are to minimise the inherent potential consequences for a PIE (point 1.4 in Table 10 on page 60) and to minimise the radioactive waste (point 1.7 in Table 10). Also afterheat production is one of the major safety concerns. Substantial mobilisation of activation products from solids (ignoring here per definition the first wall protection material and related dust problems) can only occur in conjunction with severe accident scenarios, mainly in beyond design basis accidents (BDBAs). On the other hand, minimising the amount and level of long-term waste is another key requirement for fusion technology (see issue No. 16). Overall, the issue is ranked as very important with a weighting factor of 8.

Remark: It could have been ranked even higher, say 10, but given the ferritic steel, MANET, as structural material for all the four DEMO blanket concepts, differences among concepts are small and the prospects for a low activation structural material for a DEMO are fair.

Issue 6: Minimise the activation products in fluid blanket materials

The mobilisation of activation products (tritium will be treated separately in issue No. 8) from liquids, particularly in conjunction with chemical reactions and aerosol formation (DBAs and BDBAs) after a leak is easy. Afterheat in fluids needs to be considered, but will generally play a minor role, since activation levels are low compared to structural materials. Likewise, the waste problem with fluids can be alleviated by implementing purification processes. Issues associated with personnel exposure are treated separately in issue No. 17. Overall, a weighting factor of 8 (very important) is applied.

Issue 7: Minimise the tritium inventory in solid blanket materials

Tritium build-up or implantation in the structural material (MANET) is moderate (see point 8 in Table 11 of Appendix B) and is not expected to pose a safety problem. The amount of tritium bred in the solid breeder material is very large but is supposed to come out readily and to be carried away by the purge gas. Yet, a substantial fraction will reside in the ceramics. An even larger amount of tritium will remain in the beryllium multiplier. Upon accidental temperature rises the tritium may be released, posing a potential hazard in case of severe blanket damage or rupture of the purge gas system. Thus, minimisation of the tritium inventory in solid blanket materials (and likewise in fluids, issue No. 8) reduces the inherent potential consequences for the PIE on the prevention level. The same weighting factor as for the fluids is applied, namely a factor of 6.

Issue 8: Minimise the tritium inventory in fluid blanket materials

Tritium is easily mobilised upon flushing so that 100 % release into the containment is postulated in most current safety assessments. Nevertheless, predictions of the biological hazards in case of accidental release to the environment indicate moderate impact as long as the amount of tritium released is of the order of 100 grams, which is the range of the total tritium inventory in the DEMO blanket fluids involved, when on-line extraction is applied. A number of further issues related to tritium inventory in fluids result in the field of operational safety and in tritium extraction and fuel management systems which are treated separately (see issues No. 17, 18, 21) and by WG3, tritium. Hence, in the context of consequences for a LOCA a weighting factor of 6 is chosen, that is, above average importance.

Issue 9: Minimise the consequences of events initiated by failure inside the steam generator

Medium size or large leaks in steam generator tubes can lead (depending on the parameters) to pressurisation of the circuits at the low pressure side, to material (including activation products) transport, to chemical reactions, and, in the case of the dual coolant concept, to degradation of the thermal contact between the primary and secondary side. In the worst case these events can result in classical DBAs like (a) in-vessel LOCAs, (b) ex-vessel LOCAs, (c) activation products release to the steam system, and (d) activation products and tritium mobilisation within the confinement. Events of type (a), (b), and (d) will be addressed in issue No. 23 so that here only the activation products release to the steam system (type c) has to be considered, suggesting an average importance level with a weighting factor of 5.

Issue 10: Design for natural convection of first wall primary coolant

An effective thermal convection capability limits temperature transients and eases the proof of afterheat removal in the case of a single pump failure or loss of power events. The effectiveness of the natural convection depends on the type of coolant, the characteristics of the loop, heat transport mechanisms within the blanket to adjacent (still cooled) regions, and on the elevation of the thermal centre of the heat sink (the steam generator) above that of the heat source (the first wall). The latter is an open design parameter. The lack of detailed analyses for the DEMO blankets calls for a qualitative judgement on the issue at a moderate importance level, weighting factor of 6, which has to be seen in conjunction with the issue No. 11.

Issue 11: Design for natural convection of the breeder/multiplier coolant

The rationale as stated in issue No. 10 for the first wall coolant applies, although the flow and heat characteristics are different. The same weighting factor of 6 is assumed.

Issue 12: Ensure adequate thermal inertia

High thermal inertia of the blanket and related cooling systems limits temperature transients and amplitudes in upset or faulted conditions and, thereby, contributes inherently to minimise potential consequences for the PIE and eases plant control by making the blanket system more forgiving (point 2.2 in Table 10). The thermal inertia is mainly dictated by the blanket concept (materials, masses) and cannot easily be altered by design once the concept is fixed. It can be expressed by, for instance, the adiabatic temperature rise of the isolated blanket alone (driven by afterheat) or by the temperature drift of the primary cooling systems in case of a complete loss of heat sink. Typical values for the adiabatic heat-up are 150 °*C* to

300 °C in the first day. The issue is closely related to No. 22 and should, therefore, obtain a moderate weighting factor of 6.

Issue 13: Reduce the potential for chemical reactions leading to hydrogen production and heat generation

The hydrogen issue causes substantial R&D and protection effort in fission reactor technology (fuel cladding/steam reactions in partially voided cores). Similar problems arise in tokamaks when, for example, hot first wall protection material reacts with steam in accidental situations. Likewise, reactions of beryllium multiplier or liquid metal with water (steam) have to be considered in hypothetical accident scenarios, since water will most probably be used as coolant in other in-vessel components. Prevention or reduction of hydrogen productions are, therefore, a high level safety goal (points 1.4 and 4.2 in Table 10). Within BCSE the problem is alleviated by ignoring the first wall protection material according to the terms of reference valid for this exercise. However, in general it is an unresolved key issue, also with regard to implications on tests in ITER (WG12, compatibility with ITER). The potential for hydrogen production can, as a first approach, be assessed by filing the reactants inventory and evaluating their threshold temperatures for severe reactions. The issue is qualified as very important (weighting factor of 8).

Remark: During the safety issues evaluation (Chapter 5) it became obvious that the issue was already covered in issue No. 2 (compare page 13 of Table 5).

Issue 14: Minimise the risk for plugging and local flow reduction of the first wall primary coolant

The first wall coolant flow is generally a high velocity multi-channel parallel stream. Plugging can cause local or gross overheating of the first wall which can lead to material degradation and eventually to LOCAs. Blockages of individual subchannels cannot be detected. A gross and sudden blockage is unlikely to occur, but spurious and irregular blockages are conceivable, depending on the nature of the coolant flow (e.g., restrictions, velocities, coolant/channel wall chemistry, temperature differences, mass transfer). Minimising the potential for plugging is, thus, a first level design and safety issue which ought to be classified as extremely important. However, with view to the preliminary and qualitative nature of the evaluation for the DEMO blanket concepts, the issue is ranked as very important with a weighting factor of 8.

Issue 15: Minimise the risk for plugging and local flow reduction of the breeder/multiplier primary coolant

The breeder/multiplier coolant flow is a moderate velocity multi-channel parallel stream. Plugging can cause local or gross overheating of structures and breeder/multiplier material which can lead to temperature drifts outside the design windows (associated with swelling and tritium retention issues), to material degradation, and eventually to structural damage. A gross and sudden flow blockage in a large channel is unlikely to occur, but spurious and irregular blockages of individual small channels are conceivable, depending on the nature of the coolant flow (e.g., restrictions, velocities, coolant/channel wall chemistry, temperature differences, deposits by mass transfer, phase changes). Flow disturbances due to loss of insulation for liquid metal flows will be addressed in WG1 (design). The related issues are primarily design relevant with limited and only indirect impact on the plant safety. Therefore, the importance level is lower then the one of the equivalent issue for the first wall flow (issue No. 14), resulting in a weighting factor of 5.

Issue 16: Reduce the long-term waste

Substantial amounts of radioactive material are produced in in-vessel components, mainly in the blanket. Within the blanket the highest specific activity (per unit mass or volume) will occur in the structural material which has a relatively short mission time (2-3 years) and the capability for recycling is only at the R&D stage. On the other hand, there is a good perspective to reuse breeder and multiplier materials. Hence, the structure will dominate the waste problem together with process waste evolving from recycling of reusable materials. Since (a) the structural material is the same for the four DEMO blanket concepts within BCSE, (b) the issues related to recycling of breeder/multiplier are subject to be covered in WG 9 (breeder) and WG10, (beryllium), and (c) activation characteristics are also addressed in issues No. 5 and 6, a moderate importance with a weighting factor of 6 is assigned.

Issue 17: Minimise the contact dose of heat transport systems

The design objective is to minimise the personnel exposure at the prevention level (point 1.8 in Table 10). Heat transport systems in ex-vessel compartments with complex pipework, valves, pumps, and heat exchangers are subject to recurring inspection, maintenance and repair and will give rise to substantial accumulated personnel doses in normal operation. At present only a qualitative assessment of personnel exposure can be made regarding the gamma-dose rate of the heat transport fluids, the type of radioactive products carried by the fluids or being deposited somewhere in the circuits, potential leakage, and tritium permeation through compartment and pipe walls. In principle the problem can be fought by design, control, and administrative means so that at the present state of knowledge (and with view to the tight link with the issue No. 18) a relatively low safety importance level (weighting factor of 4) is foreseen.

Issue 18: Limit the length and complexity of circuits which carry activated fluids

With view to the tremendous pipe length (the total pipe length of a primary cooling system approaches several kilometres, typically 5 km) the pipework bears a safety hazard not only in terms of personnel exposure (issue No. 17) but also in the sense of potentially increasing the frequency for abnormal situations (point 1.2 in Table 10). Besides the pipe length also typical diameters, wall thickness, number of welds and joints, and the accessibility for quality assurance and surveillance measures need to be considered. The issue obtains extra appreciation in design (WG4, loops) and reliability assessment (WG6b) but the safety implications should be discussed separately at a moderate importance level, i.e., a weighting factor of 6.

Issue 19: Extend well established technologies

Employing well established technologies is primarily a design issue to be covered in several WGs, viz. WG1(design), WG3 (tritium), WG4 (loops), WG7 (MHD), WG8 (coatings), WG11 (development risk). Safety is involved in as much as established technologies minimise the uncertainties in plant control (point 2.3 in Table 10) like, for instance, corrosion product transport, tritium control, impact of MHD effects, reliability of valves and pumps, reliability of sensors, durability of coatings, material fatigue, etc. The issue can only be assessed qualitatively but its importance in safety is ranked high applying a weighting factor of 8.

Issue 20: Provide for redundancy of cooling systems

The aim is to minimise the uncertainties in controlling abnormal operation by redundant and/or diverse cooling systems (point 2.3 in Table 10). Diverse cooling systems supplying the same blanket segment help inherently in short term afterheat removal in case of LOCAs or LOFAs at moderate temperature transients. They, thereby, simplify the incidental scenarios to be designed for in the safety systems and protection systems layout (point 3.4 in Table 10). The importance level of the issue is ranked very high, i.e., with a weighting factor of 8.

Issue 21: Minimise the tritium permeation to steam systems

The aim is to minimise the radioactive release during normal operation (point 5.2 in Table 10). Tritium permeating to the steam system is considered to be released to the environment, for which an upper limit of 10 to 20 Ci per day is presently assumed to be acceptable for normal operation. The permeation rate through steam generator tubes depends on temperatures, tritium partial pressure in the primary coolant, coatings, tube material and surface area. Small leakages have to be taken into account if the primary pressure is higher than the pressure on the steam side (compare issue No. 9). Those parameters are specific to the blanket concepts and will be evaluated in a consistent way by WG3 (tritium). Yet, large uncertainties will remain and the safety implications have to be addressed separately at an average importance level. A weighting factor of 5 will be applied.

Issue 22: Minimise the release of activation products in case of loss of heat sink

Complete loss of heat sink is an event in the BDBA domain in which heat removal via the blanket cooling systems (at least for part of the torus) is lost for a prolonged period of time. The amount of decay heat and the thermal inertia of the blanket are the driving parameters for temperature rises which are influenced by the blanket concept. The effectiveness of the emergency heat removal means (radiation to the VV or cryostat, conduction to the intact blanket segments (if any), cooling of VV or cryostat walls) is then a matter of plant design beyond BCSE. Favourable features of the blanket, like low decay heat, high thermal inertia (issue No. 12) and large margin before structure melting alleviate the design and licensing. The issue is considered to be important. However, with view to the separate treatment of the issue 12, which is based on similar arguments, a weighting factor of 4 (below average importance) is assigned.

Issue 23: Minimise the release of activation products in case of DBAs

The issue includes a number of safety objectives on the severe accident management level and the consequences mitigation level, (points 4 and 5, respectively, of the defence-in-depth strategy, Table 10). The ultimate release of activation products to the environment involves a series of mechanisms starting from the accident scenario via dispersion of radioactive material within the affected compartment, mobilisation in form of gaseous effluents or aerosols, transport and perhaps plate-out in compartments, ventilation and filter efficiency, leakage through confinement barriers, release to and dispersion in the environment under varying weather conditions, and finally the biological implications to the public. This sequence can only be assessed in a simplified and enveloping way by (a) defining the worst case accident scenario, (b) estimating the radioactive inventory, (c) estimating the amount that can escape in the worst DBA, (d) estimating a mobilisation fraction (nuclide by nuclide), (e) assuming a confinement retention factor, and (f) assessing the radiological conversion factors (again nuclide by nuclide). Within the BCSE steps (a), (b), and (c) can be addressed at most in terms of total activity (in Becquerels) escaping into the affected compartment. Nevertheless, the importance is ranked very high giving a weighting factor of 8.

Table 4. Safety issues and weighting factors

Issue	Weighting Factor	Principal Investigator
PREVENTION		
1. Minimise the fluids internal energy (system pressure)	10	Kleefeldt
2. Minimise the amount of chemically reactive material	10	Marbach
3. Minimise the frequency of occurrence of LOCA due to extreme disruptions	5	Kleefeldt
4. Minimise the mechanical energy release upon flushing of primary coolant	6	Kleefeldt
5. Minimise the activation products in solid blanket materials	8	Porfiri
6. Minimise the activation products in fluid blanket materials	8	Porfiri
7. Minimise the tritium inventory in solid blanket materials	6	Porfiri
8. Minimise the tritium inventory in fluid blanket materials	6	Porfiri
9. Minimise the consequences of events initiated by failure inside the steam generators	5	Marbach
10. Design for natural convection of first wall primary coolant	6	Marbach
11. Design for natural convection of breeder/multiplier primary coolant	6	Marbach
12. Ensure adequate thermal inertia	6	Kleefeldt
13. Reduce the potential for chemical reactions leading to hydrogen production and heat generation	8	Porfiri
14. Minimise the risk for plugging and local flow reduction of the first wall primary coolant flow	8	Kleefeldt
15. Minimise the risk for plugging and local flow reduction of the breeder/multiplier coolant flow	5	Kleefeldt
16. Reduce the long term waste	6	Porfiri
17. Minimise the contact dose of heat transport systems	4	Kleefeldt
18. Limit the length and complexity of circuits which carry activated fluids	6	Porfiri
CONTROL		
19. Extend well established technology	8	Kleefeldt
20. Provide for redundancy of cooling systems	8	Marbach
MITIGATION		
21. Minimise the tritium permeation to steam systems	5	Marbach
22. Minimise the release of activation products in case of loss of heat sink	4	Marbach
23. Minimise the release of activation products in case of design basis accidents (DBA)	8	Kleefeldt

5. Safety Issues Evaluation

The safety issues evaluation, that is the rating of each blanket concept against each of the issues according to step 5 in Chapter 3, is the most difficult part of the exercise, since many of the issues can only be assessed qualitatively, leaving room for subjective influences. A two step procedure was adopted in working group 6a:

1. Draft evaluation of one third of the issues by each of the three WG6a members (principal investigator as indicated in in Table 4 on page 19).
2. Discussion, refinement, and agreement on the draft evaluation within WG6a for submission to the Blanket Co-ordination Group.

After discussion of the safety issues evaluation at a workshop [9] involving all working groups, a few modifications to 6 of the 23 issues evaluations became necessary, leading to the rating presented in this report.

In general the basis for the evaluation was

- the projects summary reports prepared for each concept [1], [2], [3], [4]
- the data compiled by WG6a in the data sheets (Appendix B on page 65)
- information requested by WG6a from experts on demand.

In order to make the results as transparent as possible, half of the issues could be broken down to several sub-issues (typically 3 to 5). These sub-issues were then rated individually and the mean of the sub-issues ratings was taken as the rating for the whole issue. This implies that the sub-issues had to be defined as to have an equal weight among the set of sub-issues.

The rationale for the sub-issues and issues ratings is summarised in Table 5 on page 22 (one page per issue). The tables give a brief and general description of the concerns and then list for the four blanket concepts the relevant background information (second column), the issues (or sub-issues) evaluation and the sub-issues ratings on a scale from -2 to 0 (third column), and finally the issues ratings (fourth column).

For abbreviations, please refer to Chapter 9 on page 57.

Table 5 (Page 1 of 23). Issues evaluation and rating

Issue No. 1: Minimise the fluids internal energy (system pressure)

Issue description: The stored energy in compressible fluids is the driving source for mobilising radioactivity within the confinement, associated with work potential giving rise to severe accident scenarios. Minimisation of the stored energy is, therefore, a basic design objective on the prevention level and is mainly directed towards beyond design basis accident scenarios initiated from outside the plant. (The more conceivable design basis accidents with failure of a single subsystem and their consequences are covered elsewhere, for instance in issues No. 4 and 23). The issue considered here is the isentropic work potential of the compressed fluids inventory when released into the atmosphere. (The chemical energy potential is discussed in issue No. 2)

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT	The total helium inventory for the FW cooling circuits and the breeder/multiplier cooling circuits has not been evaluated. It is assumed that BIT has, despite the lower system pressure but because of the large steam generators, the same helium inventory as BOT, i.e., 20,000 kg (10300 FW and 9700 BZ). It is further assumed that 25 % of the thermal power be removed by the FW cooling system at 6.5 MPa and a mean temperature of 312°*C*, and 75 % are carried by the breeding zone system at 5 MPa, 375 °*C*.	(i) The isentropic work potential of the total helium inventory is 30.6 GJ. Large expansion volumes are required; considerable problems. (-2.0)	-2.0
BOT	The total helium inventory for FW and breeder/multiplier cooling is approximately 20,000 kg (see data sheets) at a pressure of 8 MPa and an average temperature of 350°*C*, corresponding to 3300 m^3.	(i) The isentropic work potential of the total helium inventory is 32.1 GJ. Large expansion volumes are required; considerable problems. (-2.0)	-2.0
DC	The total helium inventory for FW cooling is approximately 6400 kg (see data sheets) at a pressure of 8 MPa and an average temperature of 300°*C*, corresponding to 950 m^3.	(i) The isentropic work potential of the total helium inventory is 9.4 GJ; some problems. (-1.0)	-1.0
WC	The total water inventory in the two FW cooling circuits and the 4 breeding zone cooling circuits is given in the data sheets to be 142,000 kg (33,000 kg per FW cooling circuit and 19,000 kg per breeding zone cooling circuit).The use of water condensation in affected rooms other than the vacuum vessel is an efficient means to mitigate pressurisation.	(i) The enthalpy change of the water inventory is 29.8 GJ for an isentropic expansion to 0.1 MPa, steam quality of 34 %. (179 GJ for full condensation); some problems. (-1.0)	-1.0

Table 5 (Page 2 of 23). Issues evaluation and rating

Issue No. 2: Minimise the amount of chemically reactive material

Sub-Issues description: Chemically reactive materials are included in all four blanket concepts in large quantities, i.e., Pb-17Li in the DC and WC concepts, NaK in the tritium removal circuit of the DC concept, and solid beryllium in the BIT (as sintered pellets) and in the BOT (as small pebbles) concept. Hence, the following potential hazards are considered qualitatively as sub-issues: (i) Pb-17Li/water reaction, (ii) Pb-17Li/oxygen reaction, (iii) NaK/water reaction, (iv) NaK/oxygen reaction, (v) beryllium/water reaction, and (vi) beryllium/oxygen reaction.

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT	The total beryllium inventory is about 530 tons, peak operating temperature is 450°*C*, sintered pellets, 80 % dense, 40 micrometer grain size results in a large surface (theoretically larger than in BOT) but the amount of open porosity is not known.	(i) not applicable (ii) not applicable (iii) not applicable (iv) not applicable (v) in the case of a break in the steam generator steam and water can enter the helium circuit and lead to beryllium/water reactions with hydrogen production. There are two barriers, one in the blanket (a 0.5 mm cladding in the inner module rows) and another one in the SG. (vi) air ingress into the helium circuit can lead to beryllium/air reaction. Again, two barriers would have to fail. Sub-issues rating: (v) and (vi) are much more hypothetical than (i) to (iv) for DC and WC, therefore BIT and BOT must have a better rating than DC and WC, i.e., (-0.2).	-0.2
BOT	The total beryllium inventory is about 300 tons, the peak operating temperature declines from 640°*C* at BOL to 500°*C* at EOL, molten pebbles of typically 2 and 0.13 mm size, almost 100 % dense, easy to mobilise if not baked together.	(i) not applicable (ii) not applicable (iii) not applicable (iv) not applicable (v) in the case of a break in the steam generator steam and water can enter the helium circuit and lead to beryllium/water reactions with hydrogen production (despite the fact that in normal operation primary pressure higher than secondary pressure). There are two high pressure barriers, one in the blanket and another one in the SG. (vi) air ingress into helium circuit can lead to beryllium/air reaction, risk of fire. Again, two barriers would have to fail. Sub-issues rating: similar rating as BIT, much smaller beryllium inventory, probably smaller surface, and two high pressure barriers are assumed to almost compensate for higher mobility and somewhat higher operating temperature (-0.4).	-0.4
DC	The total Pb-17Li inventory is 15 x 10^6 kg at 425°*C* outlet temperature. The total NaK inventory is about 41,000 kg at maximum temperature of ca. 350 °*C*, divided into 10 separate loops.	(i) limited Pb-17Li/water reaction possible in SG; double wall tube barrier, however see (iii). (ii) Pb-17Li/oxygen reaction possible in rooms containing pipes and SG; one barrier; very limited reaction. (iii) potential NaK/water reaction in SG very violent; limited by amount of NaK, but protection and mitigation system have to be implemented. (iv) Risk of NaK fire in SG rooms, protection and mitigation needed. (v) not applicable (vi) not applicable Sub-issues rating: no in-vessel reactions of type (i) to (iv); concerns are mainly for ex-vessel events, some problems (-1.0).	-1.0
WC	The total Pb-17Li inventory is about 8 x 10^6 kg at peak temperatures close to 500 °*C* (4 loops). The total water coolant inventory is 142,000 kg at an outlet temperature of 325 °*C* (6 loops).	(i) problem to manage the Pb-17Li/water reaction in case of LOCA inside the blanket despite the brazed double wall tubes; pressurisation of blanket box; protection and mitigation needed. (ii) Pb-17Li/oxygen reaction possible in rooms containing pipes and SG; one barrier only, but very limited reaction. (iii) not applicable (iv) not applicable (v) not applicable (vi) not applicable Sub-issues rating: considerable in-vessel problems with sub-issue (i)	-2.0

Table 5 (Page 3 of 23). Issues evaluation and rating

Issue No. 3: Minimise the frequency of occurrence of LOCA due to extreme disruptions

Sub-Issues description: Heavy disruptions can apply extreme loads to the blanket segments and ,thus, can endanger the integrity of the blanket structure. Since both the type and magnitude of loads and their impact location as well as the possible response of the blanket segments are unknown, only a relative and qualitative judgement can be made on the vulnerability of the different blanket concepts to different types of loads despite the promising effort spent in developing models and analysing these effects. Hence, the sub-issues are expressed in terms of the vulnerability of the blanket segments against the following types of loads: (i) electromagnetic global forces (mainly twisting and bending), (ii) gross distributed loads to the first wall (resulting in extra bending and buckling stresses), (iii) local distributed loads to the first wall, (iv) bending loads to supports and pipe connections, (v) thermal loads generated by local plasma impact, runaway electrons, or arcing. (Sub- issues iii and v apply only, if no extra first wall protection is considered as is done here.)

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT	(a) The segment box consists of a thin-walled structure with embedded circular coolant channels. (b) The plasma side is corrugated with a single 3 mm channel wall. (c) There are apparently no stiffening ribs (other than small localised fins), (d) The total number of coolant feeders per segment is 8.	(i) some problems with load type (i) due to (a) and (c) (ii) considerable problems with load type (ii) due to (a), (b), and (c) (iii) considerable problems with load type (iii) due to (a), (b), and (c) (iv) some problems with load type (iv) at module/manifold joints from forces exerted to modules. (v) some problems with load type (v) due to (a) and (b).	-0.7
BOT	(a) The segment box consists of a duplex sheet, diffusion welded with integral rectangular (machined) cooling channels, 25 mm overall thickness. (b) At the rear side there are numerous toroidal-radial cooling plates attached by welding which act as stiffeners in the entire breeding region. (c) The total number of coolant feeders is 4.	(i) no relevant problems with load type (i) due to (b) (ii) some problems with load type (ii) (with regard to bending) due to (b) (iii) no problems with load type (iii) due to (b) (iv) minor problems with load type (iv) (v) no problems with load type (v) due to (a).	-0.15
DC	(a) The segment box consists of a duplex sheet, diffusion welded with integral rectangular (machined) cooling channels. (b) Several internal, relatively thick, plates in both directions of the cross section make the box extremely stiff. (c) The wall is comparably thick (38 mm). (d) The total number of coolant feeders per segment is 6, 2 Pb-17Li pipes being very heavy.	(i) no relevant problems with load type (i) due to (b) and (c) (ii) no problems with load type (ii) due to (a), (b), and (c) (iii) no problems with load type (iii) due to (a), (b), and (c) (iv) some problems with load type (iv) due to (d) (v) no problems with load type (v) due to (a) and (c).	-0.1
WC	(a) The segment box consists of a thin-walled (13 mm) structure with embedded soft-brazed circular coolant tubes. (b) The plasma side is corrugated with wall thickness of 3-4 mm. (c) There are several internal plates in both directions of the cross section making the blanket box very stiff. (d) The number of coolant feeders per OB segment is 6 (central segments) and 8 (lateral segments) with double and triple walls.	(i) no relevant problems with load type (i) due to (c) (ii) no problems with load type (ii) due to (c) (iii) no problems with load type (iii) due to (a) and (c) (iv) some problems with load type (iv) particularly at divertor segments. (v) some problems with load type (v) due to (a) and (b).	-0.2

Note: No consensus could be achieved between ENEA and FZK on the sub-issues ratings and on the issues ratings. Therefore, the issues ratings given in the right column represent mean values of votings from T. Porfiri: 0/0/0/0 and K. Kleefeldt: -1.4/- 0.3/-0.2/-0.4, which were afterwards also accepted by G. Marbach.

Table 5 (Page 4 of 23). Issues evaluation and rating

Issue No. 4: Minimise the mechanical energy release upon flushing of primary coolant
Sub-Issues description: Although the probability for a pipe rupture of the primary cooling system (PCS) resulting in high momentum forces and subsequent damage propagation (involvement of other loop components or damage of confinement barriers) is very low, such events are considered as design basis accidents. The extremely unlikely case of a double-ended pipe rupture is postulated here as a reference case to occur either in-vessel or ex-vessel. The resulting sub-issues are: (i) pressurisation of the vacuum vessel (assuming 5000 m^3 free volume) in combination with required expansion volumes (assuming 0.2 MPa absolute end pressure), (ii) momentum forces and potential consequences for in-vessel LOCAs (feeder break), (iii) pressurisation of containment compartments for ex-vessel LOCAs, (iv) momentum forces and potential consequences for ex-vessel LOCAs (hot leg rupture).

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT	The PCS comprises 4 independent cooling circuits (CC), 2 for the segment boxes and two for the breeding zone. The largest CC has a helium inventory of 5200 kg and a work potential of 8.3 GJ. Pipe diameters are 2.2 m for the hot leg and 0.28 m for the feeders.	(i) Pressurisation of VV would be 1.17 MPa without expansion volume, required extra expansion volume 56,000 m^3; substantial problems (-1.5) (ii) Momentum forces in case of a double-ended feeder break 160 kN per side; some problems (-1.0) (iii) Pressurisation of containment (20,000 m^3 free volume filled with air) 0.4 MPa; substantial problems (-1.5) (iv) Momentum forces in case of a double-ended hot leg break 8300 kN per side; considerable problems (-2.0) Subtotal: -6.0	-1.5
BOT	The PCS comprises 18 CC, 2x3 for the inboard and 2x6 for the outboard. The largest independent cooling sub-system comprises 6 circuits for the outboard with a helium inventory of ca. 7000 kg and a work potential of 11 GJ. Pipe diameters are 1.1 m for the hot leg and 0.3 m for the feeders.	(i) Pressurisation of VV would be 1.5 MPa without expansion volume, requiring 70,000 m^3 extra expansion volume; considerable problems (-2.0) (ii) Momentum forces in case of a double-ended feeder break would be ca. 250 kN per side; substantial problems (-1.5) (iii) Pressurisation of containment (20,000 m^3 free volume filled with air) 0.49 MPa; considerable problems (-2.0) (iv) Momentum forces in case of a double-ended hot leg break 4220 kN per side; some problems (-1.0) Subtotal: -6.5	-1.6
DC	The PCS comprises 10 helium CCs for the FW and 10 Pb-17Li CCs for the breeding zone. The cooling sub-system with the largest work potential comprises 3 helium CCs for the FW with an inventory of ca. 2000 kg and a work potential of about 3 GJ. Pipe diameters are 0.76 m for the hot leg and 0.15 m for the feeders.	(i) Pressurisation of VV approx. 0.45 MPa, required expansion volume 14,000 m^3; minor problems (-0.5) (ii) Momentum forces in case of a double-ended feeder break 54 kN per side; minor problems (-0.5) (iii) Pressurisation of containment (20,000 m^3 free volume filled with air) 0.2 MPa; minor problems (-0.5) (iv) Momentum forces in case of a double-ended hot leg break 2000 kN per side; minor problems (-0.5) Subtotal: -2.0	-0.5
WC	The PCS comprises 6 water CCs, viz. 2 for the FW and 4 for the breeding zone. The largest cooling subsystem comprises 1 circuit serving 24 OB and 16 IB segment boxes. It contains 33,000 kg of pressurised water with an enthalpy of 47 GJ. Pipe diameters are 0.54 m (hot leg) and 0.1 m (feeders).	(i) Pressurisation of VV would be 0.38 MPa with a steam content of 28 %. This can be enhanced by afterheat. Required expansion volume without condensation 10,000 m^3; minor problems (-0.5) (ii) Momentum forces in case of a double-ended feeder break 21 kN per side; some problems due to triple-wall tubes. (-1.0) (iii) Pressurisation of containment (20,000 m^3 free volume filled with air) 0.19 MPa, condensation possible; minor problems (-0.5) (iv) Momentum forces in case of a double-ended hot leg break 560 kN per side; minor problems (-0.5) Subtotal: -2.5	-0.6

Table 5 (Page 5 of 23). Issues evaluation and rating

Issue No. 5: Minimise the activation products in solid blanket materials

Sub-Issues description: It is distinguished between activation products in the structural material, breeder, and multiplier. Due to the lack of detailed data on the spatial activation product distribution (e.g., in the first wall, breeding zone, and shield/manifold region) only typical numbers are considered here as a preliminary evaluation in sub-issues (i) structural material, (ii) solid breeder, and (iii) solid multiplier, i.e., beryllium. (All values refer to the time = 0 (after 20,000 h of operation)

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT		(i) no detailed data are reported for BIT, however, it is assumed that the problem with MANET is similar for all concepts, particularly in the first wall region; some problem. (-1.0) (ii) specific activity in the breeder (outboard) is 4.48E13 Bq/kg, being rated as minor problem (-0.5) (iii) specific activity in multiplier (outboard) is 2.98E14 Bq/kg; rated as substantial problem because of the large beryllium inventory (-1.5) Subtotal: -3.0	-1.0
BOT		(i) specific activity in FW/breeding zone/shield is reported as 6.4E14/1.6E13/ 1.2E13 Bq/kg, and the total activity in the corresponding regions is 4.8E19/ 6.3E19/2.8E19 Bq; some problems (-1.0) (ii) specific activity in the breeder (outboard) is 9.2E13 Bq/kg, being rated as minor problem (-0.5) (iii) specific activity in multiplier (outboard) is 2.1E14 Bq/kg; rated as substantial problem because of the large beryllium inventory. (-1.5) Subtotal: -3.0	-1.0
DC		(i) the total activity in FW/breeding/manifold is 5.2E19/ 9.0E19/4.4E18 Bq; same order of magnitude as BOT; some problem (-1.0) (ii) no solid breeder, not applicable. (+0.0) (iii) no solid multiplier, not applicable. (+0.0) Subtotal: -1.0	-0.3
WC		(i) no detailed data are reported for WC, however, it is assumed that the problem with MANET is similar for all concepts, particularly in the first wall region; some problem. (-1.0) (ii) no solid breeder, not applicable. (+0.0) (iii) no solid multiplier, not applicable. (+0.0) Subtotal: -1.0	-0.3

Table 5 (Page 6 of 23). Issues evaluation and rating

Issue No. 6: Minimise the activation products in fluid blanket materials

Sub-Issues description: It is distinguished between activation products in the liquid breeder material Pb-17Li, coolant, and purge gas. Due to the lack of detailed data on the spatial activation products distribution only typical numbers are considered here as a preliminary evaluation of sub-issues (i) Pb-17Li for DC and WC, (ii) coolant, i.e., helium for BIT, BOT, and DC (first wall only), and water in WC concept, and (iii) purge gas for BIT and BOT. (All values refer to the time = 0 after 20,000 h of operation)

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT		(i) no liquid breeder, not applicable. (0.0) (ii) activation products in helium are small; provisions must be taken for on-line removal of sputter products from the main stream; minor problems. (-0.5) (iii) activation products in purge gas (helium) is small; removal will occur in the tritium extraction system; minor problems. (-0.5) Subtotal: -1.0	-0.3
BOT		(i) no liquid breeder, not applicable. (0.0) (ii) activation products in helium are small; provisions must be taken for on-line removal of sputter products from the main stream; minor problems. (-0.5) (iii) activation products in purge gas (helium) are small; removal will occur in the tritium extraction system; minor problems (-0.5) Subtotal: -1.0	-0.3
DC		(i) the total activity in the liquid breeder is 6E20 Bq (front channel row), ignoring any dilution due to circulation in the loops; strong decay after a few seconds and after one day, but long-lived isotopes like Po-210 and Hg- 203 encounter considerable problems. (-2.0) (ii) activation products in helium coolant for the first wall are small; provisions must be taken to on-line removal of sputter products from the main stream; minor problems (-0.5) (iii) no purge gas, not applicable. (0.0) Subtotal: -2.5	-0.8
WC		(i) no detailed data are reported for WC, however it is assumed that the problem with Pb-17Li is similar to that in the DC concept. The specific activity is expected to be higher than in DC because of the small dilution effect, considerable problems. (-2.0) (ii) no data available for the water coolant, effective purification has to be employed, which is rated similar as the helium purification in the DC concept. The N-16 activation is addressed in Issue No. 17, minor problems. (-0.5) (iii) no purge gas, not applicable. (0.0) Subtotal: -2.5	-0.8

Table 5 (Page 7 of 23). Issues evaluation and rating

Issue No. 7: Minimise the tritium inventory in solid blanket materials

Sub-Issues description: It is distinguished between the tritium inventory in (i) structural material, (ii) solid breeder (Li_2ZrO_3 or $LiAlO_2$ for BIT and Li_4SiO_4 for the BOT concept), and (iii) beryllium as multiplier (as pellets for BIT and pebbles for BOT).

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT		(i) The reported total inventory for the structure is 35 g. Large uncertainties exist in the assessment due to the unknown effect of tritium implantation in the first wall from the plasma. As an upper bound 300 g are currently assumed. Because of the low mobilisation the problem is rated as minor. (-0.5) (ii) The reported total inventory in the breeder is 100 g in case of $LiAlO_2$ and would be much less for Li_2ZrO_3. In general this is not considered as a safety problem (0.0) (iii) The total inventory in beryllium is in the range of 400 g - 3400 g (BIT report [1]). There is agreement that the tritium inventory will be larger than in BOT because of the much larger beryllium inventory and the lower operating temperature (see Issue No. 2).The release rate upon a temperature rise will be smaller than in BOT (lower temperature). Nevertheless, the large inventory is rated as considerable safety problem. (-2.0) Subtotal: -2.5	-0.8
BOT		(i) The reported total inventory for the structure is 30 g. Large uncertainties exist in the assessment due to the unknown effect of tritium implantation in the first wall from the plasma. As an upper bound 300 g are currently assumed. Because of the low mobilisation the problem is rated as minor. (-0.5) (ii) The reported total inventory in the breeder is 10 g for Li_4SiO_4. In general this is not considered as a safety problem. (0.0) (iii) The reported total tritium inventory in beryllium is 1280 g. The tritium release from beryllium pebbles upon a temperature rise will be slow (several % immediately and less than 0.1 % per hour afterwards). The same rating is applied as for BIT. The higher relative release rate in BOT in case of a temperature transient is expected to be compensated by the much smaller tritium inventory. (-2.0) Subtotal: -2.5	-0.8
DC		(i) The reported total inventory for the structure is 19 g. Large uncertainties exist in the assessment due to the unknown effect of tritium implantation in the first wall from the plasma. As an upper bound 300 g are currently assumed. Because of the low mobilisation the problem is rated as minor. (-0.5) (ii) not applicable (0.0) (iii) not applicable (0.0) Subtotal: -0.5	-0.2
WC		(i) The reported total inventory for the structure is 13 g. Large uncertainties exist in the assessment due to the unknown effect of tritium implantation in the first wall from the plasma. As an upper bound 300 g are currently assumed. Because of the low mobilisation the problem is rated as minor. (-0.5) (ii) not applicable (0.0) (iii) not applicable (0.0) Subtotal: -0.5	-0.2

Table 5 (Page 8 of 23). Issues evaluation and rating

Issue No. 8: Minimise the tritium inventory in fluid materials

Sub-Issues description: It is distinguished between the tritium inventory in (i) Pb-17Li for DC and WC, (ii) coolant, i.e., helium for BIT, BOT, and DC (first wall only), and water in the WC concept, and (iii) purge gas for BIT and BOT.

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT		(i) no liquid breeder, not applicable (ii) The total tritium inventory in the helium coolant is reported to be 5 g. Tritium permeation into the coolant is uncertain but should not significantly influence the equilibrium content, if on-line extraction is provided. (iii) The total tritium inventory in the purge gas is reported to be 0.06 g. The total tritium inventory is about 5 g. This is rated as a minor problem. Sub-issues rating (i) to (iii): (-0.5)	-0.5
BOT		(i) no liquid breeder, not applicable (ii) The total tritium inventory in the helium coolant is reported to be 0.5 g. (iii) The total tritium inventory in the purge gas is reported to be 0.16 g. The total tritium inventory is less than 1 g. This is rated as a minor problem. Sub-issues rating (i) to (iii): (-0.5)	-0.5
DC		(i) The total tritium inventory in the Pb-17Li is reported to be 60 g. (ii) The total tritium inventory in the helium coolant is assumed to be 0.3 g (scaled down from BOT). (iii) no purge gas, not applicable. The total tritium inventory is about 60 g. This can cause some safety problem. Sub-issues rating (i) to (iii): (-1.0)	-1.0
WC		(i) The total tritium inventory in the Pb-17Li is reported to be 50 g. (ii) The total tritium inventory in the water coolant is reported to be 5 g at a tritium concentration of 0.5 Ci/kg of water (corresponding to 100 m^3 of water inventory which is perhaps too low). Realisation of this low concentration needs to be proved. (iii) no purge gas, not applicable. The total tritium inventory is about 55 g. This can cause some safety problem. Sub-issues rating (i) to (iii): (-1.0)	-1.0

Table 5 (Page 9 of 23). Issues evaluation and rating

Issue No. 9: Minimise the consequences of events initiated by failure inside the steam generators

Issue description: A possible breach inside the steam generator, on the secondary cooling circuit or between the primary and secondary cooling circuits might lead to pressurisation of the second confinement barrier, to the release of activation products, to chemical reactions, and to the loss of heat sink. In any case, the expansion of the cooling fluid, spread from the breach, and the dispersion of activated products may be managed through specific expansion volumes or appropriate reducing devices. (This is also treated in Issue No. 4.)

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT		Issue evaluation: Since the tritium inventory in the helium is moderate (a few grams per circuit, see Issue No. 8) and the primary pressure is lower then the secondary pressure, leakage of helium into the steam circuit is not a safety problem. (The potential for chemical reactions in the case of water ingress into the helium circuit is addressed in Issue No. 2.) Issue rating: (0.0)	(0.0)
BOT		Issue evaluation: Since the tritium inventory in the helium is extremely low (a few tenths of grams per circuit, see Issue No. 8) leakage of helium into the steam circuit is not a safety problem. Issue rating: (0.0)	(0.0)
DC		A major concern is the chemical reaction in case of a double-ended pipe break in the steam generator, in which the simultaneous presence of NaK and water may induce exothermic and violent reactions. The amount of NaK involved is predicted to be moderate. Nevertheless, this issue needs further attention. The issue has also been addressed in issue No. 2 and is rated here as to cause some problems. Issue rating: (-1.0)	(-1.0)
WC		Issue evaluation: Since the tritium inventory in the water coolant is moderate (of the order of one gram per circuit, see Issue No. 8) leakage of water into the steam circuit is not a safety problem. Issue rating: (0.0)	(0.0)

Table 5 (Page 10 of 23). Issues evaluation and rating

Issue No. 10: Design for natural convection of first wall primary coolant

Issue description: The fluids involved in the first wall cooling are helium (for BIT, BOT, and DC) and water (for WC), whose density is particularly sensitive to temperature. Moreover, the limited pressure drop due to appropriate cooling circuits designs, the possible elevation of the steam generators (heat sink) relative to the first wall (heat source) are efficient features to enhance natural circulation. Hence, the first wall cooling loops can, in general, easily be designed to provide sufficient natural convection, suitable for temperature transients limitation and afterheat removal. This may be more difficult under degraded operating condition, where the use of helium would particularly need the implementation of suitable safety systems because of lower natural circulation capabilities, especially at reduced pressure.

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT	The use of helium and the rather narrow channel widths require further analyses on the problem of how fast an effective natural circulation can be established	Issue evaluation: Some problems are expected in establishing the natural convection in time (-1.0).	-1.0
BOT	The extreme narrow channels in the breeding zone which are in series with the first wall coolant channels cause a relatively high pressure drop. First assessments state that afterheat can be removed by natural circulation at full pressure and a heat sink elevation above the source of at least 5 m. Further analyses will be needed on transients under abnormal conditions	Issue evaluation: Some problems are seen in establishing the natural convection in time (-1.0).	-1.0
DC	The first wall channels are relatively large, but the helium flows in multiple passes (meander type) through the first wall (as opposed to the other concepts with a single pass).	Issue evaluation: Some problems are seen in establishing the natural convection in time (-1.0).	-1.0
WC	The nominal outlet temperature is 325 °*C*, the pressure is 15.5 MPa (saturation temperature 343°*C*). The coolant channels are rather small and in parallel for the entire first wall. The coolant channels in the bottom part of the outboard segments form upside-down U-bends prone to steam binding and subsequent overheating.	Issue evaluation: The water is ranked more favourable compared to helium and, in general, no problems are seen. Steam binding in parallel channels needs analyses (-0.2).	-0.2

Table 5 (Page 11 of 23). Issues evaluation and rating

Issue No. 11: Design for natural convection of breeder/multiplier primary coolant

Issue description: The fluids involved for cooling the breeding zone are helium (for BIT, BOT), Pb-17Li (for DC), and water (for WC). Again, the elevation of the steam generators (heat sink) relative to the breeding zone (heat source) is an efficient feature to enhance natural circulation. Hence, the breeding zone cooling loops can, in general, easily be designed to provide sufficient natural convection, suitable mainly for afterheat removal (whereas transients play a minor role in the breeding zone as opposed to the first wall).

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT	The helium flows in annular ducts downwards (cold leg), is reversed at the bottom of the breeder modules and flows upwards in the breeding rod bundle (hot leg). Heat is introduced into the stream from structures, beryllium, and breeder material. The difference of the heat fed into the cold and hot leg creates the driving buoyancy force for the natural convection. It is not clear if flow reversal will take place and how fast effective cooling will be established.	Issue evaluation: Minor problems are expected in establishing the natural convection in time. Further analysis is needed (-0.5).	-0.5
BOT	The extreme narrow channels in the breeding zone which are in series with the first wall coolant channels cause a relatively high pressure drop. First assessments state that afterheat can be removed by natural circulation at full pressure and a heat sink elevation above the source of at least 5 m. Further analyses will be needed on transients under abnormal conditions (same argument as for first wall in Issue No. 10).	Issue evaluation: Minor problems are seen in establishing the natural convection in time. Further analysis is needed (-0.5).	-0.5
DC	The breeding channels are very large. The only concern are MHD effects which, upon local failure of the insulation layer, may cause substantial pressure drop and flow redistribution. Analyses for a similar design have shown that the afterheat can be removed at full magnetic field by natural circulation if the heat sink elevation above the source is at least 5 m [10]. In addition the high heat capacity of the blanket (see Issue No. 12) can guarantee to shut off the field in time (e.g., within an hour).	Issue evaluation: Minor problems are seen in establishing the natural convection in time. Further analysis is needed (-0.5).	-0.5
WC	The nominal outlet temperature is 325 °C, the pressure is 15.5 MPa (saturation temperature 343°C); small margin to boiling. The coolant channels are hairpin type tubes with downward flow in the front region of the breeding zone and upward flow in the rear region. This configuration requires flow reversal when establishing natural circulation and the transient behaviour needs to be investigated.	Issue evaluation: In general the water would be ranked more favourable than helium. With view to the required flow reversal and the small margin to boiling (possibility of steam binding) the same rating is applied as for the other concepts. Further analysis is needed (-0.5).	-0.5

Table 5 (Page 12 of 23). Issues evaluation and rating

Issue No. 12: Ensure adequate thermal inertia

Sub-Issues description: High thermal inertia of the blanket and cooling system makes the whole system tolerant against upset conditions, faults, and accidents. In most such cases one can assume that the plasma is shut down so that the adiabatic heat-up of portions of the blanket system due to afterheat production is an appropriate measure for the thermal inertia. The following sub-issues are regarded: (i) heat-up of FW in case of FW LOCA, (ii) heat-up of FW in case of FW LOFA, (iii) heat-up of blanket segment in case of entire LOCA, (iv) heat-up of blanket segment in case of entire LOFA.

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT	Material composition and afterheat production in the different materials of the OB blanket in segment midplane as tabulated in data sheets in Appendix B on page 65.	(i) The adiabatic FW temperature rise has not been evaluated but should be similar to the other concepts, considerable problems (-2.0) (ii) same as sub-issue i, considerable problems (-2.0) (iii) expected to be similar to BOT concept, no relevant problems (0.0) (iv) same as sub-issue iii, no relevant problems (0.0) Subtotal: -4.0	-1.0
BOT	Material composition and afterheat production in the different materials of the OB blanket in segment midplane as tabulated in data sheets in Appendix B on page 65.	(i) adiabatic FW temperature rise after 1 min, 10 min, 1 h: 10°*C*, 90°*C*, 410°*C*, considerable problems (-2.0) (ii) same as sub-issue i, considerable problems (-2.0) (iii) OB segment temperature rise after 1 h, 10 h, 100 h: 40°*C*, 150°*C*, ca. 400°*C*, no relevant problems (0.0) (iv) same as sub-issue iii, no relevant problems (0.0) Subtotal: -4.0	-1.0
DC	Material composition and afterheat production in the different materials of the OB blanket in segment midplane as tabulated in data sheets in Appendix B on page 65.	(i) adiabatic FW temperature rise after 1 min, 10 min, 1 hr: 10°*C*, 90°*C*, 410°*C*, considerable problems (-2.0) (ii) same as sub-issue i, considerable problem (-2.0) (iii) not assessed but expected to be similar to sub-issue iv, some problems expected (-1.0) (iv) OB segment temperature rise after 1 h, 10 h, 100 h: 52°*C*, 190°*C*, ca. 600°*C*, some problems (-1.0) Subtotal: -6.0	-1.5
WC	Material composition and afterheat production in the different materials of the OB blanket in segment midplane as tabulated in data sheets in Appendix B on page 65.	(i) The adiabatic FW temperature rise has not been evaluated but should be similar to the other concepts, considerable problems (-2.0) (ii) same as sub-issue i, considerable problems (-2.0) (iii) expected to be similar to DC concept, some problems expected (-1.0) (iv) expected to be similar to DC concept, some problems expected (-1.0) Subtotal: -6.0	-1.5

Table 5 (Page 13 of 23). Issues evaluation and rating

Issue No. 13: Reduce the potential for chemical reactions leading to hydrogen production and heat generation

Issue description: The potential for hydrogen production has been considered in Issue No. 2, minimise the amount of chemically reactive material. In order to avoid duplication, this issue is rated as zero for all concepts, meaning that no additional problems or differences among concepts are identified at this qualitative level.

Blanket	**Background**	**Sub-issues Evaluation (Rating)**	**Rating**
BIT		Issue evaluation: see Issue No. 2	0.0
BOT		Issue evaluation: see Issue No. 2	0.0
DC		Issue evaluation: see Issue No. 2	0.0
WC		Issue evaluation: see Issue No. 2	0.0

Table 5 (Page 14 of 23). Issues evaluation and rating

Issue No. 14: Minimise the risk for plugging and local flow reduction of the FW primary coolant flow

Sub-Issues description: The FW primary coolant is helium (BIT, BOT, and DC) and water (WC). One can generally expect that helium is superior to water in terms of plugging potential because of the water chemistry and related corrosion products transport. Furthermore, the risk for plugging is enhanced, the smaller the channel diameter is, in areas of sudden changes of the channel cross section, and in channels with changing temperatures along the coolant path. Therefore, the following features are considered as sub-issues in this evaluation, regarding an OB segment only: (i) coolant medium, (ii) typical FW channel diameter or cross section, (iii) number and degree of channel restrictions or enlargements, (iv) channel wall temperature gradients in downstream direction.

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT		(i) coolant: helium, no relevant problems (ii) circular coolant channels with 17.5 mm diameter, 24 mm pitch, no relevant problems (iii) The box has about 2x250 parallel channels (approx. 3 m long) with 1000 transitions with a cross section ratio of about 25, no relevant problems (iv) The channel wall temperature will drop in the side wall channels from about 500°*C* to ca. 315°*C* (mean of inlet/outlet), some problems Sub-issues rating (global): No or minor problems are expected; if any, then due to sub-issue iv. (-0.25)	-0.25
BOT		(i) coolant: helium, no relevant problems (ii) rectangular channels with about 16 mm hydraulic diameter, 24 mm pitch, no relevant problems (iii) The box has about 2x250 parallel channels (approx. 3 m long) with 500 transitions with a cross section ratio of 30, and 500 transitions with a ratio of 7. There are further transitions to the breeding zone coolant channels (see Issue No. 15), no relevant problems (iv) The channel wall temperature will drop in the side wall channels from about 500°*C* to 275°*C* (mean of inlet/outlet), worse than average, some problems Sub-issues rating (global): No or minor problems are expected; if any, then due to sub-issue iv. (-0.25)	-0.25
DC		(i) coolant: helium, no relevant problems (ii) square channels with 25 mm hydraulic diameter, 30 mm pitch (much better than average), no problems (iii) The box has about 2x50 parallel channels (approx. 10 m long) with 800 transitions with cross section ratios of about 12, no problems (iv) The channel wall temperature will drop in the side wall channels from about 500°*C* to about 300 °*C* (mean of inlet/outlet), some problems Sub-issues rating (global): No or minor problems are expected; if any, then due to sub-issue iv. (-0.25)	-0.25
WC		(i) coolant: pressurised water, minor problem (ii) circular coolant channels with 8 mm diameter, 28 mm pitch, minor problems (iii) The box has about 430 parallel channels (2.7 m long) with 860 transitions with a cross section ratio of about 270 (much worse than average), minor problem (iv) The channel wall temperature will drop in the side wall channels from about 470°*C* to about 300°*C* (mean of Pb-17Li inlet/outlet), some problems Sub-issues rating (global): Minor problems are expected, mainly due to sub-issues i and iv, to some extent due to ii. (-0.5)	-0.5

Table 5 (Page 15 of 23). Issues evaluation and rating

Issue No. 15: Minimise the risk for plugging and local flow reduction of breeder/multiplier coolant flow

Sub-Issues description: The breeder/multiplier coolant is helium (BIT, BOT), the breeder (Pb-17Li) itself (DC), and water (WC). One can generally expect that helium is superior to Pb-17Li and water in terms of plugging potential because of the liquid metal and water chemistry and related corrosion products transport. Comparing Pb-17Li with water, it is not clear at present, which one is worse. Furthermore, (as already discussed in Issue No. 14) , the risk for plugging is enhanced, the smaller the channel diameter is, in areas of sudden changes of the channel cross section, and in channel sections with decreasing channel wall temperatures in downstream direction. If elaborated orificing would be required for flow adjustment, this would make the design sensitive to plugging. Therefore, the following features are considered as sub-issues in this evaluation, regarding an OB segment only: (i) coolant medium, (ii) typical breeder/multiplier channel diameter or cross section, (iii) number and degree of channel restrictions or enlargements, (iv) channel wall temperature gradients, (v) elaborated orificing required.

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT		(i) coolant: helium, no relevant problems (0.0) (ii) poloidal annular (cold leg) and circular (hot leg, with 7 breeder rods) coolant channels with typically 20 cm^2 cross section area, no problems (0.0) (iii) The breeding zone has 83 parallel channels (about 24 m long), groups of typically 11 such channels being connected to common inlet and outlet headers. There is a total of 166 transitions with cross section ratio of at most 5, no problems (0.0) (iv) The channel wall temperature tends to continuously rise, so that a plate-out of helium-born particles in the blanket segment is unlikely, no problems (0.0) (v) Elaborated orificing not required, no problems (0.0) Subtotal: 0.0	0.0
BOT		(i) coolant: helium, no relevant problem (0.0) (ii) convoluted radial/toroidal rectangular coolant channels with typically 0.24 cm^2 cross section area, imbedded in sandwich steel plates, some problems (-1.0) (iii) The breeding zone has about 7200 parallel channels (typically 2 m long), groups of approx. 40 such channels being connected to common inlet and outlet headers. There are about 14400 transitions with cross section ratios of the order of 40, no relevant problems (0.0) (iv) The channel wall temperature drops in radial channel sections by approximately 100 °C, some problems (-1.0) (v) Elaborated orificing for temperature control is needed, some problems (-1.0) Subtotal: -3.0	-0.75
DC		(i) coolant: Pb-17Li, some problems (-1.0) (ii) poloidal rectangular coolant channels with typically 190 cm^2 (front channels) and 300 cm^2 (rear channels) cross section area, no problems (0.0) (iii) The breeding zone has 18 rear channels (downward flow) connected in series to 6 front channels via the return chamber at the bottom. There are no abrupt transitions with large cross section ratios, no problems (0.0) (iv) The channel wall temperature tends to continuously rise, so that significant deposits in the blanket segment are not likely, no problems (0.0) (v) Elaborated orificing not required, however, some risk from local flow reduction due to coating failure. (-1.0) Subtotal: -2.0	-0.5
WC		(i) coolant: pressurised water, some problems (-1.0) (ii) poloidal circular coolant channels with 0.95 cm^2 cross section area, minor or some problems (-0.8) (iii) The breeding zone has 205 hairpin type coolant tubes which are connected to common inlet and outlet headers. There are 410 transitions with cross section ratios of approx. 10 to the inlet header and 15 to the outlet header (average), no problems (0.0) (iv) The channel wall temperature decreases in downstream direction from ca. 450°C to perhaps 300°C, some problems (-1.0) (v) Elaborated orificing not required, no problems (0.0) Subtotal: -2.8	-0.7

Note: Remark: Sub-issue iii has been ignored in the subtotals because of zeros throughout.

Table 5 (Page 16 of 23). Issues evaluation and rating

Issue No. 16: Reduce the long term waste

Issue description: Large amounts of radioactive material are produced in in-vessel components, mainly in the blanket. Within the blanket the highest specific activity will occur in the structural material which has a relatively short mission time and the capability for recycling seems to be low. On the other hand, there is a good perspective to reuse breeder and especially multiplier material. Hence, the structure will dominate the waste problem along with process waste evolving from recycling of reusable materials.

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT	(a) The concept has Al in the breeder material as long term waste. (b) Beryllium is supposed to be recycled at 90 %. Due to the large beryllium inventory (on the order of 500 tons) large amounts of process waste will be produced.	Issue evaluation: There will be substantial problems with recycling of breeder and beryllium due to (a) and (b) as well as corresponding concerns (c) and (d) listed for BOT; (-1.5).	-1.5
BOT	(a) Ar-39 is produced from impurities in the breeder material and dominates the activation parameters (except for the gamma dose) in the 1 to 100 year range. (b) Al-26 is produced from silicon in the breeder material and dominates the gamma dose rate in the long term (> 100 years). (c) Co-58, Co-60, Mn-54, Al-26, Ba-137 dominate the gamma dose rate in beryllium in the 100 years range. (d) Minimise the uranium impurities in Be to avoid alpha-emitting nuclides like Pu-239, Pu-240, Am-241.	Issue evaluation: There will be substantial problems with recycling of breeder and beryllium due to (a) to (d); (-1.5).	-1.5
DC	(a) Long term activation parameters in Pb- 17Li are dominated by Pb isotopes (204 and 205) or products of Pb (Hg-203, Tl-204, Bi-208). (b) Minimise Bi to reduce Po production. (c) Minimise Ag and Cd impurities. (d) Purification and reuse of Pb-17Li can minimise the long term waste from the liquid breeder. (e) The waste problem for structural material is assumed to be similar for all concepts. (f) The Al bearing coating may become dominating in the long term (> 10^5 years) because of AL-26 and, perhaps, requires separation before disposal.	Issue evaluation: Some problems are encountered due to (a) to (d), but mainly because of (e); (-1.0).	-1.0
WC	No detailed analysis is available in WG6a, but the issue is considered to be equivalent to that of DC, although the amount of Pb-17Li is smaller.	Issue evaluation: Same arguments and rating as DC; (-1.0).	-1.0

Table 5 (Page 17 of 23). Issues evaluation and rating

Issue No. 17: Minimise the contact dose rate of heat transport systems

Sub-Issues description: The heat transport systems carry helium (BIT, BOT, DC), Pb-17Li (DC, WC for tritium extraction only), and water (WC). The concerns with helium are sputtered products which have to be removed on-line in sizeable filter units. The filters, in turn, may have to be regenerated from time to time. Furthermore, tritium leakage and permeation through pipe walls must be considered, both during normal operation and maintenance periods. The major problem with the Pb-17Li is the contact gamma-dose rate (of the order of several hundreds of Sv/h after 10 s and still several Sv/h after 1 day) which makes rooms with Pb-17Li components inaccessible (which is not an operational problem but only for maintenance and repair). Tritium permeation through component walls may require extra suction systems (double pipe walls or conduits). Water carrying systems prohibit access during normal operation, basically because of the N-16 activity (as with pressurised water reactors). This, however, decays within a few hours and is no severe problem for maintenance. In short, the following sub-issues are regarded, assuming the relative severeness of the sub-issues to be proportional to the coolant inventory: (i) helium purification and routine tritium escape, (ii) Pb-17Li gamma-dose rate and routine tritium escape, (iii) water gamma-dose rate.

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT		(i) The helium inventory has not been assessed but is assumed to be similar as that in BOT. Some problems are expected. (-1.0) (ii) No Pb-17Li inventory, sub-issue is not applicable. (0.0) (iii) No water inventory, sub-issue is not applicable. (0.0) Subtotal: -1.0	-0.3
BOT		(i) The helium inventory is about 20000 kg, some problems (-1.0) are expected. (ii) No Pb-17Li inventory, sub-issue is not applicable. (0.0) (iii) No water inventory, sub-issue is not applicable. (0.0) Subtotal: -1.0	-0.3
DC		(i) The helium inventory in the FW cooling system is about 6400 kg. Some problems are expected but less than for BIT and BOT. (-0.5) (ii) The Pb-17Li inventory is about 15,000,000 kg, i.e., the largest of all concepts. On-line or bypass removal of corrosion products, in particular Al (with the gamma emitter Al-28) from insulation layers, is envisaged. Considerable problems are expected. (-2.0) (iii) No water inventory, sub-issue is not applicable. (0.0) Subtotal: -2.5	-0.8
WC		(i) No helium coolant, sub-issue is not applicable. (0.0) (ii) The Pb-17Li inventory is about 8,000,000 kg. Some problems are expected but less than for DC because of much smaller loops and flow rates. (-1.0) (iii) The water inventory is about 142,000 kg. The N-16 activity needs attention. Some problems are expected. (-1.0) Subtotal: -2.0	-0.6

Table 5 (Page 18 of 23). Issues evaluation and rating

Issue No. 18: Limit the length and complexity of circuits which carry activated fluids

Issue description: With view to the tremendous pipe length (the total pipe length of a primary cooling system approaches several kilometres, typically 5 km) the pipework bears a safety hazard not only in terms of personnel exposure (Issue No. 17) but also in the sense of potentially increasing the frequency for abnormal situations. Besides the pipe length also typical diameters, wall thickness, number of welds and joints, and the accessibility for quality assurance and surveillance measures need to be considered. The issue obtains extra appreciation in the design group (WG4) and reliability assessment group (WG6b), but the safety implications should be discussed separately at a moderate importance level. Besides, the circuitry is in the first place a matter of plant layout and is not blanket concept immanent.

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT	The concept has 2 circuits for first wall cooling and 2 circuits for the breeding zone, making a total of 4. Typical hot leg diameters are 1.9 to 2.2 m, typical feeder diameters are 0.28 m. The total number of coolant feeders per segment is 8, plus 2 for the purge gas.	Issue evaluation: The tremendous pipe diameter and the large number of feeders, connecting the segments and the ring collectors, cause similar problems as in other concepts, despite the relatively simple circuit design; (-1.0).	-1.0
BOT	The concept has a total of 18 circuits, 6 for the inboard and 12 for the outboard, being arranged in 2x3 and 2x6 sub-systems for redundancy purposes. Typical pipe diameters are 1.1 m for the hot legs and 0.3 m for the feeders. The total number of coolant feeders is only 4, plus 2 small feeders for the purge gas.	Issue evaluation: The relatively large number of circuits increases the complexity compared to BIT but makes pipes and components smaller and easier to maintain. Overall, the circuitry is more complex than in pressurised water reactors causing some safety problems; (-1.0).	-1.0
DC	The concept has 10 helium cooling circuits for the first wall (4 for the inboard and 6 for the outboard), and the same number of Pb-17Li circuits for the self-cooled breeding zone. Typical pipe diameters are 0.8 m for the helium hot legs and 0.8 to 1.15 m for the Pb-17Li hot legs. Feeders range from 0.13 to 0.33 m. The total number of coolant feeders is 6 per segment, plus two small lines for liquid metal draining.	Issue evaluation: The relatively large number of circuits increases the complexity compared to BIT and WC but makes pipes and components smaller and easier to maintain. Overall, the circuitry is more complex than in pressurised water reactors causing some safety problems; (-1.0).	-1.0
WC	The concept has 2 circuits for first wall cooling and 4 circuits for the breeding zone, making a total of 6 water cooling circuits. There are 4 smaller Pb-17Li loops for tritium extraction. Typical diameters are 0.4 to 0.8 m for the hot legs and 0.1 m for the feeders. The total number of coolant feeders per outboard segment is 6 (central segments) and 8 (lateral segments) with double and triple walls.	Issue evaluation: The external loop system is perhaps the one closest to conventional designs but still with a mix of water and liquid metal piping. The feeders are extremely complex because of their staggered configuration, making quality assurance and in-service inspection impossible. Therefore, the rating is the same as for the other concepts; (-1.0).	-1.0

Table 5 (Page 19 of 23). Issues evaluation and rating

Issue No. 19: Extend well established technology

Sub-Issues description: New technologies bear uncertainties in plant control, prediction and control of abnormal situations and, thereby, call for extra margins and provisions in safety assessment. Most of the concerns with new technologies in the blanket systems are treated in other working groups, especially in the risk assessment group (WG6b). However, in their synergism, new technologies can impede safety. Therefore, the following sub-issues are considered here in a qualitative way: (i) corrosion and sputter product transport, (ii) durability of coatings with regard to tritium control, (iii) impact of MHD on thermal-hydraulics and temperature control, (iv) reliability of valves and pumps on demand, (v) reliability of instrumentation and leak control, (vi) material fatigue, mainly at joints, (vii) hazards from steam generators.

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT		(i) some problems with helium systems (-1.0) (ii) considerable problems with helium steam generators (-2.0) (iii) not applicable (0.0) (iv) some problems with helium technology, particularly blowers (-1.0) (v) some problems with leak control (-1.0) (vi) considerable problems with first wall fabrication (deep drilling, bending, welding) (-2.0) (vii) minor problems with helium steam generators (-0.5) Subtotal: -7.5	-1.1
BOT		(i) some problems with helium systems (-1.0) (ii) considerable problems with helium steam generators (-2.0) (iii) not applicable (0.0) (iv) some problems with helium technology, particularly blowers (-1.0) (v) some problems with leak control (-1.0) (vi) some problems with first wall fabrication (diffusion welding) (-1.0) (vii) some problems with helium steam generators because primary pressure higher than secondary pressure. (-1.0) Subtotal: -7.0	-1.0
DC		(i) some problems with helium systems and Pb-17Li systems (-1.0) (ii) some problems with helium steam generators (lower then BIT and BOT) because of relatively low temperature (-1.0) (iii) considerable problems (-2.0) (iv) considerable problems with Pb-17Li technology (-2.0) (v) some problems with leak control (-1.0) (vi) considerable problems with first wall fabrication (diffusion welding, bending of thick wall) (-2.0) (vii) considerable problems with Pb-17Li/NaK/water steam generators (-2.0) Subtotal: -11.0	-1.6
WC		(i) not relevant in water systems, vast experience (0.0) (ii) considerable problems with cooling tubes in segments (-2.0) (iii) minor problems because of low flow velocities (-0.5) (iv) no problems with water technology, some problems with Pb-17Li technology (smaller loops compared to DC). (-1.0) (v) considerable problems with leak control in water/Pb-17Li piping and manifolding (-2.0) (vi) considerable problems with first wall fabrication (deep drilling, brazing, bending) and severe tube fabrication (bending, tube sheet welding) (-2.0) (vii) no problems with water/steam generators (0.0) Subtotal: -7.5	-1.1

Table 5 (Page 20 of 23). Issues evaluation and rating

Issue No. 20: Provide for redundancy of cooling systems

Issue description: The aim is to minimise the uncertainties in controlling abnormal operation by redundant and/or diverse cooling systems. Diverse cooling systems supplying the same blanket segment help inherently in short term afterheat removal in case of LOCAs or LOFAs at moderate temperature transients. They, thereby, simplify the incidental scenarios to be designed for in the safety systems and protection systems layout.

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT	Two independent helium systems cool the segment box (each one feeding in an alternate way half of the segment box cooling channels). 2 independent helium systems cool the breeding zone.	Issue evaluation: The redundancy function, from the safety point of view (in case of LOFA), is provided for all the concepts. The conceptual design way to fulfil this function is different, though, but the overall function is provided. All the concepts seem to be equivalent from this point of view and no relevant problem is seen; (0.0).	0.0
BOT	Two independent helium systems cool in series the segment box and the breeding zone (each one feeding half of the segment box and breeding zone channels).	Issue evaluation: same rationale as for BIT; (0.0).	0.0
DC	Due to the choice of two cooling fluids, helium for the segment box and lead-lithium for the breeding zone, there is an independence between the two cooling systems.	Issue evaluation: same rationale as for BIT; (0.0).	0.0
WC	Two independent water systems cool the segment box and the breeding zone (one for the segment box, the other one for the breeding zone).	Issue evaluation: same rationale as for BIT; (0.0).	0.0

Table 5 (Page 21 of 23). Issues evaluation and rating

Issue No. 21: Minimise the tritium permeation to steam systems

Issue description: The aim is to minimise the radioactive release during normal operation. Tritium permeating to the steam system is considered to be released to the environment, for which an upper limit of 10 to 20 Ci per day is presently assumed to be acceptable during normal operation. The permeation rate through steam generator tubes depends on temperature, tritium partial pressure in the primary coolant, coatings, tube material and surface area. Leakage has to be taken into account if the primary pressure is higher then the pressure on the steam side (compare Issue No. 9). Those parameters are specific to the blanket concepts and will be evaluated in a consistent way by WG3. Yet, large uncertainties will remain and the safety implications have to be addressed separately.

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT	The tritium permeation from the breeder rods into the coolant has been determined for the old 19 rod bundle geometry and with a He, H2, HT chemistry in the purge gas. The calculated permeation was 25 g/d. All helium cooled blankets assume optimistically, that a permeation reduction factor (PRF) of 400 in the steam generators can be realised. With this assumption a permeation to the steam system of < 10 Ci/d can be achieved, if the necessary tritium activity limit of ca. 10^{-3} *Pa* is not exceeded. This can be done by adopting a water chemistry in the purge gas and the coolant. In these conditions, a PRF of 10 can be expected on the breeder rods (permeation < 10 g/d). Furthermore, 99 % of the permeated tritium will be present in form of HTO (not permeable), so that in theory the 10 Ci/d limit (or 20) could be respected. The necessary helium purification system is of the same size as for BOT. The largest uncertainty will be the permeation from the first wall into the coolant (see descriptions (b) and (c) for BOT)	Issue evaluation: see comment for BOT; (-1.0).	-1.0
BOT	(a) The tritium losses to the steam generators have been calculated accounting for the losses into the main helium coolant system (blanket and first wall) and the effect of the helium purification system (preoxidised incoloy 800, no account for tritium dilution caused by hydrogen). The so calculated tritium losses to the steam/water circuit are 22 Ci/d. (b) Large uncertainties are associated with tritium permeation through the first wall into the helium coolant. Estimates range from 1 to 100 g/d. Values substantially larger than 1 g/d would require additional means for tritium control. (c) Another problem are temperature transients which can exert a temporary detrimental effect on the oxide barrier of the steam generator tubes.	Issue evaluation: Large uncertainties allow at this stage only a qualitative and uniform rating for all the concepts; some problems are expected; (-1.0).	-1.0
DC	(a) Similar problems as for BOT exist for the helium first wall cooling system, however on a lower level due to the smaller helium inventory. (b) Tritium permeation from the NaK system in the Pb17Li/NaK/water steam generators requires also a permeation barrier on the water side with a permeation reduction factor of at least 100 in order to respect the 10 Ci/d limit allocated for this system.	Issue evaluation: see comment for BOT; (-1.0).	-1.0
WC	(a) The maximum acceptable concentration of tritium in the water coolant is assumed to range between 0.1 to 1.0 Ci/kg. (b) Water leakage from the primary circuit (15.5 MPa) to the secondary circuit (7 MPa) is very uncertain and can vary by orders of magnitude. Values for water leaks could be 0.1 kg/h per steam generator, leading to a tritium leakage in 6 steam generators of 15 Ci/d [4].	Issue evaluation: see comment for BOT; (-1.0).	-1.0

Table 5 (Page 22 of 23). Issues evaluation and rating

Issue No. 22: Minimise the release of activation products in case of loss of heat sink

Issues description: Complete loss of heat sink is an event in the BDBA domain in which heat rejection via the blanket cooling systems (at least for part of the torus) is lost for a prolonged period of time. The amount of decay heat and the thermal inertia of the blanket are the driving parameters for temperature rises which are influenced by the blanket concept. The effectiveness of the emergency heat removal means (radiation to the VV or cryostat, conduction to the intact blanket segments (if any), cooling of VV or cryostat walls) are then a matter of plant design beyond BCSE. Favourable features of the blanket, like low decay heat, high thermal inertia (Issue No. 12), and large margin before structure melting alleviate the design and licensing.

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT	(a) This corresponds to a complete loss of coolant which annihilates the convective thermal heat extraction. (b) Each of the designs employ more than one independent cooling system for the first wall and the breeder (see issue No. 20). This redundant cooling may act as an emergency system, if an efficient thermal link between the first wall and breeder is available, and if only one system is affected. (c) It is shown that conduction or radiation to surrounding structures like vacuum vessel or cryostat is already an important way for heat removal so that the integrity of the structures is generally not endangered. (d) It is necessary to provide an efficient automatic plasma shutdown device to avoid excessive temperature transients in the blanket in case of total loss of heat sink in an entire segment.	Issue evaluation: The issue raises some safety problems; (-1.0).	-1.0
BOT	Comments (a) to (d) given for BIT apply.	Issue evaluation: The issue raises some safety problems; (-1.0). Remark: With respect to afterheat removal (comment c in the background column) BIT and BOT may have advantage over DC and WC because of the lower decay heat addressed in Issue No. 12.	-1.0
DC	Comments (a) to (d) given for BIT apply.	Issue evaluation: The issue raises some safety problems; (-1.0).	-1.0
WC	Comments (a) to (d) given for BIT apply.	Issue evaluation: The issue raises some safety problems; (-1.0).	-1.0

Table 5 (Page 23 of 23). Issues evaluation and rating

Issue No. 23: Minimise the release of activation products in case of DBAs
Issue description: The worst case accident scenario for an in-vessel LOCA is considered as design basis accident.

Blanket	Background	Sub-issues Evaluation (Rating)	Rating
BIT	Worst case accident scenario: Rupture of a breeder module: • pressurisation of box (pressure relief?) • burst of box • pressurisation of vacuum vessel by both first wall cooling circuits and at least by 1 breeding zone cooling circuit (perhaps both of them) • Release of a small fraction (kg range) of beryllium from one module into VV • Afterheat removal to be verified • Be/air reactions unlikely or minor • Be/water reactions only in case of water access from other components • Activation products mobilisation from helium inventory and from small fractions of Be and breeder from a single module	Issue evaluation: If pressurisation can be handled, some problems (a little less than BOT), rating: (-0.8).	-0.8
BOT	Worst case accident scenario: Rupture of first wall (both cooling systems) towards the inside: • pressurisation of box • rupture of box (despite the design goal to withstand the design pressure) • pressurisation of VV by both FW/BZ cooling sub-system (propagation to other segments unlikely) • afterheat removal to be verified • Be/air reactions unlikely or minor • Be/water reactions only in case of water access from other components • Activation products mobilisation from helium inventory and from small fractions of Be and breeder from a single module (both are in form of small pebbles, leading to a larger fraction that can be liberated compared to BIT).	Issue evaluation: If pressurisation can be handled, some problem; rating: (-1.0).	-1.0
DC	Worst case accident scenario: Rupture of first wall (both cooling systems) towards the inside: • pressurisation of box • pressurisation of Pb-17Li cooling system (including bypass loops to tritium extraction) • rupture of box (despite design goal to withstand helium pressure) • pressurisation of VV by both first wall cooling sub-system (propagation to other segments unlikely) • release of Pb-17Li into VV, in the worst case on the order of 200 m^3. • chemical reactions only in case of ingress of air or water from other components, minor reactions only • activation products mobilisation from Pb-17Li (Po-210, Hg-203, H-3)	Issue evaluation: If pressurisation of containment can be handled, some problems; if containment fails or leaks, tolerable radiological hazards but very difficult to prove. In any case severe clean-up problem, considerable problems; rating: (-2.0).	-2.0
WC	Worst case accident scenario: Rupture of FW or rupture of cooling tube towards the inside of the segment box: • pressurisation of box (pressure relief is an open question) • Pb-17Li/water reactions • failure of box • pressurisation of VV by water vapour • release of Pb-17Li into VV, but much less than for DC • considerable Pb-17Li/water reactions in the VV • activation products mobilisation from Pb-17Li (Po-210, Hg-203, H-3) • limited chemical energy and limited hydrogen production	Issue evaluation: If pressurisation of containment can be handled, some problems; if containment fails or leaks, tolerable radiological hazards but very difficult to prove. In any case severe clean-up problem, considerable problems; rating: (-2.0).	-2.0

6. Results and Future Developments

6.1 Total ratings and comparison of concepts

A summary of the ratings and the weighted ratings for the 23 issues is listed in Table 7 on page 51 along with the summation to the overall ratings of safety issues (OSR) according to equation 1 in Chapter 3. The OSR and the normalised overall safety ratings (osr) according to equation 2 read as follows:

Table 6. Overall safety ratings (OSR) and normalised overall safety ratings (osr)

	BIT	BOT	DC	WC
OSR	-110.1	-114.5	-120	-119.5
osr	0.638	0.623	0.605	0.607

The individual safety issues ratings have been obtained by consensus within WG6a, except for the rating of issue No. 3 (minimise the occurrence of LOCA due to extreme disruptions), where the mean of the voting from two WG6a members was taken which was then accepted by the third WG6a member (see footnote to Table 5 on page 22, issue No. 3). The following results were obtained:

- The overall safety ratings (OSR) for the four concepts range from -110.1 to -120 points. This is a maximum deviation of 5 % from the mean rating.
- The mean value of the overall safety ratings (-116 points) reaches 38 % of the theoretically worst rating which is -304 points.
- The normalised overall safety rating (osr) on a scale from 0 to 1 for the four concepts is even tighter and differs by 3.3 percent points only.
- The difference among the solid breeder group (4.4 points in favour of BIT vs. BOT) and especially the liquid metal breeder group (0.5 points in favour of WC vs. DC) is marginal.
- There is a slight advantage for the solid breeder blankets as compared to the liquid metal blankets in terms of safety, but again the difference is marginal.
- The big penalty points in a direct comparison of BIT vs. BOT, DC vs. WC, and (BIT, BOT vs. DC, WC) are presented in Table 8 on page 52. The major concerns in which the penalty points in the direct contest are equal to, or exceed, 5 points are listed below:

Issue No. 1:	Large fluids internal energy (BIT, BOT inferior to DC, WC)
Issue No. 2:	Amount of chemically reactive material (DC, WC inferior to BIT, BOT; and WC inferior to DC)
Issue No. 4:	Mechanical energy release from primary coolant (BIT, BOT inferior to DC, WC)
Issue No. 5:	Activation products in solid blanket materials (BIT, BOT inferior to DC, WC)
Issue No. 9:	Events due to failure inside the steam generator (DC inferior to WC)
Issue No. 23:	Release of activation products in case of DBAs (DC, WC inferior to BIT, BOT)

- Overall the score is extremely tight and not free from subjective influences, so that a ranking of the concepts in terms of 1st, 2nd, 3rd, 4th place is not appropriate with view to safety.

6.2 Areas of future developments in blanket safety

From the identification and evaluation of the safety concerns a number of future activities evolved to be studied in more detail in the course of further blanket development which could be addressed in this comparative study qualitatively only. These future tasks related to safety (which have to be complemented by tasks evolving from other working groups) are outlined below. Some of them are common to all the four blanket concepts and are listed in a first block (Section 6.2.1) in the order of their appearance in the issues evaluation Table 5 on page 22. The others are specific to particular blanket concepts and are presented in additional blocks pertaining to the BIT, BOT, DC, and WC concept, respectively. An overview of the tasks is given in Table 9 on page 54.

6.2.1 Future activities common to all blanket concepts

- Analysis of the consequences of extreme disruptions on the blanket structure integrity, i.e., refinement of analytical models in terms of physics phenomena, mechanical boundary conditions, design improvements, material characteristics (issue No. 3).
- Structural materials development towards low activation material (issue No. 5).
- Development of models for tritium implantation, in and permeation through, the first wall from the plasma side and assessment of tritium inventory in the first wall (issue No. 7).
- Analyses of the first wall temperature rises for LOCA and LOFA transients at different shutdown scenarios, including the influence of thermal contact to the breeding zone (issue No. 12).

- Analyses of the temperature transients for complete loss of heat sink events for different plasma shutdown scenarios and different heat removal mechanisms (radiation to the vacuum vessel or cryostat, conduction to the intact blanket segments, cooling of vacuum vessel or cryostat walls), (issue No. 22).
- Study of the worst case accident scenarios for LOCA events with escape of tritium and activation products into the vacuum vessel or other containment compartments, transport and release paths to the environment, and potential dose to the public (issue No. 23).

6.2.2 Additional activities for the BIT concept

- Analyses of depressurisation processes, i.e., pressure and temperature transients in containment compartments (vacuum vessel, cryostat, loop compartments), required expansion volumes and relief devices (issues No. 1 and 4).
- Establish scenarios and analyse beryllium/water and beryllium/air reactions in case of water or air ingress into the breeder cooling system and simultaneous failure of the beryllium cladding (issue No. 3).
- Study the potential and technical means to minimise the impurities in beryllium multiplier (in particular Co, Al, Fe, U) to reduce the activation products (issues No. 5 and 16).
- Develop means for on-line removal of sputter products from the main coolant and from purge gas (issues No. 5 and 17).
- Study the tritium inventory and release mechanisms in beryllium multiplier and their dependence on beryllium structure and parameters (issue No. 7).
- Study the natural convection capability of the first wall helium cooling including the transition from forced flow to natural convection flow (issue No. 10).
- Study the natural convection capability of the breeding zone helium cooling including the transition from forced flow to natural convection flow with possible flow reversal (issue No. 11).
- Develop economical recycle techniques for activated beryllium and solid breeder material to reduce the long term waste (issue No. 16).
- Refine models and verify tritium control in the primary coolant (permeation from the breeder into the coolant and permeation through the first wall from the plasma, purge gas chemistry) including tritium losses through the steam generator tube walls, permeation barrier effectiveness, durability, leakage (issue No. 21).

6.2.3 Additional activities for the BOT concept

The additional activities for the BOT concept are, in essence, repeated from the BIT concept with minor concept-related differences in regard to beryllium chemical reactions (2nd paragraph below), natural convection flow (6th par.), and flow maldistribution (7th par.).

- Analyses of depressurisation processes, i.e., pressure and temperature transients in containment compartments (vacuum vessel, cryostat, loop compartments), required expansion volumes and relief devices. (issues No. 1 and 4).
- Investigation of beryllium/water and beryllium/air reactions with identification of scenarios in terms of masses involved, contact modes, reaction condition, and chemical reaction consequences with view to hydrogen production and tritium release (issue No. 2).
- Study the potential and technical means to minimise the impurities in beryllium multiplier (in particular Co, Al, Fe, U) to reduce the activation products (issues No. 5 and 16).
- Develop means for on-line removal of sputter products from the main coolant and from purge gas (issues No. 5 and 17).
- Study the tritium inventory and release mechanisms in beryllium multiplier and their dependence on beryllium structure and parameters (issue No. 7).
- Study the natural convection capability of the first wall and breeding zone helium cooling (both being in series) including the transition from forced flow to natural convection flow (issues No. 10 and 11).
- Study the effect of fabrication tolerances, modelling uncertainties, and partial plugging on flow maldistribution in parallel coolant channels with view to temperature control in structure, breeder, and multiplier (issues No. 14 and 15).
- Develop economical recycle techniques for activated beryllium and solid breeder material to reduce the long term waste (issue No. 16).
- Refine models and verify tritium control in the primary coolant (permeation through the first wall from the plasma, purge gas chemistry) including tritium losses through the steam generator tube walls, permeation barrier effectiveness, durability, leakage (issue No. 21).

6.2.4 Additional activities for the DC concept

- Study NaK/water reactions in steam generators and their potential for damage propagation, including steam/water ingress into the Pb-17Li cooling system, e.g., pressure pulses, pressure relief devices, etc. (issues No. 2 and 9).
- Study the build-up of activation products in Pb-17Li with consideration of realistic in-core/ex-core sequences and operational cycles. Develop techniques for on-line removal of activation products like Hg, Bi, Po (issue No. 6).

- Develop means for on-line removal of sputter products from the first wall helium coolant stream (issues No. 6 and 17).
- Study the natural convection capability of the first wall helium cooling including the transition from forced flow to natural convection flow (issue No. 10).
- Study the natural convection capability of the Pb-17Li breeding circuit including the transition from forced flow to natural convection flow, considering MHD effects (issue No. 11).
- Identify schemes to separate the Al containing insulation coating from the structure to reduce the long term waste (issue No. 16).
- Investigate the gamma activation of Pb-17Li for operational safety and develop means to cope with the gamma activation during maintenance and repair (issue No. 17).
- Refine models and verify tritium control in the first wall helium coolant (permeation through the first wall from the plasma) including tritium losses through the steam generator tube walls, i.e., permeation barrier effectiveness, durability, leakage (issue No. 21).
- Investigate the tritium permeation from the NaK system in the Pb-17Li/NaK/water steam generators including permeation barrier effectiveness on the water side (issue No. 21).

6.2.5 Additional activities for the WC concept

- Analyses of depressurisation processes, i.e., pressure and temperature transients in containment compartments (vacuum vessel, cryostat, loop compartments), required expansion volumes and relief devices, including pressure suppression systems (issues No. 1 and 4).
- Study Pb-17Li/water reactions inside the blanket, potential for damage propagation, pressurisation of blanket box, pressure pulses, effectiveness of pressure relief devices, response times (issue No. 2).
- Study the build-up of activation products in Pb-17Li with consideration of realistic in-core/ex-core accident sequences and operational cycles. Develop techniques for on-line removal of activation products like Hg, Bi, Po (issue No. 6).
- Develop means for on-line removal of corrosion and sputter products from primary water coolant (issue No. 6).
- Study the natural convection capability of the first wall water cooling including the transition from forced flow to natural convection flow with consideration of two-phase flow and perhaps steam binding in some coolant channels (issue No. 10).

- Study the natural convection capability of the breeding zone water cooling including the transition from forced flow to natural convection flow with possible flow reversal (issue No. 11).
- Study the effect of fabrication tolerances, modelling uncertainties, and partial plugging on flow maldistribution in parallel coolant channels with view to temperature control in structure, liquid breeder (issues No. 14 and 15).
- Inspect the gamma-dose rate (N-16) of the water coolant and its consequences on shielding requirements around pipes and components (issue No. 17).
- Investigate the gamma activation of Pb-17Li for operational safety and develop means to cope with the gamma activation during maintenance and repair (issue No. 17).
- Verify tritium control in the primary cooling water at high tritium loading rates and high water through-puts, study tritium release paths in normal operation, i.e., leakage from cooling circuits and in the steam generator.

Table 7. Safety issues ratings and weighted safety issues ratings

Issue No.	F_i	Issues Ratings ($R_{i,j}$)				Weighted Issues Ratings			
		$R_{i,BIT}$	$R_{i,BOT}$	$R_{i,DC}$	$R_{i,WC}$	$F_iR_{i,BIT}$	$F_iR_{i,BOT}$	$F_iR_{i,DC}$	$F_iR_{i,WC}$
1	10	-2	-2	-1	-1	-20	-20	-10	-10
2	10	-0,2	-0,4	-1	-2	-2	-4	-10	-20
3	5	-0,7	-0,15	-0,1	-0,2	-3,5	-0,75	-0,5	-1
4	6	-1,5	-1,6	-0,5	-0,6	-9	-9,6	-3	-3,6
5	8	-1	-1	-0,3	-0,3	-8	-8	-2,4	-2,4
6	8	-0,3	-0,3	-0,8	-0,8	-2,4	-2,4	-6,4	-6,4
7	6	-0,8	-0,8	-0,2	-0,2	-4,8	-4,8	-1,2	-1,2
8	6	-0,5	-0,5	-1	-1	-3	-3	-6	-6
9	5	0	0	-1	0	0	0	-5	0
10	6	-1	-1	-1	-0,2	-6	-6	-6	-1,2
11	6	-0,5	-0,5	-0,5	-0,5	-3	-3	-3	-3
12	6	-1	-1	-1,5	-1,5	-6	-6	-9	-9
13	8	0	0	0	0	0	0	0	0
14	8	-0,25	-0,25	-0,25	-0,5	-2	-2	-2	-4
15	5	0	-0,75	-0,5	-0,7	0	-3,75	-2,5	-3,5
16	6	-1,5	-1,5	-1	-1	-9	-9	-6	-6
17	4	-0,3	-0,3	-0,8	-0,6	-1,2	-1,2	-3,2	-2,4
18	6	-1	-1	-1	-1	-6	-6	-6	-6
19	8	-1,1	-1	-1,6	-1,1	-8,8	-8	-12,8	-8,8
20	8	0	0	0	0	0	0	0	0
21	5	-1	-1	-1	-1	-5	-5	-5	-5
22	4	-1	-1	-1	-1	-4	-4	-4	-4
23	8	-0,8	-1	-2	-2	-6,4	-8	-16	-16
Overall Safety Rating (OSR)						-110,1	-114,5	-120	-119,5

Table 8. The big penalty points

BIT vs. BOT (Score > 2 points per issue)	
BIT	**BOT**
• Issue 3: Frequency of LOCA due to disruption (score -2.75 points)	• Issue 2: Minimise the amount of chemically reactive materials (score -2 points) • Issue 15: Risk for plugging of BZ coolant flow (score -3.75 points)
DC vs. WC (Score > 2 points per issue)	
DC	**WC**
• Issue 9: Events due to failure inside steam generator (score -5 points) • Issue 10: Natural convection of FW primary coolant (score -4.8 points) • Issue 19: Extend well established technology (score -4 points)	• Issue 2: Amount of chemically reactive material (score -10 points) • Issue 14: Risk for plugging and local flow reduction of the first wall primary coolant (score -2 points)
BIT, BOT vs. DC, WC (Average score > 3 points per issue)	
BIT, BOT	**DC, WC**
• Issue 1: Fluids internal energy (score -10 points) • Issue 4: Mechanical energy release from primary coolant (score -5.4 to - 6.6 points) • Issue 5: Activation products in solid blanket materials (score -5.6 points) • Issue 7: Minimise the tritium inventory in solid blanket materials (score -3.6 points)	• Issue 2: Amount of chemically reactive material (score -6 to -18 points) • Issue 6: Activation products in fluid blanket materials (score -4 points) • Issue 23: Release of activation products in case of DBAs (score -8 to -9.6 points)

7. Summary and Conclusions

In the frame of the blanket concept selection exercise the working group 6a (one of a total of 14 working groups) assessed the safety implications of the four European blanket concepts. 23 safety issues have been identified and the four concepts were evaluated against each issue, applying a methodology proposed for all working groups. Part of the issues could only be assessed qualitatively based on engineering judgement, implying subjective influences and, hence, large uncertainties in the individual ratings. These tend to be mitigated by finding consensus among experts and by the summation to yield the overall ratings.

In view of the remaining uncertainties, the small differences in the overall ratings for the four blanket concepts (Table 6 on page 45) do not allow to apply a ranking with respect to safety. This is particularly true when comparing the two liquid metal blankets or the two solid breeder blankets. For those couples the differences are marginal. In the contest of the solid breeder blankets against the liquid breeder blankets, a small advantage in favour of the solid breeder blankets has been reported, mainly due to the larger amount and mobility of radioactive material in the liquid breeder blankets. These, however, depend on engineering safeguards and assumed accident scenarios which are undefined at present.

In summary, safety does not deliver decisive arguments in favour of, or against, any of the four European blanket concepts. Nevertheless, the normalised overall safety ratings (0.638 for BIT, 0.623 for BOT, 0.605 for DC and 0.607 for WC) should be used as part of the final rating involving the results from all working groups. All concepts cause a number of safety concerns requiring further R&D activities in different fields. Some of them are common to all concepts (like extreme disruptions, low activation material, tritium implantation in first wall, different accident scenarios), others are more specific as outlined in 6.2 on page 46 and in Table 9 on page 54.

Table 9. Future developments in blanket safety

<table>
<tr><th colspan="2">Common to all Concepts</th></tr>
<tr><td colspan="2">- Extreme disruptions
- Low activation material
- Tritium implantation in FW
- LOCA, LOFA temperature transients
- LOHS transients
- Source term generation</td></tr>
<tr><th>BIT</th><th>BOT</th></tr>
<tr><td>- LOCA pressure transients
- Be chemical reactions
- Impurities in Be
- Sputter products in He
- Tritium release from Be
- Natural convection in He
- Recycling Be and breeder
- Tritium control in He
- Tritium losses in SG</td><td>- LOCA pressure transients
- Be chemical reactions
- Impurities in Be
- Sputter products in He
- Tritium release from Be
- Natural convection in He
- Flow maldistribution
- Recycling Be and breeder
- Tritium control in He
- Tritium losses in SG</td></tr>
<tr><th>DC</th><th>WC</th></tr>
<tr><td>- NaK/water reactions
- AP in Pb-17Li
- Sputter products in He
- Natural convection in He
- Natural convection Pb-17Li
- Al coating separation
- Gamma activation of Pb-17Li
- Tritium control in He
- Tritium losses in He SGs
- Tritium losses in LM SGs</td><td>- LOCA pressure transients
- Pb-17Li/water reactions
- AP in Pb-17Li
- Sputter products in water
- Natural convection in water
- Flow maldistribution
- Gamma-dose rate of water
- Gamma activation of Pb-17Li
- Tritium control in water</td></tr>
</table>

8. References

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9. Abbreviations

AP	activation products
BCG	blanket co-ordination group
BCSE	blanket concept selection exercise
BDBA	beyond design basis accident
BIT	breeder inside tube blanket concept
BOL	begin of life
BOT	breeder outside tube blanket concept
BZ	breeding zone
CC	cooling circuit
DBA	design basis accident
DC	dual coolant blanket concept
DEMO	demonstration reactor
EOL	end of life
EU	European Union
FW	first wall
ITER	international thermonuclear experimental reactor
LM	liquid metal
LOCA	loss of coolant accident
LOFA	loss of flow accident
MHD	magneto-hydrodynamics
OSR	overall safety rating
osr	normalised overall safety rating
PIE	primary initiating event
PCS	primary cooling system
SG	steam generator
TAG	test blanket advisory group
tbd	to be determined
VV	vacuum vessel
WC	water-cooled blanket concept
WG	working group

Appendix A. Design and Safety Objectives for the DEMO Blankets and Associated Cooling Systems

The identification of the safety issues to be evaluated in WG6a is based on the defence-in-depth strategy which is a widely accepted methodology in fission and fusion technology. As a suitable example the exercise performed in [7] is adopted to identify, in a comprehensive way, the design and safety concerns (or objectives) imposed by the four DEMO blanket concepts and related cooling systems. This list of design and safety objectives is given below, rendering a total of approximately 135 issues. Many of the issues listed in Table 10 (about 20) need to be assessed by other WGs and the majority of the remaining issues needs to be addressed in a later stage (labelled 'beyond BCSE') as the plant design advances. 23 issues have been selected for treatment by the safety group which are meant to be generic, inherent, and decisive to the blanket concepts. These 23 issues are labelled 'Issue No.' in the sequence of their appearance.

Table 10 (Page 1 of 5). Design and safety objectives for the DEMO blanket and associated systems

Design and safety objectives, based on the defence-in-depth strategy	Comments
1st Level: PREVENTION (conservative design, quality assurance, safety culture)	
1.1 Satisfy the design rules	
• Elaborate a design consistent with all plausible situations	
⇒ Ensure an adequate system performance: remove high heat flux (efficiency, reliability)	WG1
⇒ Ensure an adequate system performance: pulsed operation behaviour	WG1
⇒ Integrate short term unique failure for active and passive systems	beyond BCSE
1.2 Minimise the frequency for abnormal situations (Initiators):	
• Sequences initiated by extreme disruption	beyond BCSE
• Sequences initiated by tokamak related phenomena	beyond BCSE
• Sequences initiated by a leakage in primary coolant (LOCA)	WG1
⇒ Minimise the fluids internal energy (system pressure)	Issue No. 1
⇒ Minimise the corrosion potential among fluids and envelop	WG4
• Sequences initiated by loss of primary coolant flow (LOFA)	
⇒ Minimise the number of valves	beyond BCSE
⇒ Minimise the MHD effects	WG7
• Sequences initiated by loss of secondary coolant	beyond BCSE
• Sequences initiated by loss of heat sink	beyond BCSE
• Sequences related to loss of vacuum	beyond BCSE
• Sequences initiated by malfunction in magnetic systems	beyond BCSE
• Sequences initiated by fault in the electrical power supply or auxiliary systems	beyond BCSE
• Sequences initiated by faults in the tritium plant	beyond BCSE
• Sequences initiated by faults in the fuel management systems	beyond BCSE
• Sequences originating from events in the radioactive storage areas	beyond BCSE
• Analysis of events during special plant conditions	beyond BCSE
• Transport safety	beyond BCSE
• Sequences initiated by internal abnormal environment	beyond BCSE
1.3 Minimise the potential for common modes (Initiators)	
• Minimise the potential for fires	
⇒ Minimise the amount of chemically reactive material	Issue No. 2
• Separate and diversify the systems	
⇒ Separate the heat removal (HR) function from others	beyond BCSE
⇒ Separate the normal and safeguards HR systems	beyond BCSE
⇒ Separate the HR files	beyond BCSE
⇒ Diversify the systems components	beyond BCSE
1.4 Minimise the inherent potential consequences for the PIE	
• Sequences initiated by tokamak related phenomena	
⇒ Minimise the frequency of occurrence due to extreme disruptions	Issue No. 3
• Sequences initiated by a leakage in primary coolant (LOCA)	
⇒ Minimise mechanical energy upon flushing of primary coolant	Issue No. 4
⇒ Minimise the activation products in solid blanket materials	Issue No. 5
⇒ Minimise the activation products in fluid blanket materials	Issue No. 6
⇒ Minimise the tritium inventory in solid blanket materials	Issue No. 7
⇒ Minimise the tritium inventory in fluid blanket materials	Issue No. 8
• Sequences initiated by loss of primary coolant flow (LOFA)	
⇒ Provide pump inertia	WG4

Table 10 (Page 2 of 5). Design and safety objectives for the DEMO blanket and associated systems

Design and safety objectives, based on the defence-in-depth strategy	Comments
• Sequences initiated by loss of secondary coolant	
⇒ Minimise the consequences of events initiated by failure in SGs	Issue No. 9
• Sequences initiated by loss of heat sink	
⇒ Design for loss of heat sink	see Issue No. 22
• Sequences related to loss of vacuum	beyond BCSE
• Sequences initiated by malfunction in magnetic systems	
⇒ Minimise the consequences initiated by faults in the magnetic system	beyond BCSE
• Sequences initiated by faults in the electrical power supply system or auxiliary systems	beyond BCSE
• Sequences initiated by faults in the tritium plant	
⇒ Minimise the tritium inventory in the tritium extraction plant	WG3
⇒ Implement tritium removal	WG3
• Sequences initiated by faults in the fuel management systems	beyond BCSE
• Sequences originating from events in the radioactive storage areas	beyond BCSE
• Analysis of events during special plant conditions	beyond BCSE
• Transport safety	beyond BCSE
• Sequences initiated by internal abnormal environment	beyond BCSE
• Separate and diversify the systems	
⇒ Separate the heat removal (HR) function from the others	beyond BCSE
⇒ Separate the normal and safeguards HR systems	beyond BCSE
⇒ Separate the HR files	beyond BCSE
• Integrate inherent characteristics	
⇒ Design for natural convection of first wall primary coolant	Issue No. 10
⇒ Design for natural convection of breeder/multiplier primary coolant	Issue No. 11
⇒ Ensure adequate thermal inertia	Issue No. 12
⇒ Reduce the potential for chemical reactions leading to hydrogen production	Issue No. 13
1.5 Elaborate a simplified design	
• Elaborate a simplified thermal-hydraulic design	
⇒ Implement coolants which are fluid at room temperature	WG1,WG4
⇒ Elaborate a simplified HR systems architecture	WG4
⇒ Minimise induced effects (e.g. MHD)	WG1, WG7
⇒ Minimise the risk for plugging of the first wall primary coolant flow	Issue No. 14
⇒ Minimise the risk for plugging of the breeder/multiplier coolant flow	Issue No. 15
• Elaborate a simplified thermodynamic design	
⇒ Limit the number of branch connections	WG4
⇒ Limit the transients impact	WG4
⇒ Limit the number of components per circuit	WG4
⇒ Provide low pressure service	see Issue No. 1
1.6 Simplify reactor operations and maintenance procedures	
• Ensure an adequate quality of information (operation data)	
⇒ Implement adequate instrumentation for operating conditions	beyond BCSE
• Simplify and automate the procedures	beyond BCSE

Table 10 (Page 3 of 5). Design and safety objectives for the DEMO blanket and associated systems

Design and safety objectives, based on the defence-in-depth strategy	Comments
1.7 Minimise radioactive waste	
• Simplify the chemistry of the components	
⇒ Provide chemically and physically stable materials	WG1, 8, 9, 10
⇒ Minimise the incompatibility among components (potential for corrosion)	beyond BCSE
⇒ Minimise the risk for contact among incompatible components	beyond BCSE
• Reduce the self-generation of radioactive waste	
⇒ Reduce activation of structural materials	see point 1.4
⇒ Reduce the long term waste	Issue No. 16
• Ensure the good materials behaviour under irradiation	
⇒ Implement irradiation resistant materials	WG1
1.8 Minimise personnel exposure	
• Minimise the contact dose	
⇒ Minimise the contact dose of heat transport systems	Issue No. 17
⇒ Limit length and complexity of circuits carrying activated fluid	Issue No. 18
• Minimise the maintenance times	
⇒ Provide easy dismantling and access (contact maintenance)	WG5
2nd Level: CONTROL (control of abnormal operations and detection of failures)	
2.1 Detect the primary initiating event (PIE)	
• Sequences initiated by tokamak related phenomena	beyond BCSE
• Sequences initiated by a leakage in primary coolant LOCA)	beyond BCSE
• Sequences initiated by loss of primary coolant flow (LOFA)	beyond BCSE
• Sequences initiated by loss of secondary coolant	beyond BCSE
• Sequences initiated by loss of heat sink	beyond BCSE
• Sequences related to loss of vacuum	beyond BCSE
• Sequences initiated by malfunction in magnetic systems	beyond BCSE
• Sequences initiated by faults in the electrical power supply or auxiliary systems	beyond BCSE
• Sequences initiated by faults in the tritium plant	beyond BCSE
• Sequences initiated by faults in the fuel management systems	beyond BCSE
• Sequences originating from events in the radioactive storage areas	beyond BCSE
• Analysis of events during special plant conditions	beyond BCSE
• Transport safety	beyond BCSE
• Sequences initiated by internal abnormal environment	beyond BCSE
2.2 Elaborate a forgiving design	
• Take into account the unavailability for maintenance	
⇒ Foresee an internal redundancy to take unavailabilities into account	WG4
⇒ Ensure common operation range for complementary systems	WG4
• Ensure appropriate physical margins	
⇒ Provide large range before structure melting	WG1
• Ensure appropriate grace period	
⇒ Ensure an adequate internal system inertia	covered in 1.4
⇒ Ensure the access, in a passive way, to an adequate external inertia	beyond BCSE

Table 10 (Page 4 of 5). Design and safety objectives for the DEMO blanket and associated systems

Design and safety objectives, based on the defence-in-depth strategy	Comments
2.3 Minimise the uncertainties	
• Implement qualified materials	
⇒ Extend well established technology	Issue No. 19
⇒ Standardise components between operational and safeguard systems	WG1
⇒ Foresee the possibility for representative maintenance tests	WG5
⇒ Provide for redundancy of cooling systems	Issue No. 20
2.4 Minimise incidental personnel exposure	
• Strengthen the first barrier	beyond BCSE
2.5 Minimise incidental radioactive waste	
• Strengthen the first barrier	
⇒ Elaborate an architecture for the circuits permanently connected to the primary system	beyond BCSE
⇒ Elaborate an architecture for the circuits temporarily connected to the primary system	beyond BCSE
• Strengthen the second barrier	
⇒ Elaborate a design for the circuits connected to the secondary system	beyond BCSE
• Strengthen the third barrier	beyond BCSE
3rd Level: PROTECTION (Safety systems and protection systems)	
3.1 Simplify the inherent accidental plant behaviour for the PIE	
• Sequences initiated by tokamak related phenomena	beyond BCSE
• Sequences initiated by a leakage in primary coolant (LOCA)	
⇒ Provide inherent shutdown	beyond BCSE
• Sequences initiated by loss of primary coolant flow (LOFA)	beyond BCSE
⇒ Provide inherent shutdown	
• Sequences initiated by loss of secondary coolant	beyond BCSE
• Sequences initiated by loss of heat sink	beyond BCSE
• Sequences related to loss of vacuum	beyond BCSE
• Sequences initiated by malfunction in magnetic systems	beyond BCSE
• Sequences initiated by faults in the electrical power supply or auxiliary systems	beyond BCSE
• Sequences initiated by faults in the tritium plant	beyond BCSE
• Sequences initiated by faults in the fuel management systems	beyond BCSE
• Sequences originating from events in the radioactive storage areas	beyond BCSE
• Analysis of events during special plant conditions	beyond BCSE
• Transport safety	beyond BCSE
• Sequences initiated by internal abnormal environment	beyond BCSE
3.2 Simplify the accidental intervention procedures	
• Ensure an adequate information (abnormal situations)	
⇒ Implement adequate instrumentation (abnormal operating conditions)	beyond BCSE
• Ensure and simplify the reparability	
⇒ Simplify the cleanup of VV surface after an internal LOCA	WG5
• Ensure the progression of the defence-in-depth	beyond BCSE

Table 10 (Page 5 of 5). Design and safety objectives for the DEMO blanket and associated systems

Design and safety objectives, based on the defence-in-depth strategy	Comments
3.3 Minimise the potential for common modes (internal or external hazards)	
• Separate and diversify the safety systems	
⇒ Separate the HR safeguard file	beyond BCSE
3.4 Minimise the uncertainties	
• Elaborate a design that simplifies the incidental scenarios	covered elsewhere
• Implement an adequate instrumentation	beyond BCSE
3.5 Reduce the risk (frequency) versus the accidents whose consequences are not allowed	
• Take into account the loss of redundant systems (complementary situations)	
⇒ Implement functional redundancy	beyond BCSE
• Take into account internal and external hazards (fires, floods, etc.)	
⇒ Ensure a reliable backup cold source qualified to the external hazards	beyond BCSE
• Take into account major accidents	
⇒ Implement adequate instrumentation (severe accident conditions)	beyond BCSE
⇒ Envisage the HR for severe accident conditions	beyond BCSE
⇒ Protect the material (e.g. instrumentation) against potential hazards	beyond BCSE
4th Level: SEVERE ACCIDENT MANAGEMENT (confinement protection)	
4.1 Minimise the uncertainties	
• Elaborate a design that simplifies the inherent accident scenarios	
⇒ Design ultimate HR passive system inside the containment	beyond BCSE
• Implement an adequate instrumentation	beyond BCSE
4.2 Reject, by design, the cliff edge effects	
• Strengthen the third barrier	beyond BCSE
• Prevent large containment leakage	beyond BCSE
• Prevent the risk for detonation (H_2)	
⇒ Implement hydrogen mitigation features	beyond BCSE
• Prevent the containment bypass	beyond BCSE
5th Level: CONSEQUENCES MITIGATION (off-site emergency response)	
5.1 Delay the off-site release	
5.2 Minimise the off-site radioactive release	
• Minimise the release during normal operation	
⇒ Minimise the tritium permeation to steam systems	Issue No. 21
• Minimise the release during abnormal situations	beyond BCSE
• Minimise the release during accidents	
⇒ In case of loss of heat sink	Issue No. 22
⇒ In case of design basis accidents (DBA)	Issue No. 23
⇒ In case of beyond design basis accidents (BDBA)	beyond BCSE

Appendix B. DEMO Blanket Concepts Data Sheets and Drawings

This appendix contains a list of items for which data have been collected for the four European DEMO blanket concepts to be used in the blanket comparison and selection exercise (BCSE) in Working Group 6a. The data provide the basis for the safety evaluation process. Most of the data have been taken from the compact reports [1], [2], [3], [4], some of them have been provided by the WG6a members from the original literature. The items are grouped into the following 11 categories:

1. First wall cooling system
2. Breeder/multiplier cooling system
3. Liquid breeder circuit system
4. NaK system for tritium removal
5. Purge gas system
6. Solid materials inventory
7. Peak nominal operating temperatures in solids
8. Tritium inventory (after 20000 h)
9. Power production during normal operation (after 20000 h)
10. Specific activity at several decay times
11. Afterheat production at several decay times

The following abbreviations are used in Table 11 on page 66.

ib	inboard
ob	outboard
na	not applicable
-	no data available
/	separator between items

Table 11 (Page 1 of 13). DEMO blanket concepts data sheets

Item	BIT	BOT	DC	WC
1. First wall cooling system				
• Type of coolant	helium	helium	helium	pressurised H_2O
• Number of loops ib/ob/total	2/2/2	6/12/18	4/6/10	2/2/2[d]
• Number of loops connected to one segment ib/ob	2/2	6/12	4/6	1/1
• Typical pipe dimensions (m)				
- Inboard hot leg id/wall thickness/length	1.88[a]/-/-	1.08/0.07/45[c]	0.8/0.05/40	0.542/-/-
- Inboard cold leg id/wall thickness/length	-	-	0.72/-/20	0.522/-/-
- Inboard feeders id/wall thickness/length	0.174/-/-	0.289/0.0175/15[c]	0.13/0.01/20	-
- Outboard hot leg id/wall thickness/length	1.88[a]/0.025/-	1.08/0.07/45	0.76/0.05/40	0.542/-/-
- Outboard cold leg id(wall thickness/length	-	-	0.7/-/20	0.522/-/-
- Outboard feeders id/wall thickness/length	0.23[a]/0.04/-	0.289/0.0175/12	0.15/0.01/20	-
- Total number of feeders ib/ob	128/192	128/192	128/192	64/96
• Nominal pressure ib/ob (MPa)	6.5/6.5	8/8	8/8	15.5/15.5
• Operating temperature (°*C*)				
- inboard inlet/outlet	280/350	250/300	250/350	305/325
- outboard inlet/outlet	280/350	250/300	250/350	305/325
• Mass flow rate per segment ib/ob (kg/s)	14/25.5	20.4/36.5	11.1/13.3	43.5/66.9
• Mass coolant inventory (kg)				
- Single inboard loop blanket/piping/components	48.8[b]/-/-	45/1130/205	45/414/150	6000/27000[e]
- Total inboard loops blanket/piping/components	97.6/-/-	270/6780/1230	180/1656/600	12000/54000[e]
- Single outboard loop blanket/piping/components	included in ib	42/892/214	148/357/150	included in ib
- Total outboard loops blanket/piping/components	included in ib	505/10700/2570	888/2142/900	included in ib
- Escaping into VV upon single failure from ib/ob	-	4100/6900	1219/1970	33000/33000[f]

Note:

a. Estimates based on given flow rates and a helium velocity of 60 m/s.

b. Estimate based on given values for one ib segment (1.1 kg) and one ob segment (1.3 kg), i.e., =0.5(1.1x32+1.3x48).

c. Values for ib assumed to be equal to the ones for ob.

d. Each one connecting 24 ob and 16 ib first wall boxes.

e. Includes piping plus components.

f. Assuming that the two loops are not connected.

Table 11 (Page 2 of 13). DEMO blanket concepts data sheets

Item	BIT	BOT	DC	WC
2. Breeder/multiplier cooling system				
• Type of coolant	helium	helium	na	pressurised H_2O
• Number of loops ib/ob/total	2/2/2	6/12/18	na	4/4/4[d]
• Number of loops connected to one segment ib/ob	2/2	6/12	na	1/1
• Typical pipe dimensions (m)				
- Inboard hot leg id/wall thickness/length	2.2/-/-	1.08/0.07/45[c]	na	0.405/-/-
- Inboard cold leg id/wall thickness/length	-	-	na	0.372/-/-
- Inboard feeders id/wall thickness/length	0.183[a]/-/-	0.289/0.0175/15[c]	na	-
- Outboard hot leg id/wall thickness/length	2.2[a]/0.03/-	1.08/0.07/45[c]	na	0.405/-/-
- Outboard cold leg id/wall thickness/length	-	-	na	0.372/-/-
- Outboard feeders id/wall thickness/length	0.28[a]/0.05/-	0.289/0.0175/12[c]	na	0.102/0.007/-
- Total number of feeders ib/ob	128/192	128/192	na	64/96
• Nominal pressure ib/ob (MPa)	5/5	8/8	na	15.5/15.5
• Operating temperature (°*C*)				
- inboard inlet/outlet	250/500	300/450	na	265/325
- outboard inlet/outlet	250/500	300/450	na	265/325
• Mass flow rate per segment ib/ob (kg/s)	12/21.5	see *FW*[c]	na	36.3/76.3
• Mass coolant inventory (kg)				
- Single inboard loop blanket/piping/components	9.9[b]/-/-	incl. in *FW*[c]	na	5000/14000[e]
- Total inboard loops blanket/piping/components	19.8/-/-	incl. in *FW*[c]	na	20000/56000[e]
- Single outboard loop blanket/piping/components	included in ib	incl. in *FW*[c]	na	included in ib
- Total outboard loops blanket/piping/components	included in ib	incl. in *FW*[c]	na	included in ib
- escaping into VV upon single failure from ib/ob	-	same as *FW*[c]	na	19000/19000[f]

Note:

a. Estimates based on given flow rates and a helium velocity of 60 m/s.
b. Estimate based on given values for one ib segment (0.17 kg) and one ob segment (0.3 kg), i.e., =0.5(0.17x32+0.3x48).
c. Values are identical to those in the first wall cooling system since both are in series.
d. Each one connecting 12 ob and 8 ib breeding zones.
e. Includes inventory in piping plus components.
f. Assuming that the two loops are not connected.

Table 11 (Page 3 of 13). DEMO blanket concepts data sheets

Item	BIT	BOT	DC	WC
3. Liquid Breeder System				
• Type of liquid breeder	na	na	Pb-17Li	Pb-17Li
• Number of loops ib/ob/total	na	na	4/6/10	4/4/4[a]
• Number of loops connected to one segment ib/ob	na	na	4/3	1/1
• Typical pipe dimensions (m)				
- Inboard hot leg id/wall thickness/length	na	na	0.83/0.03/40	-
- Inboard feeders id/wall thickness/length	na	na	0.25/0.01/15	-
- Outboard hot leg id/wall thickness/length	na	na	1.15/0.04/40	-
- Outboard feeders id/wall thickness/length	na	na	0.33/0.02/12	0.23/0.0075/-
- Total number of feeders ib/ob	na	na	64/96	-
• Nominal pressure ib/ob (MPa)	na	na	2/2	1.5/1.5
• Operating temperature (°*C*)				
- inboard inlet/outlet	na	na	275/425	265/325
- outboard inlet/outlet	na	na	275/425	265/325
• Mass flow rate per segment ib/ob (kg/s)	na	na	484/814	4.0/8.5
• Mass liquid breeder inventory (10^3 *kg*)				
- Single inboard loop blanket/piping/components	na	na	218/619/188	1000/1000[b]
- Total inboard loops blanket/piping/components	na	na	872/2476/752	4000/4000[b]
- Single outboard loop blanket/piping/components	na	na	517/951/327	included in ib
- Total outboard loops blanket/piping/components	na	na	3102/5706/1962	included in ib
- Escaping into VV upon single failure from ib/ob	na	na	1500/2000	1000/1000[c]

Note:

a. Each one connecting 12 ob and 8 ib breeding zones.
b. Includes inventory in piping plus components.
c. Assuming that the inventory from one loop outside the segments be drained and that the loops are not interconnected.

Table 11 (Page 4 of 13). DEMO blanket concepts data sheets				
Item	**BIT**	**BOT**	**DC**	**WC**
4. NaK System for Tritium Removal				
• Type of intermediate coolant	na	na	NaK	na
• Number of loops ib/ob/total	na	na	4/6/10	na
• Typical pipe dimensions (m)				
- Inboard system hot leg id/wall thickness/length	na	na	0.10/0.004/200	na
- Outboard system hot leg id/wall thickness/length	na	na	0.15/0.005/200	na
• Nominal pressure ib/ob (MPa)	na	na	< 1/ < 1	na
• Operating temperature (°*C*)				
- inboard system inlet/outlet at steam generator	na	na	260/360	na
- outboard system inlet/outlet at steam generator	na	na	260/360	na
• Mass flow rate per loop ib/ob (kg/s)	na	na	18.5/37	na
• Mass inventory (kg)				
- Single inboard loop	na	na	2560	na
- Total inboard loops	na	na	10240	na
- Single outboard loop	na	na	5130	na
- Total outboard loops	na	na	30800	na
- Escaping into containment upon single failure from ib/ob	na	na	1300/2600	na

Table 11 (Page 5 of 13). DEMO blanket concepts data sheets

Item	BIT	BOT	DC	WC
5. Purge Gas System				
• Type of purge gas	helium	helium	na	na
• Number of loops ib/ob	1 common loop	1 common loop	na	na
• Number of loops connected to one segment ib/ob	1/1	1/1	na	na
• Typical pipe dimensions (m)				
- Inboard main pipe id/wall thickness/length	-	≃0.4/0.02/95[a]	na	na
- Inboard feeders id/wall thickness/length	-	≃0.45/0.005/12[a]	na	na
- Outboard main pipe id/wall thickness/length	0.7/0.01/-	same as ib	na	na
- Outboard feeders id/wall thickness/length	-/-/-	same as ib	na	na
- Total number of feeders ib/ob	64/96	64/96	na	na
• Nominal pressure ib/ob (MPa)	4.7/4.7	0.13/0.13	na	na
• Operating temperature (°*C*)				
- inboard inlet/outlet	200/500	20/625	na	na
- outboard inlet/outlet	200/500	20/625	na	na
• Mass flow rate per segment ib/ob (kg/s)	0.1/0.1	0.006/0.013	na	na
• Mass purge gas inventory (kg)				
- Total inboard loops blanket/piping/components	14/-/-	1.7/2.8/2.8[a]	na	na
- Total outboard loops blanket/piping/components	9/-/-	4.4/incl. in *ib*[b]	na	na

Note:

a. Based on own estimates

b. Piping and components in common with ib.

Table 11 (Page 6 of 13). DEMO blanket concepts data sheets

Item	BIT	BOT	DC	WC
6. Solid Materials Inventory (10^3 *kg*)				
• Structural material				
- first wall region total ib/ob	410 (*ib + ob*)[a]	44/69	39/58	44/69
- breeding region total ib/ob	included in FW	189/408	454/793	212/953
- shield region (removable) total ib/ob	-	862/676	758/1020	272/816
- insulating layers total ib/ob/total	-	0/0/0	0.08/0.28/0.36[b]	-/-/0.68[c]
- total structural material ib/ob	-	1095/1153	1250/1870	528/1838
• Solid breeder				
- type of breeder/effective density (kg/m^3)	$LiAlO_2$/1700	Li_4SiO_4/1490	na	na
- mass inventory total ib/ob (10^3 *kg*)	112 (ib + ob)	23.3/51.7	na	na
• Solid multiplier				
- type of multiplier/effective density (kg/m^3)	Be (pellets)/1670	Be (pebbles)/1450	na	na
- Mass inventory total ib/ob/total (10^3 *kg*)	-/-/532	93/206/299	na	na
7. Peak Nominal Operating Temperatures in Solids (°*C*)				
• Structural material				
- first wall ib/ob	400/400	520/520	490/490	480/500
- breeding zone ib/ob	530/530	450/450	450/450	457/504
• Solid breeder ib/ob	589/547	900/900	na	na
• Multiplier (beryllium) ib/ob	450/450	-/640 BOL, 500 EOL	na	na

Note:

a. Includes the structural material in the breeding zone (ib + ob)

b. Based on estimates assuming an Al layer thickness of 10^{-5} m.

c. Based on estimates assuming an Al layer thickness of 2×10^{-5} m.

Table 11 (Page 7 of 13). DEMO blanket concepts data sheets

Item	BIT	BOT	DC	WC
8. Tritium Inventory (after 20000 h)				
• in structural material (g)				
- first wall total	3 – 300[a]	5.5[c]	2.6[c]	-
- breeding region total	-	5.3	1.8	-
- manifold and shield region total	-	1.3	0.006	-
- total ib/ob segments	-	3.1/9.0	4.4 (total)	3/7
• in solid breeder (g)				
- breeding region total ib/ob	100	3/7	na	na
• in multiplier (g)				
- breeding region total	400 – 3400[b]	1278	na	na
• in fluids (g)				
- total liquid breeder ib/ob	na	na	16/41	7/13
- total first wall coolant ib/ob	-	0.17/0.3	< 2.4/ < 3.9	4.9 (ib + ob)
- total breeder/multiplier coolant ib/ob	-	included in FW	na	8.2 (ib + ob)
- total NaK circuits ib/ob	na	na	0.1/0.3	na
- total purge gas	0.01	0.08	na	na
• in tritium recovery system (g)				
- total extraction units	-	300	100	ca. 1
- maximum per unit	-	100	15	-

Note:

a. According to [1]; uncertainties from tritium implantation from the plasma.
b. According to [1]; uncertainties in the assessment.
c. FISPACT results; numbers do not include the tritium implanted from the plasma.

Table 11 (Page 8 of 13). DEMO blanket concepts data sheets

Item	BIT	BOT	DC	WC
9. Power Production in Normal Operation (after 20000 h)				
• in structural material (W/cm^3)				
- first wall region midplane average ib/ob	-	18.5/24.7	16.0/21.9	-
- first wall region total average ib/ob	-	15.4/20.6	13.4/18.4	-
- breeding region midplane average ib/ob	-	6.14/8.18	1.3/1.7	-
- breeding region total average ib/ob	-	5.12/6.82	1.1/1.5	-
- shield region midplane average ib/ob	-	5.03/6.71	0.15/0.2	-
- shield region total average ib/ob	-	4.19/5.59	0.15/0.2	-
• In solid breeder material (W/cm^3)				
- in breeding region midplane average ib/ob	-	13.8/18.4	na	na
- in breeding region total average ib/ob	-	11.5/15.3	na	na
• In solid multiplier (W/cm^3)				
- in breeding region midplane average ib/ob	-	3.68/4.90	na	na
- in breeding region total average ib/ob	-	3.06/4.08	na	na
• In liquid breeder (W/cm^3)				
- in breeding region midplane average ib/ob	-	na	3.0/4.0	-
- in breeding region total average ib/ob	-	na	2.6/3.5	-
10. Specific Activity after 0 s, 1 d, 1 y, 10 y, 500 y .				
• in structural material (Bq/kg)				
- first wall region midplane average ib/ob				
⇒ after 0 s	-	6.2e14/7.1e14	5.8e14/6.6e14	6.0e14/1.0e15
⇒ after 1 d	-	3.5e14/4.0e14	3.6e14/4.0e14	6.0e14/1.0e15
⇒ after 1 y	-	2.0e14/2.3e14	2.1e14/2.3e14	2.5e14/5.0e14
⇒ after 10 y	-	1.8e13/2.0e13	1.8e13/2.1e13	2.0e13/5.0e13
⇒ after 500 y	-	2.9e09/3.2e09	2.7e09/3.0e09	3.0e09/5.0e09

Table 11 (Page 9 of 13). DEMO blanket concepts data sheets

Item	BIT	BOT	DC	WC
- first wall region total average ib/ob				
⇒ after 0 s	-	2.9e14/3.3e14	2.4e14/4.5e14	5.3e14/8.5e14
⇒ after 1 d	-	1.5e14/1.8e14	1.5e14/2.7e14	4.5e14/8.5e14
⇒ after 1 y	-	8.5e13/1.0e14	8.5e13/1.6e14	2.3e14/4.5e14
⇒ after 10 y	-	7.6e12/8.9e12	3.8e12/1.4e13	2.0e13/4.5e13
⇒ after 500 y	-	1.5e09/1.6e09	1.3e09/2.2e09	3.0e09/4.0e09
- breeding region midplane average ib/ob				
⇒ after 0 s	-	2.3e14/1.9e14	4.0e13/4.2e13	-
⇒ after 1 d	-	1.0e14/8.3e13	1.8e13/2.5e13	-
⇒ after 1 y	-	5.3e13/4.3e14	8.6e12/1.4e13	-
⇒ after 10 y	-	4.7e12/3.8e12	8.1e11/1.2e12	-
⇒ after 500 y	-	1.3e09/9.9e08	5.0e08/6.4e08	-
- breeding region total average ib/ob				
⇒ after 0 s	-	9.8e13/7.5e13	1.6e13/2.8e13	-
⇒ after 1 d	-	4.0e13/3.1e13	6.5e12/1.6e13	-
⇒ after 1 y	-	2.0e13/1.6e13	2.9e12/9.0e12	-
⇒ after 10 y	-	1.8e12/1.4e12	1.9e11/7.8e11	-
⇒ after 500 y	-	6.2e08/4.6e08	2.3e08/4.6e08	-
- shield region midplane average ib/ob				
⇒ after 0 s	-	1.9e13/1.3e13	2.0e13/4.8e12	2.8e12/4.0e11
⇒ after 1 d	-	6.7e12/4.0e12	5.8e12/1.4e12	1.0e12/1.5e11
⇒ after 1 y	-	2.7e12/1.5e12	1.8e12/4.5e11	5.0e11/5.0e10
⇒ after 10 y	-	2.8e11/1.6e11	2.3e11/5.8e10	5.0e10/6.0e09
⇒ after 500 y	-	1.9e08/1.2e08	2.7e08/7.1e07	5.0e07/7.0e06
- shield region total average ib/ob				
⇒ after 0 s	-	8.7e12/7.0e12	8.7e12/3.5e12	-
⇒ after 1 d	-	2.8e12/2.1e12	2.4e12/1.0e12	-
⇒ after 1 y	-	1.1e12/7.6e11	7.4e11/3.2e11	-
⇒ after 10 y	-	1.2e11/8.7e10	9.9e10/4.1e10	-
⇒ after 500 y	-	8.9e07/7.3e07	1.2e08/5.2e07	-

Table 11 (Page 10 of 13). DEMO blanket concepts data sheets

Item	BIT	BOT	DC	WC
• In solid breeder material (Bq/kg)				
- breeding region midplane average ib/ob				
⇒ after 0 s	1.5e14/2.7e14	1.1e14/8.2e13	na	na
⇒ after 1 d	-	2.5e11/1.9e11	na	na
⇒ after 1 y	-	1.1e10/8.7e09	na	na
⇒ after 10 y	-	1.2e09/9.6e08	na	na
⇒ after 500 y	-	1.6e08/1.2e08	na	na
- breeding region total average ib/ob				
⇒ after 0 s	4.8e13/4.5e13	3.6e13/2.7e13	na	na
⇒ after 1 d	-	9.4e10/7.0e10	na	na
⇒ after 1 y	-	4.0e09/2.9e09	na	na
⇒ after 10 y	-	4.3e08/3.2e08	na	na
⇒ after 500 y	-	5.7e07/4.3e07	na	na
• In solid multiplier (beryllium) (Bq/kg)				
- breeding region midplane average ib/ob				
⇒ after 0 s	-/3.0e14	3.2e14/2.7e14	na	na
⇒ after 1 d	-	1.5e13/1.2e13	na	na
⇒ after 1 y	-	1.3e13/1.1e13	na	na
⇒ after 10 y	-	7.5e12/6.3e12	na	na
⇒ after 500 y	-	4.4e08/3.4e08	na	na
- in breeding region total average ib/ob				
⇒ after 0 s	-	1.2e14/1.1e14	na	na
⇒ after 1 d	-	4.9e12/4.3e12	na	na
⇒ after 1 y	-	4.0e12/3.5e12	na	na
⇒ after 10 y	-	2.4e12/2.1e12	na	na
⇒ after 500 y	-	2.0e08/1.6e08	na	na

Table 11 (Page 11 of 13). DEMO blanket concepts data sheets

Item	BIT	BOT	DC	WC
• In liquid breeder (Bq/kg)				
- mixed mean (from circulation) ib/ob				
⇒ after 0 s	na	na	3.3e13/3.3e13	-
⇒ after 1 d	na	na	6.9e11/7.0e11	-
⇒ after 1 y	na	na	3.2e09/3.0e09	-
⇒ after 10 y	na	na	3.7e08/3.8e08	-
⇒ after 500 y	na	na	4.8e06/3.9e06	-
11. Afterheat Production after 0 s, 1 h, 1 d, 1 month, 1 y				
• in structural material (W/cm^3)				
- In first wall region midplane average ib/ob				
⇒ after 0 s	-	8.9e-1/1.0e0	7.4e-1/8.4e-1	7.5e-1/1.0e0
⇒ after 1 h	-	6.3e-1/7.1e-1	5.2e-1/5.9e-1	5.0e-1/7.0e-1
⇒ after 1 d	-	7.8e-2/8.8e-2	7.0e-2/7.9e-2	6.5e-2/9.0e-2
⇒ after 1 month	-	6.4e-2/7.3e-2	5.9e-2/6.6e-2	5.0e-2/7.0e-2
⇒ after 1 y	-	2.9e-2/3.3e-2	2.5e-2/2.9e-2	-
- first wall region total average ib/ob				
⇒ after 0 s	-	4.2e-1/4.7e-1	3.2e-1/5.8e-1	-
⇒ after 1 h	-	3.0e-1/3.4e-1	2.2e-1/5.8e-1	-
⇒ after 1 d	-	3.6e-2/4.1e-2	3.0e-2/5.4e-2	-
⇒ after 1 month	-	2.9e-2/3.3e-2	2.5e-2/4.5e-2	-
⇒ after 1 y	-	1.3e-2/1.5e-2	1.1e-2/2.0e-2	-
- breeding region midplane average ib/ob				
⇒ after 0 s	-	4.0e-1/3.3e-1	6.5e-2/5.5e-2	-
⇒ after 1 h	-	2.9e-1/2.3e-1	4.6e-2/3.9e-2	-
⇒ after 1 d	-	3.3e-2/2.7e-2	5.2e-3/5.8e-3	-
⇒ after 1 month	-	2.6e-2/2.1e-2	3.8e-3/4.7e-3	-
⇒ after 1 y	-	1.2e-2/9.6e-3	1.8e-3/2.0e-2	-

Table 11 (Page 12 of 13). DEMO blanket concepts data sheets

Item	BIT	BOT	DC	WC
- breeding region total average ib/ob				
⇒ after 0 s	-	1.8e-1/1.4e-1	2.8e-2/3.7e-2	-
⇒ after 1 h	-	1.3e-1/9.9e-2	2.0e-2/2.8e-2	-
⇒ after 1 d	-	1.4e-2/1.1e-2	2.0e-3/3.8e-3	-
⇒ after 1 month	-	1.1e-2/8.3e-3	1.4e-3/3.1e-3	-
⇒ after 1 y	-	5.2e-3/4.0e-3	6.9e-4/1.3e-3	-
- shield region midplane average ib/ob				
⇒ after 0 s	-	3.8e-2/2.6e-2	4.1e-2/9.7e-3	1.1e-3/1.5e-3
⇒ after 1 h	-	2.8e-2/1.9e-2	3.0e-2/7.1e-3	7.5e-4/1.0e-3
⇒ after 1 d	-	2.8e-3/1.9e-3	2.4e-3/5.6e-4	4.5e-5/6.5e-5
⇒ after 1 month	-	2.0e-3/1.4e-3	1.5e-3/3.5e-4	2.8e-5/4.0e-5
⇒ after 1 y	-	1.1e-3/7.8e-4	9.3e-4/2.2e-4	-
- shield region total average ib/ob				
⇒ after 0 s	-	1.7e-2/1.4e-2	1.8e-2/7.0e-3	-
⇒ after 1 h	-	1.3e-2/1.1e-2	1.3e-2/5.1e-3	-
⇒ after 1 d	-	1.2e-3/9.7e-4	1.0e-3/4.0e-4	-
⇒ after 1 month	-	8.7e-4/6.9e-4	6.6e-4/2.5e-4	-
⇒ after 1 y	-	4.9e-4/4.0e-4	4.1e-4/1.5e-4	-
• In solid breeder material (W/cm^3)				
- breeding region midplane average ib/ob				
⇒ after 0 s	-	1.7e-1/1.3e-1	na	na
⇒ after 1 h	-	1.6e-3/1.2e-3	na	na
⇒ after 1 d	-	2.6e-4/2.0e-4	na	na
⇒ after 1 month	-	5.0e-6/3.9e-6	na	na
⇒ after 1 y	-	7.4e-7/5.5e-7	na	na
- breeding region total average ib/ob				
⇒ after 0 s	-	8.5e-2/4.3e-2	na	na
⇒ after 1 h	-	1.4e-3/5.3e-4	na	na
⇒ after 1 d	-	1.5e-4/7.1e-5	na	na
⇒ after 1 month	-	2.6e-6/1.3e-6	na	na
⇒ after 1 y	-	4.0e-7/2.0e-7	na	na

Table 11 (Page 13 of 13). DEMO blanket concepts data sheets

Item	BIT	BOT	DC	WC
• In solid multiplier (beryllium) (W/cm^3)				
- breeding region midplane average ib/ob				
⇒ after 0 s	-	1.3e-1/1.1e-1	na	na
⇒ after 1 h	-	9.7e-4/7.7e-4	na	na
⇒ after 1 d	-	3.5e-4/2.9e-4	na	na
⇒ after 1 month	-	9.4e-5/7.7e-5	na	na
⇒ after 1 y	-	4.6e-5/3.6e-5	na	na
- breeding region total average ib/ob				
⇒ after 0 s	-	5.8e-2/4.4e-2	na	na
⇒ after 1 h	-	5.8e-4/3.5e-4	na	na
⇒ after 1 d	-	1.6e-4/1.2e-4	na	na
⇒ after 1 month	-	3.6e-5/3.1e-5	na	na
⇒ after 1 y	-	1.7e-5/1.5e-5	na	na
• In liquid breeder (W/cm^3)				
- mixed mean (from circulation) ib/ob				
⇒ after 0 s	na	na	7.6e-2/7.7e-2	-
⇒ after 1 h	na	na	2.2e-3/2.1e-3	-
⇒ after 1 d	na	na	3.9e-4/4.0e-4	-
⇒ after 1 month	na	na	1.3e-5/1.2e-5	-
⇒ after 1 y	na	na	2.7e-6/1.9e-6	-

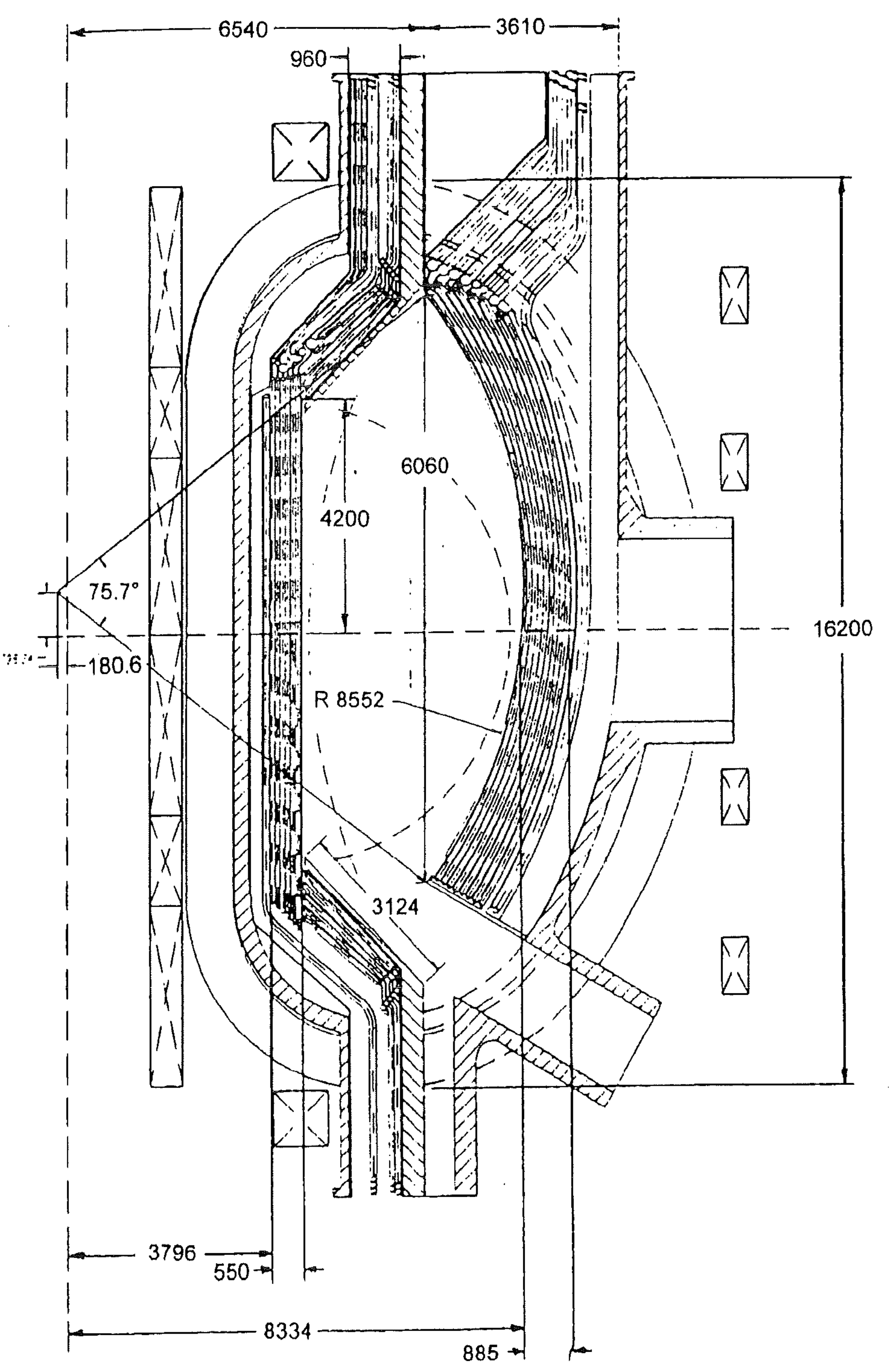

Figure 1. Vertical cross section of the DEMO reactor equipped with the BIT blanket. (reproduced from [1])

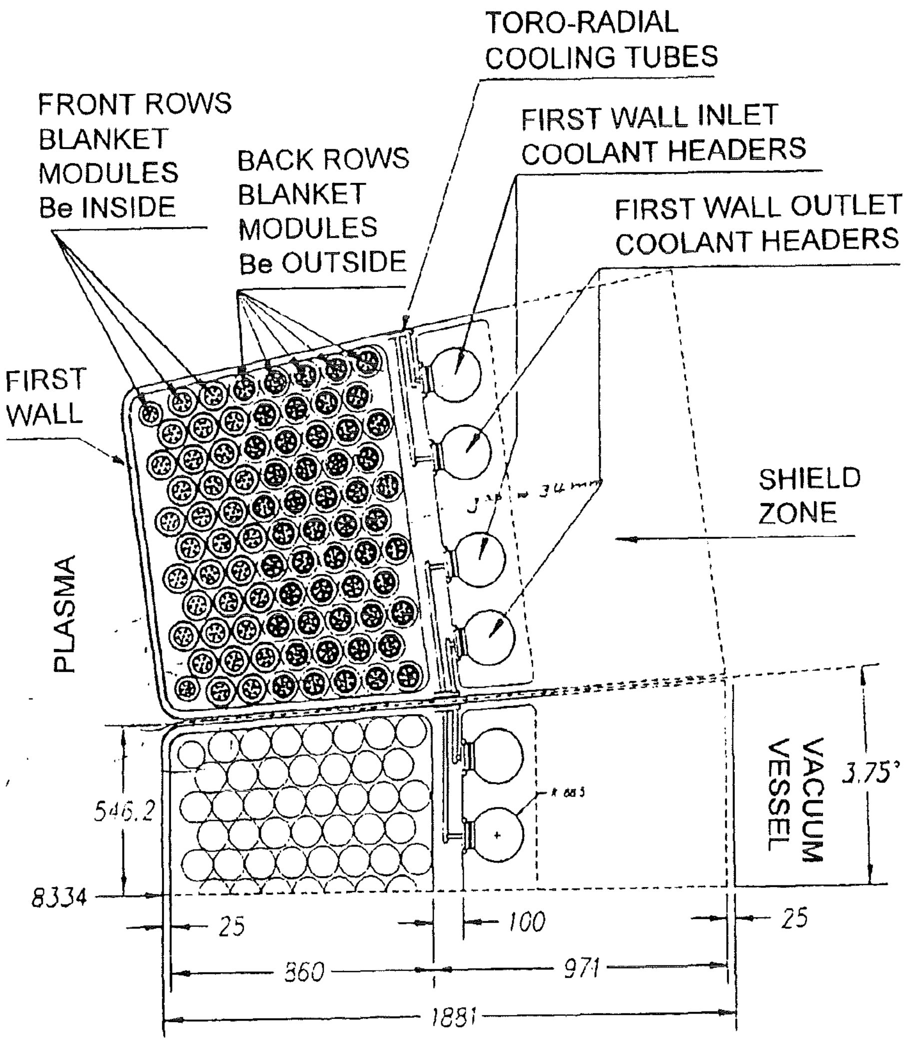

Figure 2. Outboard midplane cross section of the BIT blanket.
(reproduced from [1])

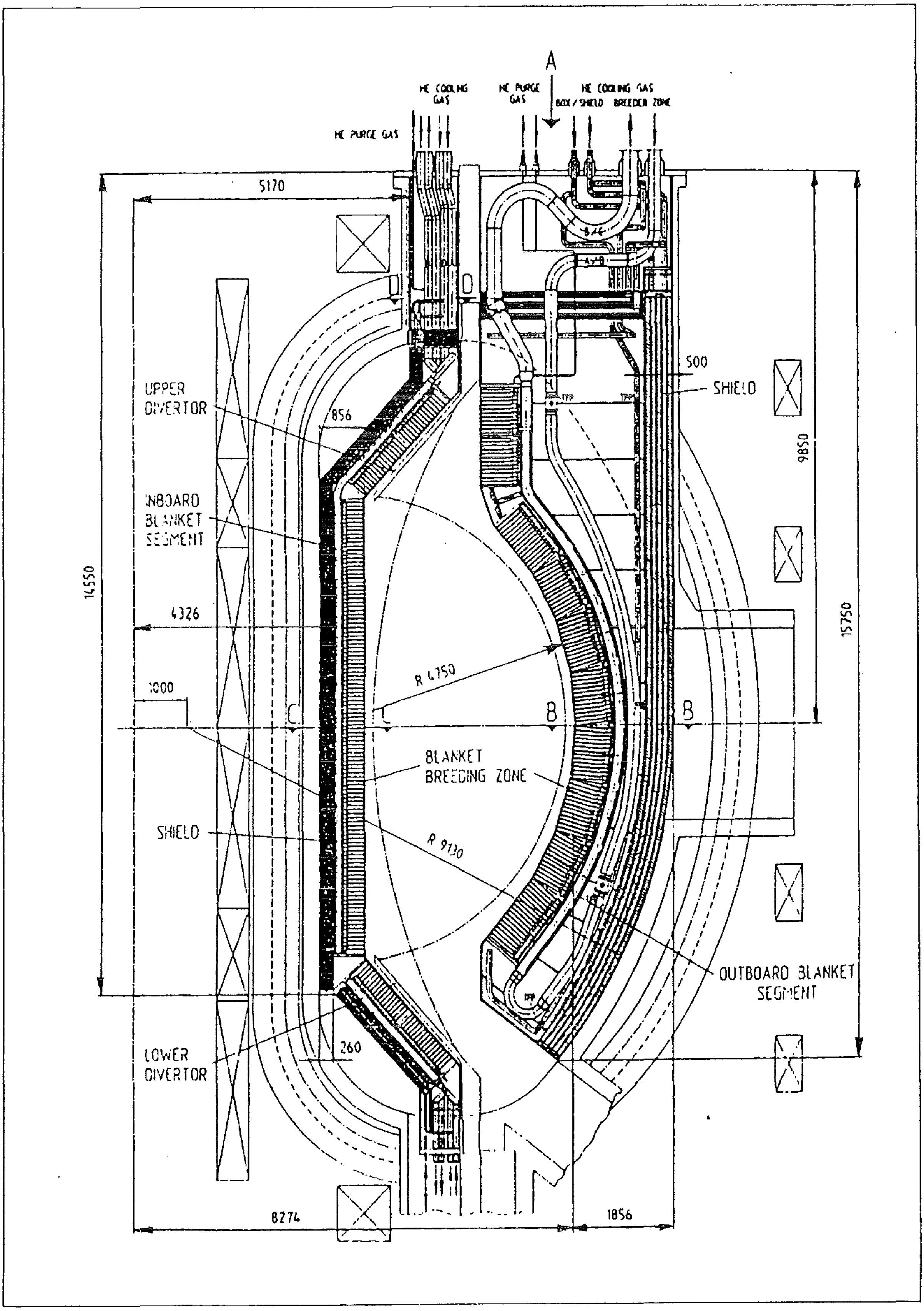

Figure 3. Vertical cross section of the DEMO reactor equipped with the BOT blanket. (reproduced from [2])

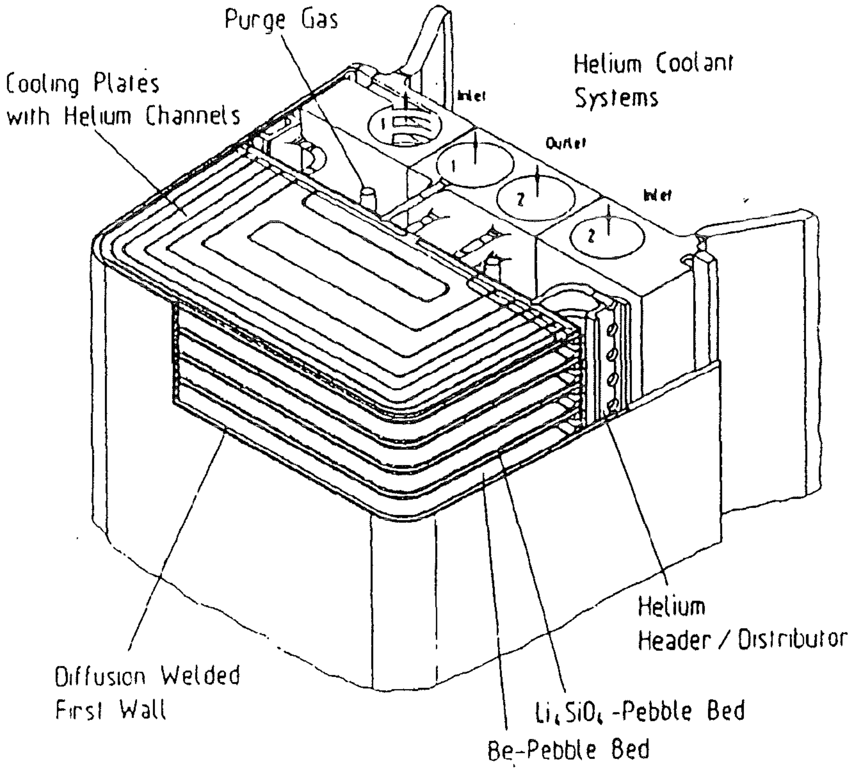

Figure 4. Isometric view of the BOT blanket (outboard segment).
(reproduced from [2])

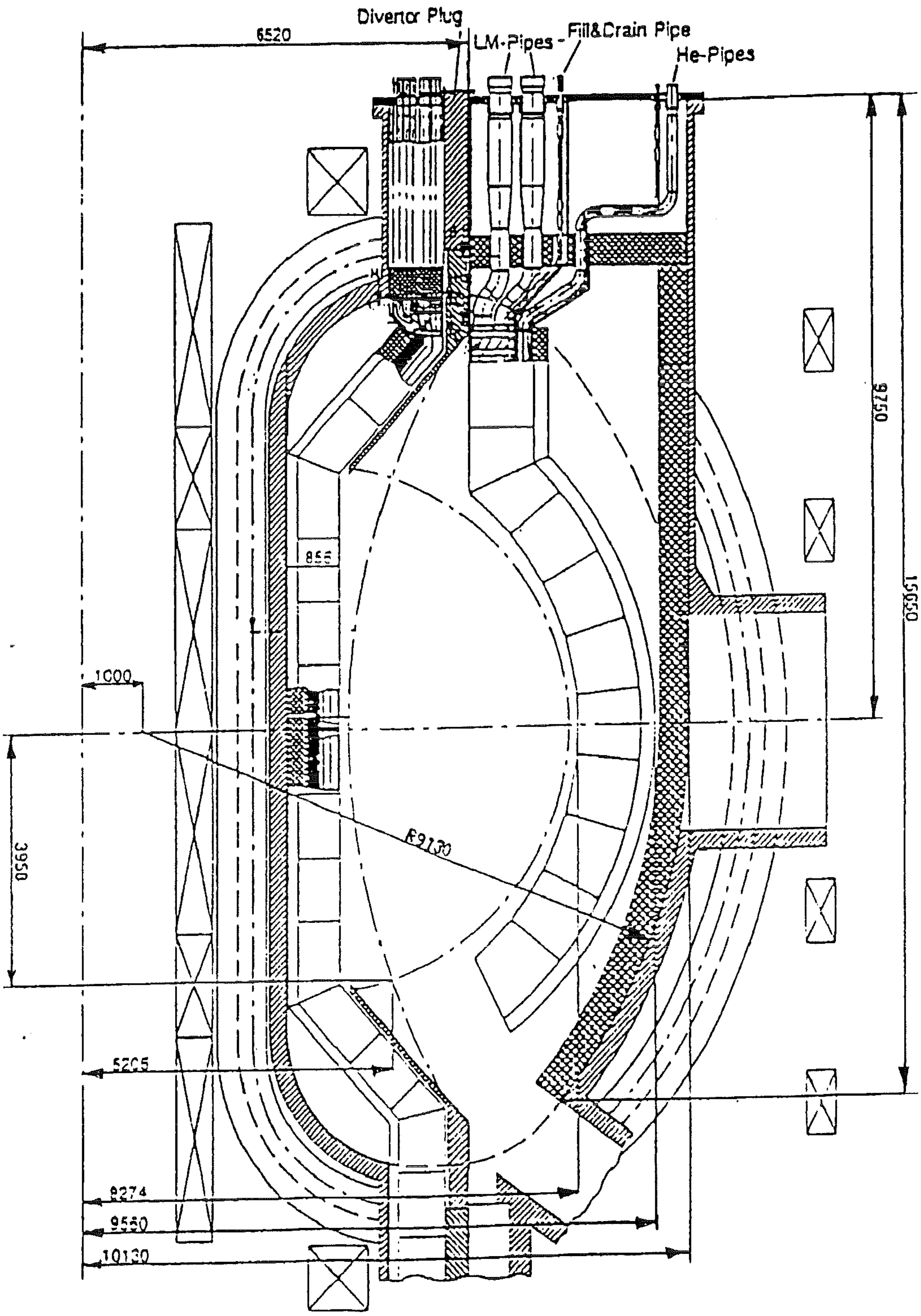

Figure 5. Vertical cross section of the DEMO reactor equipped with the DC blanket. (reproduced from [3])

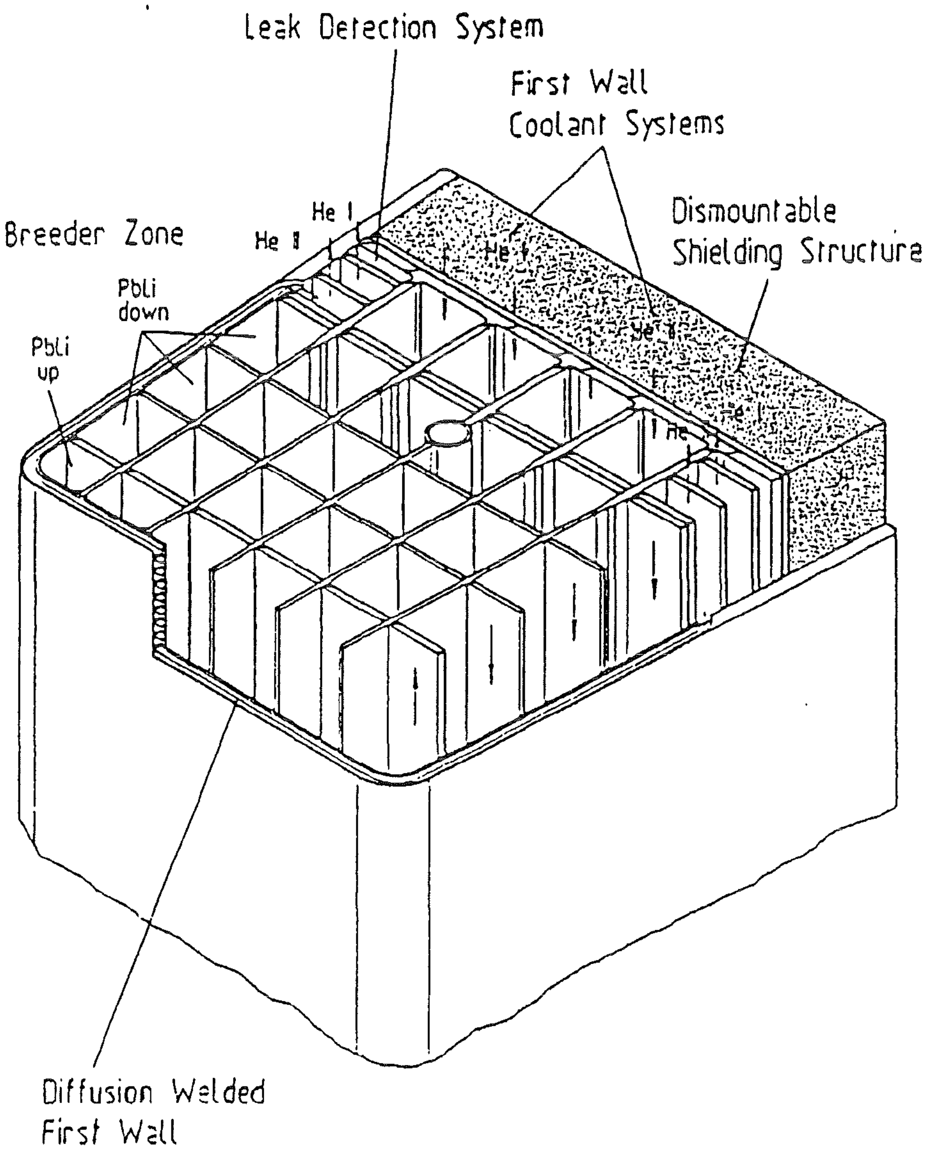

Figure 6. Isometric view of the DC blanket (outboard segment).
(reproduced from [3])

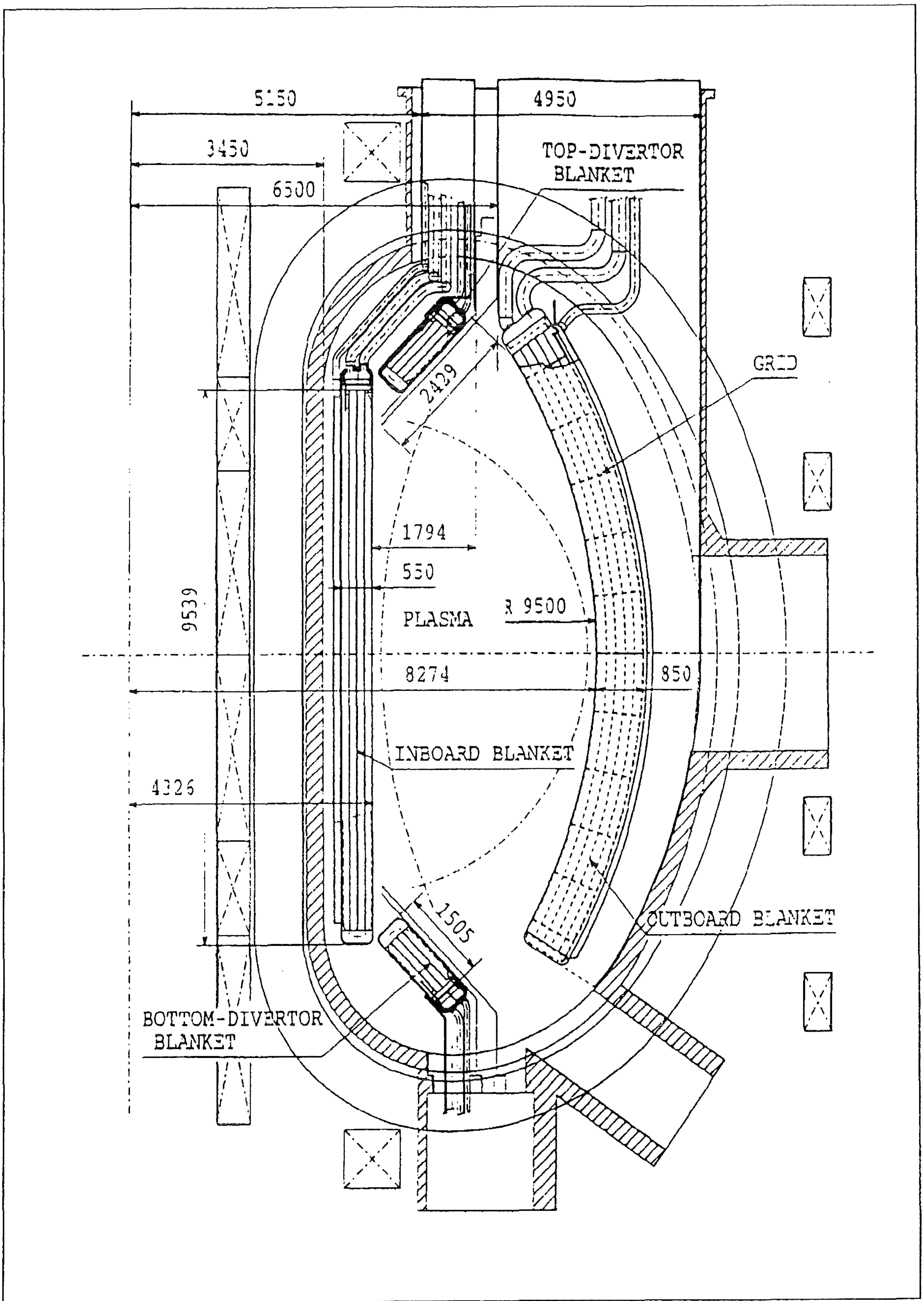

Figure 7. Vertical cross section of the DEMO reactor equipped with the WC blanket. (reproduced from [4])

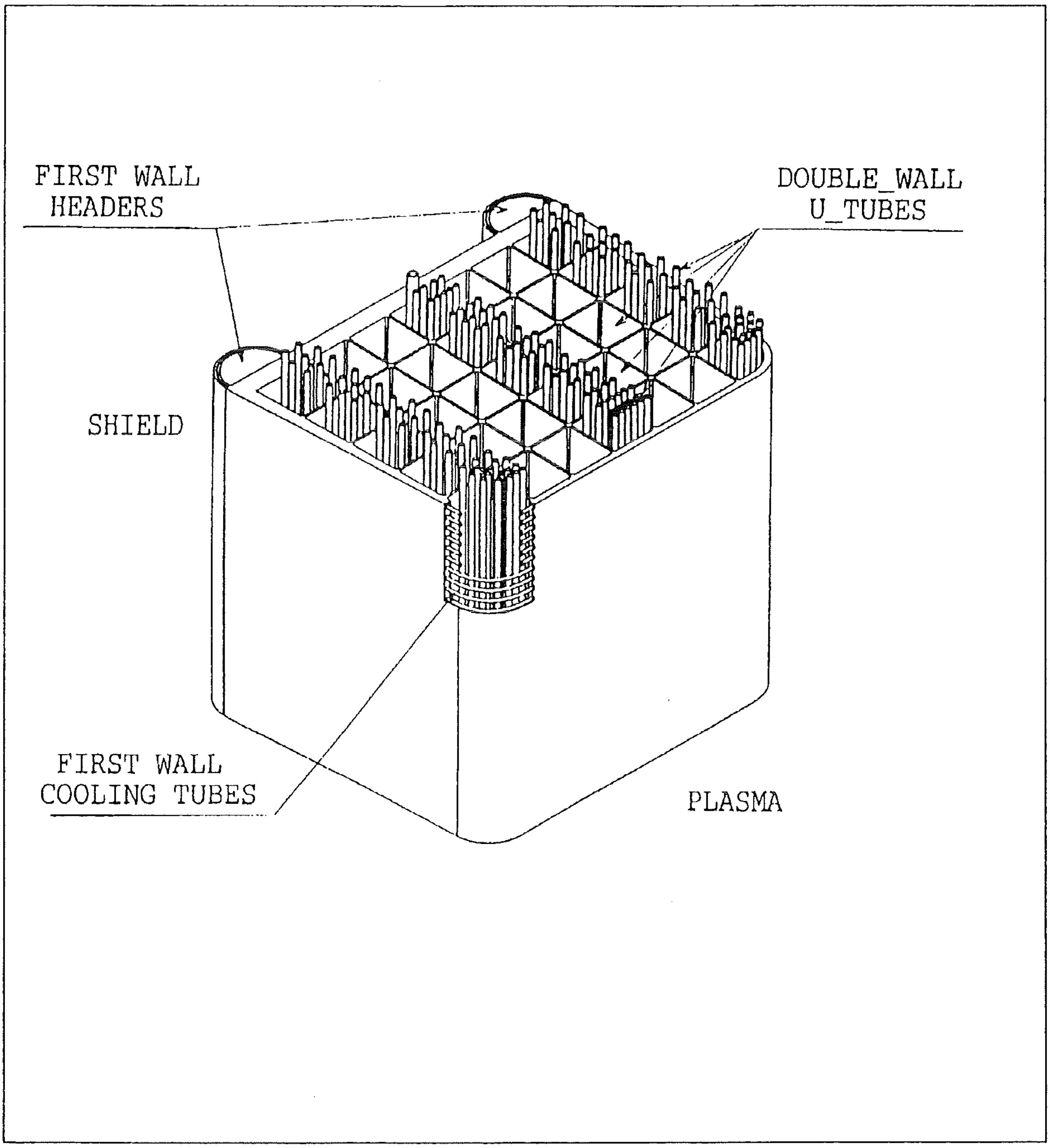

Figure 8. Isometric view of the WC blanket (outboard segment).
(reproduced from [4])