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Breeding blanket concepts for fusion and materials requirements

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Abstract

This paper summarizes the design and performances of recent breeding blanket concepts and identifies the key material issues associated with them. An assessment of different classes of concepts is carried out by balancing out the potential performance of the concepts with the risk associated with the required material development. Finally, an example strategy for blanket development is discussed.

1. Introduction

A variety of breeding blanket concepts has been considered, ranging from more conservative concepts to higher-risk higher-payoff concepts for future reactors. The major candidate breeding materials consist of liquid breeders, mainly liquid metals although recently some attention has been given to FLiBe, and lithium ceramic breeders. The degree of conservatism in the concept is often linked with the choice of structural material since more advanced concepts generally require operation at high temperature to provide for high cycle efficiency and power production performance and, thus, a greater degree of extrapolation in structural material properties and technology. The choice of structural material in turn influences the choice of breeding material based on accommodation of key issues such as material compatibility and temperature limits.

Most of the recent blanket studies were performed for magnetic fusion energy reactors and this paper focuses on blankets for this application. The paper also focuses on the more widely studied blankets with solid walls. Liquid wall concepts have received some attention lately mostly as part of the APEX study [1]. A thick liquid wall blanket would be a completely different category of concept and out of the scope of this paper. Thin wall concepts proposed for wall protection would still require blanket and structural materials similar to solid wall concepts and, as such, would have to address many of the blanket material issues discussed in this paper.

The paper summarizes the range of blanket concepts being currently considered, highlighting some of the key material-based issues associated with different classes of blanket concepts. Performance and attractiveness parameters are discussed and an example ranking of concepts based on the level of attractiveness and the development risk is provided. Finally, a strategy for blanket development and supporting material R&D is discussed.

2. Performance and attractiveness measures

The performance and attractiveness of a blanket concept is dependent on a number of parameters, including:

Power production for given plant size: Power production is proportional to the fusion power, the neutron

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energy multiplier and the cycle efficiency. The choice of blanket material directly affects the neutron energy multiplier. It also affects the cycle efficiency since material temperature limits directly influence the maximum allowable coolant temperature and, in turn, the power cycle efficiency.

Safety: This is a key area which particularly influences public perception and acceptance. Blanket materials with low short-term activation are attractive in particular if the corresponding blanket and shield system provides for passive accommodation of off-normal scenarios such as LOCA and LOFA without major consequences. Long-term activation of blanket materials influences the end of life waste disposal requirements.

Availability: Commercial reactors would require high availability and thus minimum planned and unplanned downtime for replacement. Key blanket parameters influencing this are the reliability, lifetime and replacement time of the blanket system.

Design and Fabrication: Simplicity in the blanket and design and fabrication process tends to result in lower capital cost and more reliable system and is preferred.

Tritium: Tritium issues relate to the need to provide self-sufficiency from blanket tritium breeding and to provide acceptable safety parameters including the total inventory in the blanket system and the possibility of permeation and contamination in ancillary equipment and in the tritium processing system (influenced by permeation of tritium from cooling and purge lines). Blanket material and coolant choices directly influence these issues.

Economics: The cost of electricity represents the bottom line for commercial fusion reactor. It is influenced by most of the other parameters discussed above and would be the ultimate economic measure.

The performance and attractiveness of a blanket is coupled with the design and requirements of other reactor systems. For example, any blanket must play a significant role in shielding the magnets and breeding performance would compete with shielding performance in space restricted regions such as the mid-section of the inboard region. Blankets with higher specific shielding capability and with higher local breeding ratio would provide substantial advantage in this case. The blanket must also be compatible with other systems. For example, it is often desirable to have the same coolant for both blanket and divertor, which places additional demands on the coolant heat transfer performance.

3. Summary description of representative blanket concepts

To help focus the discussion, the blanket concepts are divided among different classes based on the structural and breeder materials. For each class of concept, an example blanket design is described to set the stage for a discussion of the overall issues associated with that class of concepts. To facilitate the understanding and comparison of different concepts, a summary of major parameters for some of the main concepts being currently considered is shown in Table 1.

3.1. Ceramic breeder + ferritic/martensitic steel structure concepts

This class of concepts includes a combination of a ceramic breeder, a beryllium-based multiplier, and a ferritic/martensitic steel (FMS) as structural material. The ceramic breeder and Be multiplier can be in the form of sintered blocks or pebble beds. Candidate breeder materials are (in the order of decreasing lithium density): Lithium oxide (Li_2O), lithium orthosilicate (Li_4SiO_4), lithium metatitanate (Li_2TiO_3) and lithium metazirconate (Li_2ZrO_3). Two different coolants have been considered: water and helium. The major material and design issues generally associated these concepts can be summarized as follows:

(1) Chemical compatibility between the Be multiplier and water/air if water is used as a coolant or in case of air/water ingress in an accident scenario. Hydrogen production due to Be-water reaction is a key safety issue.
(2) Tritium production, release and trapping characteristics of the breeding material and more importantly of the Be multiplier. Tritium permeation to the coolant is also an issue which is of major concern if water is used as coolant because of the difficulty in processing the tritium out of the water.
(3) Thermo-mechanical interactions between the pebbles and the structure including neutron irradiation effects.
(4) Limits on allowable power density due to the relatively low thermal conductivity of the ceramic breeder.
(5) Limits on blanket lifetime due to irradiation damages in ceramic breeder and beryllium.
(6) Neutron shield performance in particular with He as coolant.
(7) Cost of fabrication and re-processing of the ceramic breeder material. For tritium breeding reasons, the lithium contained in this material must be enriched to 30–60% Li-6 (above the natural level of 7.5%). Cost and waste considerations mandate re-processing of replaced blanket modules and re-use of the lithium.

A water-cooled concept is described as an example below; some of the major features and issues of a He-cooled concept are then highlighted.

3.1.1. Water-cooled concepts

Fig. 1 illustrates the design of a water-cooled ceramic breeder blanket with F82H reduced activation ferritic

Table 1
Some design parameters for different breeding blanket concepts

Example concept	SSTR [2]	HCPB [5]	WCLL [12]	DC [10]	ARIES-RS [13]	ARIES-AT [15]	A-SSTR2 [19]	EVOLVE [20]	FFHR-2 [21]
Breeder (form)	Li_2O or Li_2TiO_3 (pebble bed)	Li_4SiO_4 or Li_2TiO_3 (pebble bed)	Pb–17Li	Pb–17Li	Li	Pb–17Li	Li_2TiO_3 (pebble bed)	Li	FLiBe
Multiplier (form)	Be (pebble bed)	Be (pebble bed)	–	–	–	–	Be (pebble bed)	–	Be (pebble bed)
Coolant	H_2O	He	H_2O	Self + He	Self	Self	He	Li (evap.)	Self
Structure	F82H (RAFS)	FMS	FMS	FMS	V–4Cr–4Ti + CaO Ins. Layer	SiC_f/SiC	SiC_f/SiC	W Alloy	FS
Structural T_{max} (°C)	550	550	550	550	700	1000	1157	1300	550
Structural T_{min} (°C)	$\sim$280	300	265	300	330	764	700		
Breeder T_{max} (°C)	600–900	890	550	700	610	1000	$\sim$800	1200	550
Breeder T_{min} (°C)	$\sim$300	400	285	460	330	764	$\sim$700	1100	450
Multiplier T_{max} (°C)	600	700	–	–	–	–	$\sim$800	–	
Multiplier T_{min} (°C)	$\sim$300	400	–	–	–	–	$\sim$700	–	
Coolant T_{max} (°C)	320 (520[a])	500	325	He: 480	610	1100	900	1200	550
Coolant T_{min} (°C)	280 (290[a])	250	265	He: 300	330	764	600	1100	450
Coolant P (MPa)	15 (25[a])	8	15.5	14	<1	1.1	10	0.035	0.5
Max. neutron wall load (MW/m^2)	3–5	3.5	5.5	5.0	5.6	4.8	6	10	1.5
Max. surf. heat flux (MW/m^2)	1	0.7	1.0	0.9	0.5	0.34	<1	2.0	0.1
Energy multiplication factor	1.3	1.39	1.18	1.17	1.21	1.11	1.3	1.2	
TBR	1.2	1.11	1.1	1.1	1.1	1.1	$\sim$1.3	>1	>1
Cycle η (%)	$\sim$35 ($>$40[a])	37	33	45	46	58.5	>50	>55	38
Structural material lifetime and criteria	$>$10 $MW\text{-}a/m^2$ 100–200 dpa	15 $MW\text{-}a/m^2$ 150 dpa swelling	15 $MW\text{-}a/m^2$ 150 dpa swelling	15 $MW\text{-}a/m^2$ 150 dpa swelling	15 $MW\text{-}a/m^2$ 200 dpa embrittlement	18 $MW\text{-}a/m^2$ Assuming 3% SiC burnup	10 $MW\text{-}a/m^2$	Not available	15 $MW\text{-}a/m^2$ 150 dpa swelling

[a] Supercritical-pressure water.

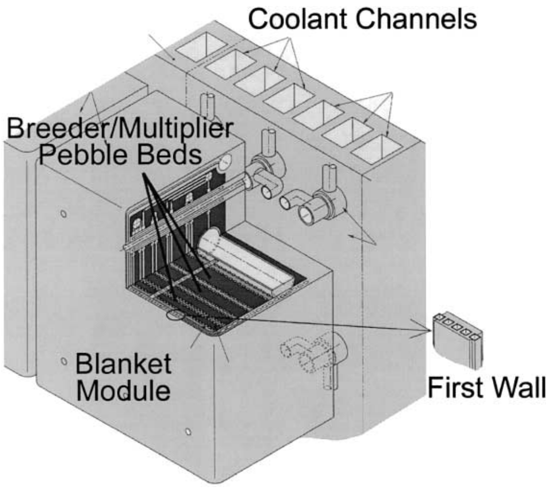

Fig. 1. SSTR water-cooled ceramic breeder blanket with reduced activation ferritic steel structure [2].

steel (RAFS) proposed by JAERI. Its design parameters are summarized in Table 1 [2]. The coolant water conditions are similar to those of a PWR. The use of supercritical-pressure water, e.g. ~500 °C/25 MPa, is also under consideration with the goal of increasing the power cycle efficiency to about 40–45%. Packed beds of binary spheres, e.g. of diameters 1–2 and 0.1–0.3 mm, are currently considered for both the ceramic breeder and the Be neutron multiplier for maximizing the rather modest effective thermal conductivities of the pebble bed regions and the breeding performance. Li_2O is the first candidate as breeder material with ternary ceramic materials such as Li_2TiO_3 as alternative candidates. It has been reported that F82H has good compatibility with Li_2O or Be [3]. Safety analyses have also been performed to help address issues such as water-Be reaction [4]. One possible solution to reduce hydrogen production would be the use of $Be_{12}Ti$, which has better compatibility with water. The use of supercritical-pressure water results in high thermal stresses in the first wall and breeding regions. In this case, use of stronger advanced ferritic steel, such as Dispersion Strengthened Ferritic Steel, is under consideration.

3.1.2. Helium-cooled concepts

There are a number of design concepts employing a lithium-ceramic as breeder material, mostly in combination with beryllium as neutron multiplier, ferritic/martensitic steel as structural material, and helium as coolant [5–7]. The ceramic breeders as well as the beryllium multiplier are compatible with the structural materials up to the temperature limits given by strength considerations. In some concepts coatings are required as tritium permeation barrier in order to reduce tritium fluxes to the coolant.

The main advantage of this class of ceramic breeder blankets is the good compatibility between breeder, structural material, and coolant. Use of He as coolant alleviates the safety concerns associated with the high chemical reactivity of beryllium with water and/or air and the possibility of release of the high tritium inventory in this material. Table 1 shows the typical parameters of such a class of concept, as represented by the helium cooled pebble bed (HCPB) blanket [5] under development in the frame of the European Union Blanket Development Programme. The listed parameters were generated from an attempt to find the performance limits of the concept.

3.2. Pb–17Li+ferritic/martensitic steel structure concepts

The eutectic lead-lithium alloy Pb–17Li is an attractive breeder material due to its high tritium breeding capability, its relatively large thermal conductivity, and its immunity to irradiation damage. It can lead to tritium self-sufficiency without employing additional neutron multipliers and allows for tritium extraction outside the vacuum vessel. Moreover, it offers unlimited lifetime of the breeder material due to the possibility to replenish on-line the Li-6 burn-up which implies that the liquid breeder can be even re-used in new power stations after a power station comes to the end of its operating time. Pb–17Li has also the advantage of being almost inert in air and of having only a relatively mild and controlled reaction with water. The compatibility of Pb–17Li with FMS has been experimentally demonstrated up to 480 °C [8].

The simplest conceivable system using FMS andPb–17Li is a self-cooled configuration. However, in order to avoid unacceptably high magneto-hydrodynamic (MHD) pressure drops, one needs to electrically insulate the Pb–17Li from the conducting walls. This condition is particularly difficult to achieve in the first wall (FW). Therefore, it has been shown that the best compromise is to cool the FW with helium, limiting the self-cooled part to the breeder zone. In this case, the insulation can be obtained using SiC_f/SiC flow channel inserts as utilized in the ARIES-ST [9] and FZK dual-coolant (DC) blanket concepts, the latter being described in the next section as an example of this class of blankets.

In order to avoid MHD effects, other options are to use helium or water as coolant for the whole blanket. The use of He-coolant leads to difficulties in achieving tritium breeding self-sufficiency. In contrast, the water-cooled option shows good breeding performances and has been evaluated in details in the European Union and the water-cooled lithium-lead (WCLL) concept is one of the two blanket concepts currently under development in the EU and proposed for breeding blanket testing in ITER [10]. Advantages and drawbacks of this concept are summarized below.

3.2.1. Dual-coolant blanket concept

An interesting variant of a self-cooled Pb–17Li blanket is the DC blanket concept which is characterized by a helium-cooled first wall and a self-cooled Pb–17Li breeding zone. There are flow channel inserts made of SiC_f/SiC composite arranged in the large liquid metal ducts serving as electrical insulator and, at the same time, as thermal insulator between the helium-cooled steel walls and the flowing Pb–17Li [11]. In this design, shown in Fig. 2, the blanket structure is made of a low activation ferritic–martensitic steel, and the SiC_f/SiC flow channel inserts have no mechanical loads, do not require high thermal conductivity and are relatively easy to fabricate.

The performance of this concept is limited by the maximum allowable FW temperature and by the compatibility of the structural material with Pb–17Li, limiting the allowable interface temperature to about 500 °C. Use of ODS-steels with their higher strength-based temperature limit would increase the load capabilities but welding requirements would make the fabrication more difficult. An interesting compromise is a version where the entire structure is made of ferritic steel, but the FW is plated with a few mm thick layer of ODS steel [12]. This restricts the use of ODS-steel to zones where structural temperatures >550 °C are desired. At all other places the temperature is limited to values <550 °C for compatibility reasons. It has been estimated that this concept allows for a liquid metal exit temperature up to 700 °C. With this temperature an efficiency of 45% is achievable, either with a Rankine or a Brayton cycle power conversion system. The main parameters for this concept are summarized in Table 1. From these parameters it can be concluded that the DC blanket concept combines in an interesting way high performance with a limited extrapolation of the required technology since it is based on ferritic steel as structural material and SiC has no structural functions. Degradation of thermal conductivity of SiC-composite by neutron irradiation is not a problem since this material serves here as a thermal insulator.

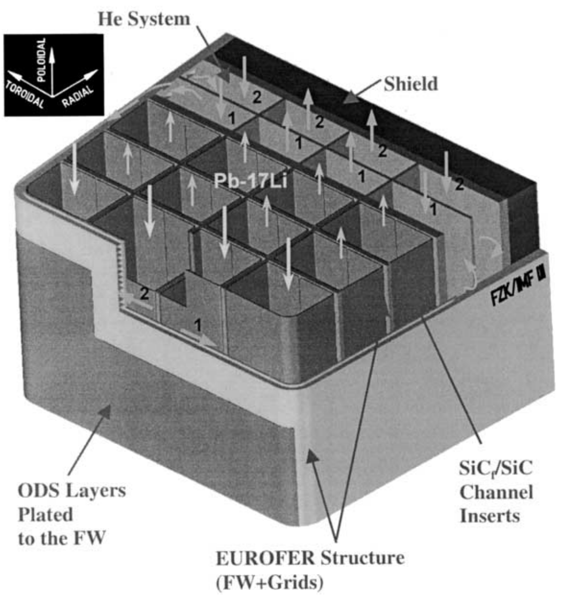

Fig. 2. DC blanket concept [11].

3.2.2. Water-cooled Pb–17Li blanket

The WCLL blanket uses pressurized water at PWR conditions as coolant for both the first wall and the breeding regions. The two coolant circuits are independent in order to improve safety. The assumed structural material is the ferritic/martensitic steel EUROFER. This blanket concept requires relatively limited extrapolation of present day technology. In particular, its coolant system can rely on the experience gained in PWR developments. Moreover, water-coolant allows relatively high heat loads on FW (>1 MW/m^2) while keeping structures and interface temperatures within acceptable limits [13].

As in a PWR, blanket thermal efficiency is limited to about 33% which is the lowest value among the potential blanket concepts. Other drawbacks could be the need of control of the Pb–17Li/water interaction in case of accidental guillotine rupture of a cooling tube and the need of limiting the tritium permeation from Pb–17Li to water. Both issues can be alleviated with appropriate counter-measures such as dimensioning the Pb–17Li container to the water-pressure, using double-wall tubes as coolant pipes (increasing the blanket reliability and availability at the same time), and applying tritium permeation barriers on the cooling tubes. All these issues are well addressed in a large R&D program performed within EU since several years [8]. A Test Breeder Module (TBM), corresponding to a mock-up of this blanket to be tested in ITER is also under development. It makes use of the technology required in a power plant blanket in order to have the experimental demonstration of the feasibility of the whole blanket system.

3.3. Self-cooled lithium + vanadium alloy structure concepts

Lithium shares much of the advantages listed for Pb–17Li in Section 3.2, namely high tritium breeding capability, high thermal conductivity, immunity to irradiation damage and possibility of unlimited lifetime if the Li-6 burn-up can be replenished [14]. Major drawbacks are the chemical reactivity of the breeder with air and water which is a safety concern, and the impact of the magnetic field on the liquid metal flow requiring electrical insulators in case of self-cooled blanket concepts [11].

A vanadium alloy has low activation, low after heat and high temperature and high heat flux capability. It is compatible with liquid lithium and is the preferred structural material candidate for self-cooled Li blanket concepts. The ARIES-RS blanket is an example of such a concept [15]. The first wall and breeding blanket use a simple box-like structure made of V–4Cr–4Ti alloy, with Li flowing in simple poloidal paths. A plan view of the outboard is shown in Fig. 3. An effective CaO insulating coating, maintained by adding 0.5% Ca in the flowing Li, is used to reduce the MHD pressure drop to an acceptable level. The development and demonstration of the performance of such insulating coatings in a fusion environment is a key R&D issue impacting the attractiveness of this blanket concept.

Multiple flow passes in the blanket provide the capability for removing at least 0.5 MW/m^2 of surface heat flux, which may be necessary with a highly-radiative divertor mode of operation. The full coolant flow is passed first through the front zone, where the surface heat flux creates large temperature gradients, and then through the back zones where the bulk temperature can be raised by volumetric heating without exceeding any structure temperature limits. Segmentation of the shield into a hot and cold zone allows partial utilization of the heat deposited, and also provides further capability for superheating the coolant away from the high heat flux region. An advanced Rankine cycle conservatively offers 46% gross thermal conversion efficiency. A double-walled IHX with a Na secondary loop is used to isolate the activated Li primary coolant from the steam side. The IHX is also the location where the transition from V to SS is made. The design parameters are summarized in Table 1.

In addition to the major issue of developing a reliable and self-healing coating compatible with low activation requirements, material interfaces and tritium recovery systems in a fusion environment, other issues with this class of concept include: (1) radiation damage effect on V-alloy from fusion neutron spectrum; (2) demonstration of fabrication of large scale V-alloy components; (3) joining of V-alloy to another structural material in the heat exchanger if the blanket is connected to a steam or He power cycle since it is questionable whether V-alloy would be compatible with water or He at high temperature; and cost of V-alloy under the goal of minimizing impurities to assure the low activation of the material.

3.4. SiC_f/SiC + liquid or ceramic breeders concepts

The use of SiC_f/SiC composite as structural material in a fusion reactor can be viewed as a high-risk high-

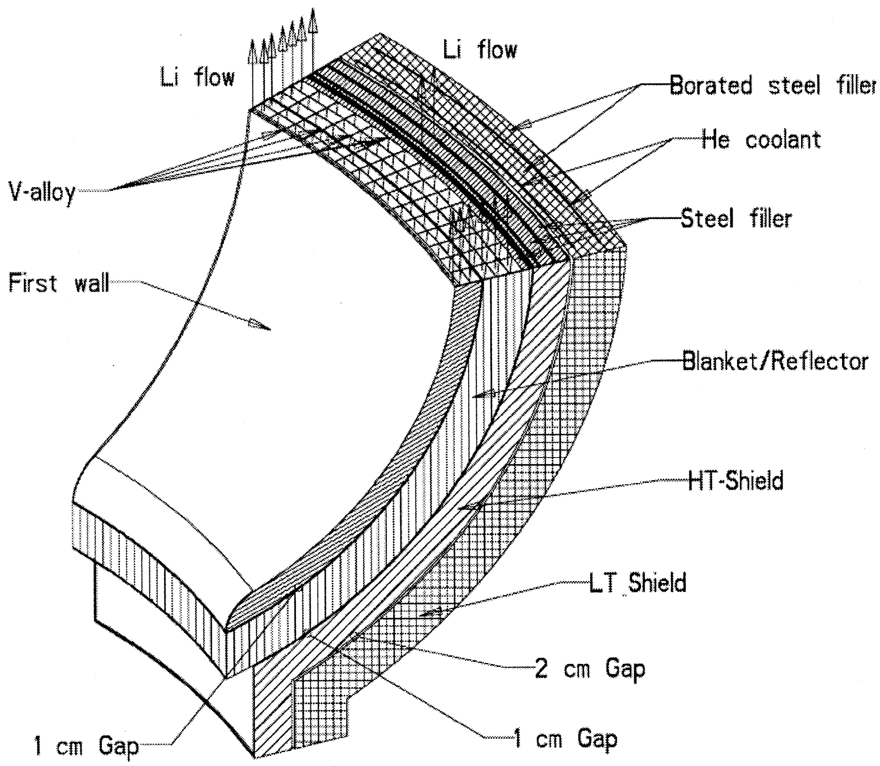

Fig. 3. Outboard cross-section of ARIES-RS blanket [15].

payoff endeavor. The high payoff is linked to the superior safety characteristics of SiC arising from its low induced radioactivity and after heat, and to the possibility of high performance through high temperature operation. The high risk is associated mainly with the uncertainty about SiC_f/SiC behavior and performance at high temperature and under irradiation, and in particular its thermal conductivity and maximum allowable operating temperature. SiC_f/SiC has been considered both with liquid metal (e.g. TAURO [16] and ARIES-AT [17]) and ceramic breeder (e.g. ARIES-I [18], DREAM [19], A-HCPB [20] and A-SSTR2 [21]) blanket concepts. Some of the key issues associated with the breeders are similar to those discussed in previous sections on concepts utilizing similar breeding materials. The discussion here will focus on the advantages and issues of this class of concepts resulting directly from the choice of SiC_f/SiC as structural material.

3.4.1. $SiC_f/SiC+Pb$–17Li concepts

The most recent concepts in this class have been developed and analyzed as part of the TAURO and ARIES-AT studies. Some differences exist between them such as in the assumed maintenance scenario leading to a smaller blanket module design for TAURO and a larger poloidal segment design for ARIES-AT, and in details of the design, fabrication and operation. However, key material-related issues and R&D tend to be similar and will be discussed within the context of the ARIES-AT design described here as an example of such a concept.

The ARIES-AT power core has been developed with the overall objective of achieving high performance while maintaining attractive safety features, simple design geometry, credible maintenance and fabrication processes, and reasonable design margins as an indication of reliability [17]. Fig. 4 shows a cross-section of an outboard segment of the ARIES-AT blanket. To minimize waste and to decrease cost, the blanket is subdivided radially into two regions: a replaceable first zone (in the inboard and outboard) and a life-of-plant second zone (in the outboard). The blanket design is modular and consists of a simple annular box through which the Pb–17Li flows in two poloidal passes. The first pass is a high-velocity flow through the annular channel region keeping the box walls cooled. The coolant then turns and flows very slowly as a second pass through the large inner channel from which the Pb–17Li exits at high temperature. This flow scheme enables operating Pb–17Li at a high outlet temperature (1100 °C) for high cycle efficiency while maintaining the SiC_f/SiC composite and the SiC/Pb–17Li interface at a lower temperature (~1000 °C) dictated by swelling and compatibility considerations. The Brayton cycle is chosen to maximize the potential gain from high temperature operation of the Pb–17Li which after exiting the blanket is routed through a heat exchanger with the cycle He as secondary fluid, resulting in a high cycle efficiency of ~59%. Credible blanket fabrication procedures have been evolved which minimize the coolant containing joints and enhances reliability. The design process strives as much as possible to maintain comfortable stress limit margins as an additional reliability measure.

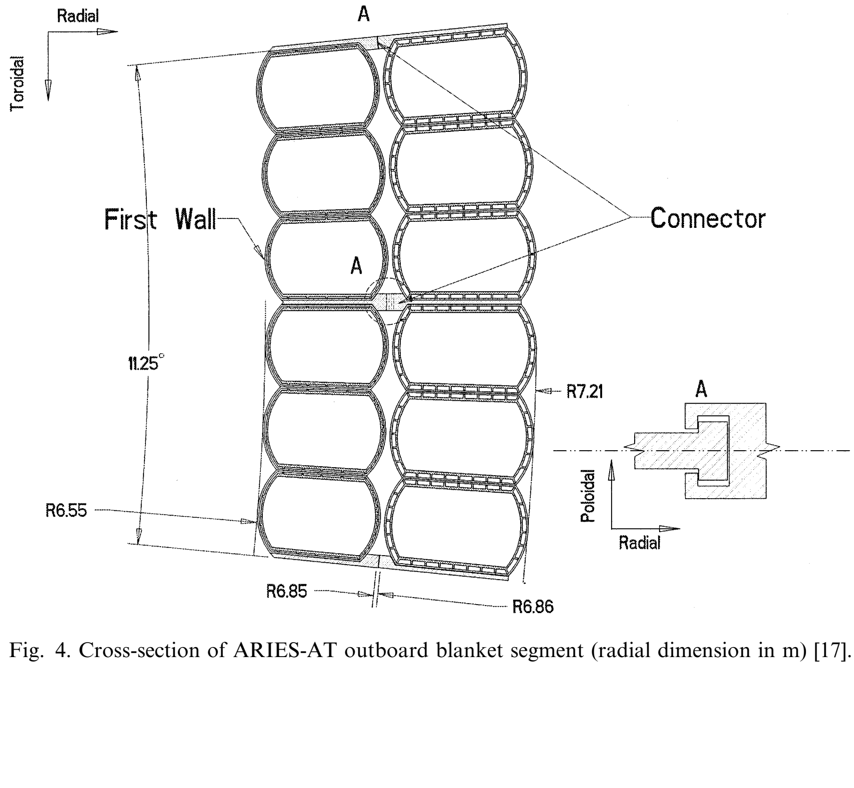

Fig. 4. Cross-section of ARIES-AT outboard blanket segment (radial dimension in m) [17].

Key issues requiring R&D attention are mostly linked with the SiC_f/SiC material. They include development of low-cost high-quality material and joining methods and characterization of key SiC_f/SiC properties and parameters at high temperature and under irradiation, in particular thermal conductivity, temperature limits (based on strength degradation, compatibility with Pb–17Li and He swelling), and lifetime. Also, Pb–17Li properties at high temperature need to be measured. Finally, even though the use of insulating walls greatly reduced MHD effects on the Pb–17Li flow, they still need to be better understood for the geometry of interest.

3.4.2. SiC_f/SiC + ceramic breeder concepts

An example of such a concept is the He-cooled blanket evolved by JAERI for the A-SSTR2 reactor study [21]. The He inlet temperature is 600 °C and its outlet temperature is 900 °C resulting in a Brayton cycle thermal efficiency of more than 50%. The ceramic breeder and the neutron multiplier are packed in the form of small spherical pebbles. Li_2TiO_3 is the first candidate as breeder material and Be is used as neutron multiplier. These material combination can avoid almost all compatibility issues. Key issues are mostly linked with the SiC_f/SiC material and are similar to those described in the previous section. One additional issue is the SiC_f/SiC hermeticity in the presence of high pressure He. Another concern comes from the neutron shielding for the superconducting coils. By employing TiH_2 pebbles mounted in a SiC_f/SiC holder as neutron shield, a low nuclear heating rate (<0.1 mW/cm^3) can be maintained in the superconducting wire.

3.5. Other concepts

For completeness, two other concepts receiving some degree of attention recently are summarized below: However, these concepts require much more design and R&D work to enable a better evaluation of their performance and attractiveness.

3.5.1. Blanket concept with tungsten alloy as structural material and heat extraction by lithium evaporation

In the frame of the US-APEX study a concept has been proposed where the heat from the FW and the breeding zone is removed by Evaporation Of Lithium and Vapor Extraction (EVOLVE) [22]. This concept meets the goal of that study which is to explore the limit of technology under very high requirements of a FW surface heat flux >2 MW/m^2 and a neutron wall load >10 MW/m^2. EVOLVE is a self-cooled blanket where the exceptional large heat of evaporation of Li (about 10 times as large as the one of water) is used to provide efficient cooling with very low flow rates. Operating point is a saturation temperature of 1200 °C corresponding to a pressure of 0.035 MPa. This low pressure has the advantage of low primary stresses in the structure, and, in connection with the low-Z breeder material, a large tolerance for leeks into the plasma chamber. Additionally, the secondary stresses are minimized by the nearly uniform temperature in the entire structure, facilitated by the two-phase cooling. The concept has the potential for exceptional high power density and thermal efficiency (>55%). However, it remains to be seen, if tungsten alloys can be qualified as structural material in a fusion blanket, operating in a temperature range between 1100 and 1400 °C. Parameters of interest are summarized in Table 1.

3.5.2. FLiBe concepts with ferritic or other structural materials

FLiBe is another possible liquid breeder with the advantage of low chemical activity with air and water and no MHD problem for self-cooled concepts. However, issues such as corrosion, temperature limits, modest tritium breeding, poor heat transfer capabilities and tritium permeation limit its attractiveness. There seems to have been up to now only limited effort on conceptual design studies for FLiBe concepts in MFE reactors. For completeness, some parameters from the FLiBe blanket considered for an helical-type reactor (FFHR-2) are included in Table 1 [23].

4. Example strategy for breeding blanket development and role of material R&D

Substantial progress has been made in the last couple of decades in understanding performance and behavior of breeding, multiplier and structural materials. The effect of such progress in experimental and modeling R&D can be illustrated by considering tritium inventory predictions for ceramic breeders from past studies, which in the absence of adequate analytical tools and fundamental property data characterization tended to be overly conservative. Tritium inventory in ceramic breeders was then a major issue for this class of blankets and a focus of the R&D program. Fig. 5 shows a chronology of tritium inventory estimates for ceramic breeder blankets based on a number of different reactor studies performed over the last 15–20 years (updated from Ref. [24]). Admittedly, specific inventory predictions are dependent on a number of parameters which may differ from study to study, and this figure is only intended as a qualitative illustration rather than as a consistent comparison. Clearly, the magnitude of ceramic breeder tritium inventory in blankets has decreased dramatically over the years with the expansion of the fundamental data base and the improvement of modeling tools to such an extent that, for such classes of blanket, tritium inventory in other components and materials (such as the Be multiplier) are considered to be much more problematic now.

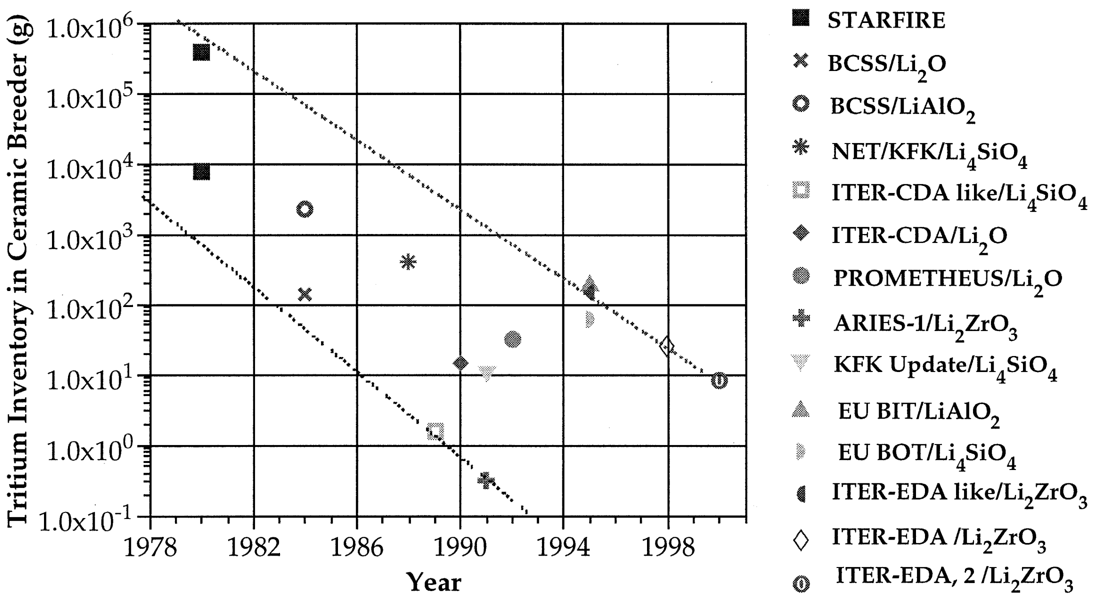

Fig. 5. Tritium inventory in ceramic breeder blanket regions estimated from different studies (updated from Ref. [24]).

However, many issues still remain for each class of concepts, often related to the structural material performance and lifetime for the given operating environment and conditions. Blanket concepts with the potential for high performance and attractive safety features tend to place more demand on the choice and performance of structural materials and to have higher associated development risk. Fig. 6 shows a semi-qualitative classification of different classes of blanket concepts based on a measure of attractiveness as a function of development risk. The attractiveness measure is a subjective assemblage of attractive features listed in Section 2, such a cycle efficiency, safety, and lifetime some of which are illustrated quantitatively in Table 1. The measure of risk that the development will not be successful is also subjective and includes consideration such as the degree of extrapolation from current material and component performance and the complexity and scale of effort required to validate the concept. Admittedly, to the eye of the beholder, individual concept classifications could change over a certain range. However, the relative overall classification by choice of structural materials and of breeder materials is not likely to vary appreciably.

The objective of blanket R&D should be to lead at least to the development of a blanket with an acceptable level of performance and attractiveness for a commercial reactor. An example blanket development strategy is suggested here with the idea of helping to maintain a healthy portfolio of blanket concepts within a clear development pathline. Lower-bound blanket performance levels which would still result in an acceptably attractive commercial fusion reactor should be developed. Blanket concepts with the lowest development risk meeting these performance criteria should be developed and tested. These would be medium-risk medium-performance concepts representing a fall back position and providing a reference scale to judge more advanced concepts. It is foreseen that a number of these concepts will be tested in ITER in order to have for the first time the operation of full blanket systems in a fusion environment. These tests will not be sufficient for giving answer on blanket lifetime but will give important information on various aspects such as tritium handling, heat extraction, and component functional performances. In parallel, critical

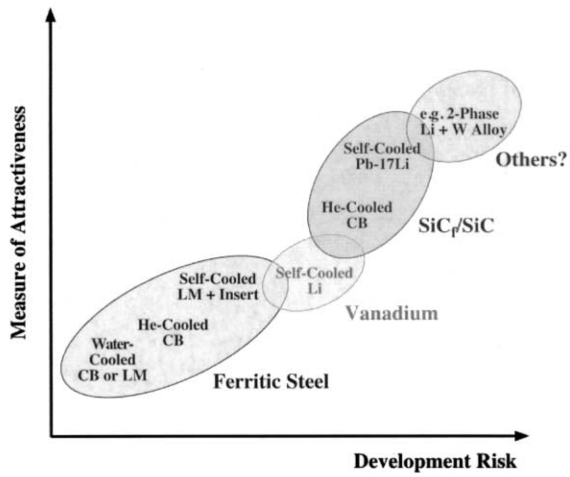

Fig. 6. Example classification of blanket concepts based on attractiveness and development risk.

R&D should be done for the more advanced, higher risk but higher pay off concepts. This R&D tends to be very much material related and the promises offered by the performance of advanced concepts provides a challenge to the material R&D community to help the blanket design to achieve this. For example, the high cycle efficiency offered by high temperature operation from SiC_f/SiC requires that the material can operate at these temperatures while being compatible with the coolant and accommodating swelling. Design effort on advanced blanket conceptual development should also be pursued to help guide the material R&D toward high performance material and to provide a vision and a goal for attractive concepts for the future. Clearly, close interaction and coordination between the material and design communities are required for successfully advancing breeding blanket development.

5. Conclusions

Several classes of blanket concepts are being considered with differing level of performances. Blanket concepts with the potential for high performance and attractive safety features tend to place more demand on the choice and performance of structural materials and to have higher associated development risk. An example classification described here shows that higher performance and potentially more attractive concepts tend also to have higher associated development risk. In many ways, this is driven by structural material considerations; for example, both performance and development risk tend to increase with classes of concept utilizing ferritic steel, vanadium alloy and SiC_f/SiC, respectively. An example blanket development strategy is suggested with the goal of maintaining a healthy portfolio of blanket concepts. Blanket concepts with the lowest development risk meeting a minimum attractiveness and performance criteria for commercial application should be pursued. These would represent a fall back position and provide a reference scale to judge more advanced concepts. In parallel, critical R&D should be done for the more advanced, higher risk but higher pay off concepts to provide the required information and guide the choice for the most attractive possible blanket concepts to be utilized in commercial reactors and to strengthen the case for fusion energy.

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