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Molten Salt Breeding Blanket: investigations and proposals of pre-conceptual design options for testing in DEMO

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In Europe, the DEMO test facility for Breeding Blankets (BB) will be the next step for fusion energy after ITER. The BB is a key component facing the plasma and ensuring tritium self-sufficiency, shielding against neutrons and heat extraction for electricity production. Within the EU research program, the two concepts candidates as driver BB in DEMO consider high-pressure coolants (water or helium) and Lithium-Lead or Beryllium pebble beds as breeder. In this article, an advanced BB concept is propounded as a candidate to be tested in DEMO taking into account Molten Salt (MS) as breeder and coolant and, consequently, named Breeder and Coolant Molten Salt (BCMS) BB.

BCMS BB have several advantages, which lead to their investigations. As the MS is not pressurized during operation, high requirements associated to Nuclear Pressure Equipment (ESPN / PED) could be relaxed. Furthermore, the MS magnetohydrodynamic (MHD) flow is low due to its weak electrical conductivity. Besides, MS BB have identified drawbacks such as the structural material compatibility and the MS chemistry control needed during irradiation.

A bibliographic review of MS and compatible materials is conducted. Promising BCMS BB are analysed regarding the Tritium Breeding Ratio (TBR) to test the capability of such MS breeders to reach the targeted TBR. The main nuclear quantities are evaluated with various MS on a dedicated model via the TRIPOLI-4® Monte-Carlo code: TBR, nuclear heating, neutron flux, displacement damage and helium production are reported and discussed. Moreover, the thermal and thermo-hydraulic responses of the MS BB are evaluated regarding the pressure drops (ΔP), the Pumping Power (PP) and the maximum temperatures in the structures. Nonetheless, preliminary design options are investigated. Finally, the major purpose is to evaluate the feasibility of a BCMS BB and identify their advantages and drawbacks.

Keywords: DEMO, Breeding Blanket, Molten Salt, neutronic, design

1. Introduction and objectives

In DEMO, the BB is the component surrounding the plasma, which has to withstand severe operating conditions while insuring tritium self-sufficiency, neutron shielding and coolant temperature range suitable for heat extraction to supply a turbine for producing electricity.

Within the EU research program, the two concepts candidates as Breeding Blanket (BB) in DEMO [1] consider high-pressure coolants and liquid Lithium-Lead (LiPb) eutectic or solid lithium ceramic (Li) and Beryllium (Be) as breeder: WCLL (Water Cooled Lithium Lead) and HCPB (Helium Cooled Pebble Beds). It is assumed that these blankets could be developed at a sufficient grade of technical maturity to make possible the operation of DEMO before the middle of this century. However, key issues as economic viability (e.g. high efficiency, long lifetime) could be not fully addressed by these concepts.

For this reason, advanced blanket configurations, that could be used to start a commercial exploitation of the fusion energy after DEMO [1], are explored. Their structural material will have to withstand more than 100 dpa (displacement per atom) and its design will have to demonstrate a high thermo-hydraulic efficiency, necessarily above to the driver BB efficiency.

In this article, an advanced blanket concept called BCMS (Fig. 1) is propounded as a candidate to be tested in DEMO taking into account Molten Salt (MS) in the double function of breeder and coolant.

Recently, a renewed interest in MS for nuclear fission and fusion reactor occurs. The last 5 years, many start-up companies design nuclear fission reactors based on MS solutions (Terrestrial energy, Seaborg technology, Moltex energy, Flibe energy, Transatomic power, Kairos power, etc.). Several national research laboratories also start or reinforce their activities on MS reactor (U.S., China, Russia, U.K., France, etc.). The main reasons of the MS fission reactor interest are the safety (low pressure operation, passive decay heat removing), the cost and nuclear fuel management (cycle closing, waste reduction, better actinide burning capability); in fusion some functions like actinide burning capability can be maximised due to the much higher energy of neutrons. In fusion domain, MS are also recently considered for instance in ARC tokamak device [2]. The U.S. also studied a MS option as a candidate for a Test Blanket Module (TBM) in ITER. [3]. Earlier works were carried out by Oak Ridge to use MS as blanket fluid [4]. MS concepts are an alternative to liquid concepts with LiPb and/or Li [5]. Issues raised (MHD, chemical reactivity, First Wall (FW) cooling) in the previous reference for self-cooling concept based on

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LiPb or Li demonstrate the need for another coolant to be studied.

In the scope of developments on the advanced BB, BCMS BB have several advantages, which lead to their investigations. The MS is not pressurized during normal operation, high requirements associated to Nuclear Pressure Equipment (ESPN / PED) [6] could clearly be relaxed which is a key advantage for a possible BCMS BB concept. Moreover, circulating MS with low MHD interaction enables its uses as a breeder and a coolant due to its weak electrical conductivity. These two features greatly simplify the BB design compared to those cooled by pressurised fluids (helium or water). On the other hand, high Melting Point (MP) temperature and corrosion are a challenge for structural material selection particularly under irradiation. The major aim of the MS chemistry control (RedOx) is to prevent corrosion phenomena and to mitigate corrosion issue (for instance control highly corrosive due to high HF or HCl concentration).

BCMS BB can be classified in advanced blanket concept for DEMO and comparison with the HCLL BB [7] is not meaningful since HCLL is a first step in the path to Self-Cooled Lithium-Lead (SCLL) blanket. To reduce MHD interaction LiPb velocity is reduced, helium is used to cool the structure as well as the LiPb. The next step is the DCLL (Dual Cooled Lithium-Lead) concept [8] [9] in which the velocity of LiPb is increased, MHD interaction are reduced using a coating, the FW is cooled by helium (LiPb FW cooling still need theoretical model and experimental data [5]). MS could be an alternative to this pathway; the aim of this article is to review MS solutions and proposes a preliminary design to evaluate the concept with regard to reference LiPb option. As suggested in [10], opportunities for synergistic development strategies between fission, fusion, and solar salt technologies could help the MS technology diffusion [11].

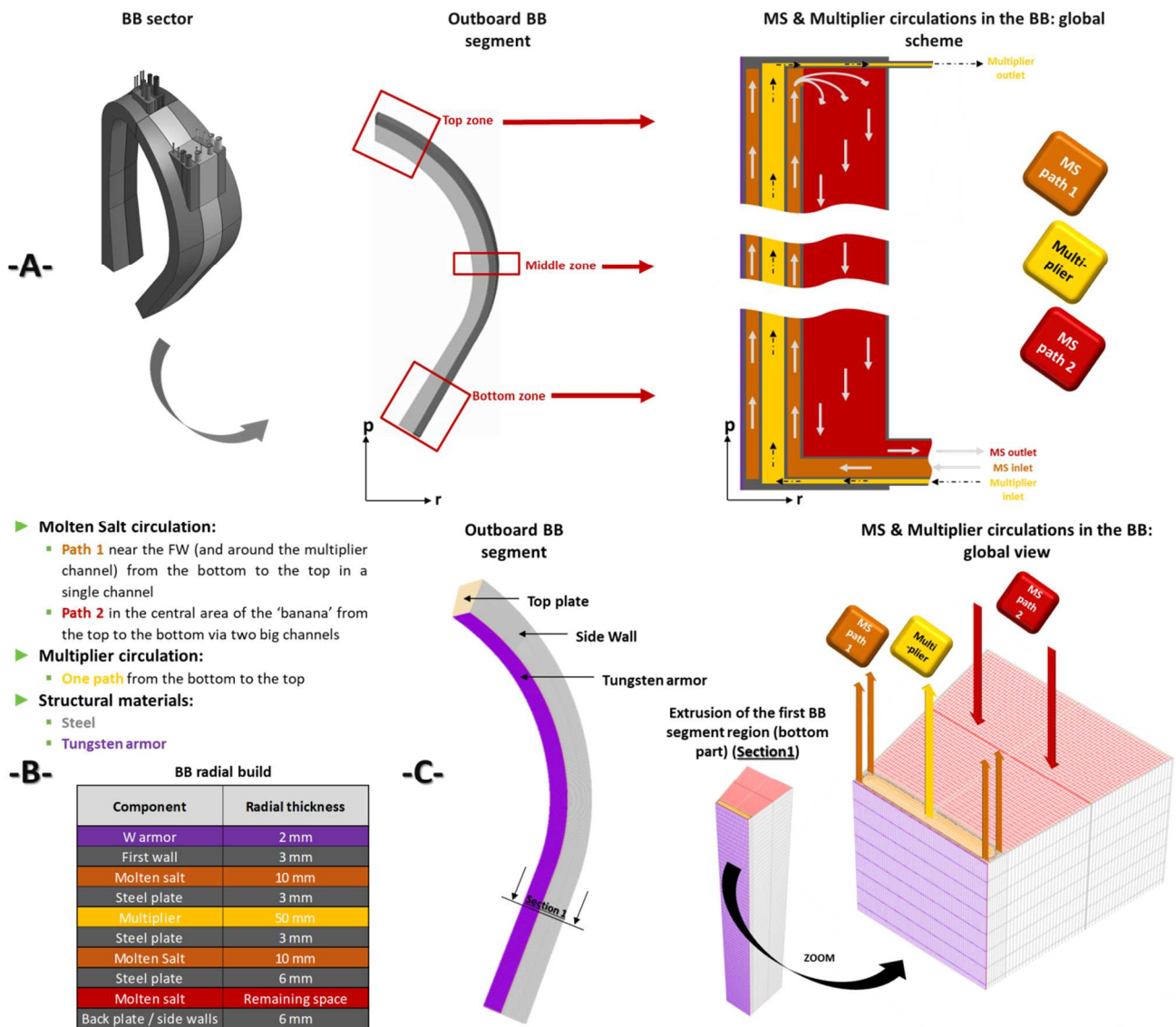


Fig. 1. Global Molten Salt and Multiplier layout inside the BB structure – principle, concept and BB radial build

2. Pre-conceptual design of the BCMS BB

The pre-conceptual design of an advanced BCMS BB concept with a MS as coolant and breeder is presented

hereafter. Low Normal Pressure Operation is the key advantage for a possible BCMS BB concept: the BB would not be considered as a Nuclear Pressure Equipment component that simplifies the positioning regarding regulation. Nevertheless, the regulation will be present to the extent that the equipment remains a nuclear application (but, with less pressure, it can be easily imagined that the criteria will be different as well as adapted). Thus, the design will have necessarily to fulfil C&S design criteria (such as RCC-MRx [12]) in order to ensure the component structural integrity when it has to withstand the thermal and mechanical loads it undergoes under both nominal and accidental conditions. Furthermore, the MS, as mentioned previously, has a low MHD interaction, which is a great advantage for a fluid as well as for a material inside a fusion tokamak, in which the magnetic fields and forces (Lorentz ones etc...) are important. This low interaction (in term of pressure drops and turbulence) allows us to use the breeder MS as an effective coolant. The two functions (breeder and coolant) simplify the BB design compared to those cooled by pressurised fluids (with an independent breeder) but some challenges remain concerning various aspects: high melting point (MP) temperature of the MS, corrosion of the structural materials (key criteria for its selection) and the MS chemistry control.

Fig. 1 (-A-) is focused on the thermo-hydraulic scheme in a BCMS BB segment (the same scheme in outboard and in inboard). In Fig. 1 (-C-), via some zooms and cuts through the structure, the BCMS BB is described: the hydraulic circulations of the MS (coolant and breeder) in orange near the FW (3 mm-thick plate) and in red (after warming up) for the segment Central Zone (CZ) and the neutron Multiplier (e. g. Pb or Be) in yellow. Globally, the MS is introduced at the bottom of the segment via a tube passing through the CZ and near the bottom plate. The MS flows up the segment through the FW chamber to the top plate: MS path 1. Next, it is reverted directly in the segment CZ two big chambers, where it flows downward to the bottom of the segment, then, it is extracted via another tube near the bottom plate too: MS path 2. In addition to the MS double circulation (FW and after CZ) inside the BB, a Multiplier collector chamber is embedded inside the FW chamber as illustrated in Fig. 1 (-C-). The Multiplier acts as a TBR booster for MS and is distributed from the bottom to the top and near the FW in the significant breeding area with the major target to maximize the tritium over-generation in the fusion tokamak. Furthermore, the BCMS design radial build is given in Fig. 1 (-B-).

3. Molten Salt choice and material adequacy

Tritium self-sufficiency of such a concept is studied with the DEMO 2017 baseline. A pre-design, derived from [3], was adapted to the DEMO geometry and plasma parameters. Note that the Tokamak machines studied in [3] had severe neutron wall loading (maximum 5.4 MW/m²) and heat flux (maximum 1 MW/m²) compared to DEMO.

Different MS compositions are studied in this article, two families are considered for comparisons:

- Fluorides' family: FLiBe, FLiNaBe and FLiPb;
- Chlorides' family: CLiPb, CLiK.

First, in the Fluorides' family, FLiBe was the MS salt used in the MSRE (Molten Salt Reactor Experiment in the US through the 1960s), that's why most of the MS BB concepts [3] [4] are based on this salt. FLiNaBe is studied since its MP is favourable and FLiPb is tested because it would give the possibility to eliminate the Be in the design, indeed, its use could be limited in the future (availability, cost, toxicity). A small amount of literature was found for FLiPb, it should be considered as a long-term option. Only its tritium breeding capability is evaluated. Table 1 gives the fluoride MS compound, MP and density as well as the multiplier used.

Secondly, chlorides salts were never considered in fusion application (to authors' knowledge), but they present some clear advantages like a lower MP but also some disadvantages discussed later. Table 1 shows the chloride salt compound, MP and density. CLiBe and CLiPb are reported to show their lower MP compared to FLiBe and FLiPb. CLiK and CLiNa are studied because no Be or Pb are used (except in the multiplier region) and K or Na are abundant and cheap.

Table 1. Fluorides / Chlorides MS, Melting Points and, densities (with their references in literature), neutron multipliers and TBR values

Molten Salt	Compound [mol%]	Melting point [°C]	Density [g/cm ³]	Multiplier	TBR
FLiBe	LiF (66.6%) BeF ₂ (33.3%)	460 ^[18]	2,035 ^[18]	Be	1.28
FLiBe*	LiF (50%) BeF ₂ (50%)	380 ^[3]	2,055 ^[10]	Be	1.27
FLiNaBe	LiF (33.3%) NaF (33.3%) BeF ₂ (33.3%)	320 ^[18]	2,151 ^[18]	Be	1.17
FLiPb	LiF (40%) – PbF ₂ (60%)	577 ^[19]	3,55 ^[20]	Pb	1.28
CLiBe	LiCl (50%) BeCl ₂ (50%)	310 ^[21]	-	-	-
CLiPb	LiCl (33%) PbCl ₂ (66%)	420 ^[22]	4,5 ^[22]	Pb	1.22
CLiK	LiCl (70%) KCl (30%)	430 ^[23]	1,6	Pb	1.18
CLiK*	LiCl (58%) KCl (42%)	355 ^[23]	1,6	Pb	1.12
CLiNa	LiCl (72%) – NaCl (28%)	550 ^[24]	1,6 ^[25]	Pb	1.29

Legend:
* the composition of the MS varies from the previous line
- lack of data

Nonetheless, in order to guarantee an adequate thermodynamic cycle with a quite high temperature in entrance of the primary circuit, the fluidic MS will have to exit the BB at quite high (~ 600°C) or very high (~ 700°C) temperatures, which has some implications, in particular regarding the structural material options. First, the classical EUROFER [12] material cannot be used for the BCMS BB in its standard formulation. This material needs some adaptations (e. g. advanced EUROFER for high temperature applications) or another material has to be chosen or even developed in considering all the constraints linked to MS. Thus, alloy-N (idem in [2]) or coating on an advanced ferritic-martensitic steel to protect the structural material can be considered. Furthermore, Oxide Dispersion-Strengthened (ODS) alloys are studied, in particular, the Fe-9Cr ODS steel and the Fe-14Cr ODS steel and are the stage of R&D

[13]. In general, in steels, the aim is to have a chromium content not too high, in particular in order to avoid the formation of secondary precipitates in the matrix of the material. Although with ODS steels this is less problematic, it is still preferable to have low chromium contents, at least as much as possible. Therefore, an ODS steel as the Fe-9Cr ODS steel will be privileged and finally preferable [13].

However, the developments of such ODS steels are at their early stages, thus an industrial reference steel with high Cr content (Fe-19Cr ODS) called PM2000 [14] is considered as a first approach for preliminary design. The PM2000 is a good support for the first BCMS BB dimensioning, taking into account the data available in literature [14], while waiting for a specific fusion alloys at high temperature. Furthermore, this assumption is consistent, especially as many data (typically: conductivity, dilatation, Young module) are very close between the PM2000 and the Fe-9Cr or 14 Cr ODS steels alloys developed in the Fusion Program. Moreover, SiCf-SiC matrix composite could be used too.

4. Nuclear analyses

To verify tritium self-sufficiency of such a BCMS BB concept, the preliminary design shown in Fig. 1 has been adapted to the DEMO 2017 generic neutronic model [15]. Fig. 2 shows the neutronic model of the BCMS BB pre-conceptual design developed via the TRIPOLI-4® Monte Carlo code [16]. Promising MS are analysed to assess if the tritium production necessary to support the T self-sufficiency in DEMO is achieved; T production that for this kind of neutronic analyses means to obtain calculated TBR values > 1.15. Other nuclear quantities are also evaluated with the selected MS: Nuclear Heating (NH), neutron flux, displacement damage and helium production are reported and discussed (Table 2) versus the target values [17]. BB structural material for the neutronic simulations is EUROFER; even if, in the future, another material should be used for thermal, mechanical and corrosion aspects at high temperatures in the MS environment

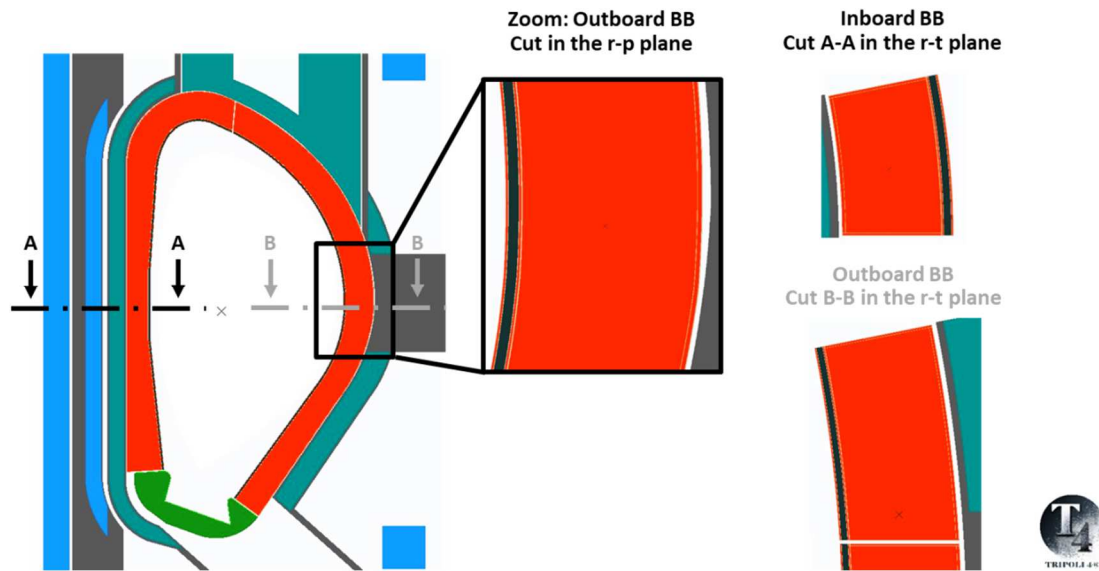


Fig. 2. BCMS BB pre-conceptual design adapted to DEMO 2017 baseline

Table 2. BCMS BB nuclear analysis results

Molten Salt	TBR	Multi-plier	Me	NH BB [MW]	NH DIV [MW]	NH VV+PP [MW]	Fast n flux in TFC [n/cm ² /s]	Nh in TFC [W/cm ³]	DPA in VV 6 FPY [dpa]	He prod in rear BB part 1.57 FPY [appm]
FLiBe	1.28	Be	1.26	1872	133	6.1	0.43 10 ⁹	1.05 10 ⁻⁵	0.07	0.2
FLiPb	1.28	Pb	1.15	1652	160	28.8	2.30 10 ⁹	6.06 10 ⁻⁵	0.75	1.2
CILiPb	1.22	Pb	1.17	1596	175	108.6	1.45 10 ⁹	7.52 10 ⁻⁵	2.65	0.9
CILiK	1.18	Pb	1.13	1568	134	107.6	5.48 10 ⁹	15.9 10 ⁻⁵	3.17	4.3
HCLL	1.15	LiPb	1.20	1641	173	100	0.48 10 ⁹	4.33 10 ⁻⁵	1.26	0.65
Target	1.15	-	-	-	-	-	10⁹	5 10⁻⁵	2.75	1.0

4.1 Nuclear quantities obtained with fluoride salts

In term of TBR, the BCMS BB concepts based on fluoride MS (FLiBe, FLiPb) are really promising with a calculated TBR of 1.28 for both, higher than the TBR of e.g. the HCLL with 1.15 [7]. In these calculations, for the FLiBe MS, Be multiplier is considered in the form of beryllium pebble beds of 1.85 g/cm³ density and 0.74 packing fraction. In TRIPOLI-4® model pebble bed is homogenised, this result in a Be media of 1.37 g/cm³. In future analysis, other Be multiplier form could be

studied, Be pebble bed was chosen as a starting point and to compare with the HCPB concept [26] too. For the FLiPb MS, lead multiplier (at low velocity) is considered liquid with a density of 10.3 g/cm³. 6Li enrichment is 40% in FLiBe and FLiNaBe MS case and 90% in other case (FLiPb, all chloride). Fluoride salts offer good tritium breeding performance with different options Be or Pb.

Nevertheless, EUROFER as a ferritic-martensitic steel is not chemically compatible with fluoride salts

[27] ($\text{HF}/\text{H}_2 = 0.01$ potential is above the Cr/CrF_2 potential implying that HF react with Cr metal to produce CrF_2 and H_2 [11]). RedOx chemistry control of FLiBe consists in HF/H₂ monitoring and Be metal is used as a reducing agent ($\text{Be} + 2\text{HF} \rightarrow \text{BeF}_2 + \text{H}_2$ [11]). Furthermore, from MSRE experience nickel based alloy are good candidates (Hastelloy-N and Alloy-N). Unfortunately, nickel is not favourable for reduced activation by neutrons (⁶³Ni half-life is 100 years). Al oxide coating over ferritic-martensitic steel could be a solution. These aspects could be considered regarding the MP of fluoride salts.

4.2 Nuclear quantities obtained with chloride salts

Chloride salts have been analysed because of their lower MP temperature (compared to fluoride). There are the same concerns about material compatibility than for Fluoride Salts. RedOx chemistry control is more complex (compared to fluoride) since Chlorine (Cl) has several oxidation numbers (+7, +5, +3, +1, -1). ³⁶Cl formation during irradiation is a concern regarding nuclear waste (³⁶Cl is a long-lived 301,000 years half-life beta emitter). Promising TBR are also obtained with chloride MS especially CILiPb (1.22) and CILiNa (1.29). TBR performance of CILiK could be improved to 1.18 using a higher LiCl content (70%) but MP is higher (430°C): this is the option precisely described after in the thermo-hydraulic part. CILiPb seems a good option too regarding the TBR, but radiolysis will inevitably produce some PbCl₄, which has a boiling point of 50 °C and would have to be separated from the melt resulting in a high vapor pressure [27]. Furthermore, tritium breeding performance of CILiNa (1.29) are interesting but its MP is too high.

4.3 Conclusions on the neutronic analyses

Table 2 summarizes the nuclear analysis of BCMS BB based on the most four promising MS studied: FLiBe, FLiPb, CILiPb and CILiK. HCLL results are also reported for comparison purpose. First, FLiBe MS fulfils all criteria (last line of Table 2) but its MP temperature is too high and Alloy-N or coating over an advanced ferritic-martensitic steel is needed to protect the structural material. In addition, the Be use could be limited in the future due to its important cost and its high toxicity. FLiPb, CILiPb and CILiK are very promising too but a neutron shielding has to be developed (especially in CILiK case) to protect the Vacuum Vessel (VV) and the Toroidal Field Coils (TFC), this solution could easily be implemented. For these MS, an increase of the blanket thickness can be considered and/or the introduction of more effective shielding materials in the rear part of the blanket. Nevertheless, very few data exists for FLiPb and CILiPb salts, radiolysis would affect CIPb. Moreover, TBR could be increased in CILiK case in modifying the salt composition. Some data exist for this salt often selected for heat storage or as a secondary MS loop in fission MS reactor, which is an advantage. Concerning the nuclear analyses, future works should address decommissioning and wastes classification aspect of BCMS BB. Furthermore, based on similar evaluations made for HCPB, HCLL and

WCLL [29], a shielding to protect the VV is needed (except for the FLiBe) to reduce neutron flux and then activity of the VV after irradiation. In addition, Alloy-N using as structural material for fluoride MS will be disadvantageous regarding waste but this should be balance by its advantages in other domains.

5. Thermo-hydraulic analyses

For the thermal and thermo-hydraulic analyses, the study has been conducted with two MS: FLiBe and CILiK (structural materials and multiplier chosen for each case are given in Table 3). Besides the development of an analytical thermal model, the option has been taken to start the development of a Finite Element Method (FEM) calculation via the Cast3M software [31] to analyse the Coolant/Breeder MS distribution and recirculation at the scale of the outboard BB segment. The major purposes are to evaluate the temperature fields in the fluids and the structure and the pressure drops ΔP through the BB segment. The 3D-massive FEM model developed for the thermal analysis respects the dimensions of the outboard BB segment with the DEMO 2017 Baseline: its characteristics are given in Table 3. The MS properties have been extracted from [28] [30] and the Heat Transfer Coefficient (HTC in [$\text{W m}^{-2} \text{K}^{-1}$]) correlation used taken from [33], its definition is given hereafter:

$$HTC = \frac{Nu \lambda}{D_H}$$

Where D_H [m] is the hydraulic diameter of the MS channel, λ [$\text{W m}^{-1} \text{K}^{-1}$] the thermal conductivity of the MS, Nu the Nusselt number is given by the equation:

$$Nu = 0.0118 Pr^{0.3} Re^{0.9} \text{ for } Pr > 20$$

Where Re and Pr are respectively the Reynold number and the Prandlt one.

Furthermore, temperature dependent material properties are used in the FEM simulations for the structural material, the MS as well as the neutron Multiplier. Moreover, a proper advection line model is implemented in order to reproduce the thermal exchanges of the MS flowing into the cooling channels of the FW as and the CZ (detailed in [34]). In the Fig. 3, the thermal and thermo-hydraulic results obtained via the FEM calculation of the BCMS BB is given. Moreover, all the thermal and thermo-hydraulic results obtained via this FE model are reported in Table 3 – in particular, the power extracted, the maximum temperatures in the BB structure and the MS, the HTC in the FW, the ΔP and the global PP.

Table 3. BCMS BB thermo-hydraulic analysis results

BB	Parameter	CILiK	FLiBe	Unit
		BB FE model	BB Ana. model	
	CAD Baseline		2017	
	Average Plasma HF considered		0.23	MW/m ²
	NWL (max. of the out. BB)		1.33	MW/m ²
Global	Total Power to be extracted		2065	MW
	Structural material	PM2000	Inconel	-
	MS in the th.-hyd. analysis	CILiK	FLiBe	-

	Neutron multiplier	Pb [32]	Be	-
	MS Melting Point	430	460	°C
	Inlet MS temperature	480	510	°C
	Outlet MS temperature	580	610	°C
	MS Delta T	100		°C
	Pumping Power (overall segments)	76	83.9	MW
	Pumping Power / Total Power	3.7%	4.1%	-
	Thermal power extr. (BB out. seg.)	18.3	20.5	MW
	MS Mass Flow Rate	45.8	86.3	kg/s
	FW hydraulic diameter	0.02		m
Out. BB seg.	FW Heat Transfer Coefficient	6495	6049	W/m ² K
	FW MS velocity	1.68	2.59	m/s
	Total ΔP	0.040	0.17	MPa
	Maximum neutron multiplier temp.	616	-	°C
	Maximum structural material temp.	591	631	°C
FE model	Mesh mathematical formulation	Linear	-	-
	Number of nodes	1.66 10 ⁶	-	-
	Number of Elements	1.63 10 ⁶	-	-

The CILiK MS is introduced at the bottom of the segment at $T_{in} = 480^{\circ}\text{C}$ (50°C above the CILiK MP). The MS flows up the segment structure through the FW chamber to the top plate, with a temperature elevation of 55°C reaching 535°C . This is the first MS path on the right part of the Fig. 3 from the blue at the bottom to the green at the top. Then, the CILiK is reverted directly in the segment CZ big chamber where it flows downward to the bottom of the segment structure with another temperature elevation of 45°C reaching at the BB outlet at $T_{out} = 580^{\circ}\text{C}$ (i.e. $\Delta T=100^{\circ}\text{C}$ for an efficiency reason in first approach, this parameter could be affined in next developments). This is the second MS path on the right part of the Fig. 3 with the two fluid lines through the CZ

from the green at the top to the red at the bottom. All these values are reported in Table 3.

Furthermore, regarding the temperature in the structure, the maximum temperatures obtained are reached in the top plate with a hot spot at 591°C (See Table 3 and Fig. 3) whereas the minimum temperature is found in the FW bottom zone at 483°C near the inlet of the BB. Therefore, even the minimum temperature in the BB is important compared to other BB concepts: the BCMS BB structure works at high temperature. Nonetheless, no major structural thermal gradient will remain locally in the structure thicknesses (which is an advantage for the thermo-mechanical stress evaluation in the future); however, the structure will be maintained at a high temperature in normal operation, which will affect the creep response. In addition, the maximum temperature reached in the neutron Multiplier (Pb) is equal to 616°C . The ΔP at the scale of the segment have been evaluated (cf. Table 3): $\Delta P = 0.040$ MPa. Note that most of the ΔP are generated via the path 1 through the FW and the PP needed for cooling the Tokamak BCMS BB has been evaluated at $PP = 76$ MW, so $76/2065 = 3.7\%$ which is acceptable. Furthermore, these results have been cross-checked with an analytical model and the results are quite similar; that's why this one is used to compare speedily the MS between them. The results obtained with the FLiBe MS are given in Table 3, globally the maximum temperature is 40°C higher in the FW for a alike thermo-hydraulic response (see Table 3).

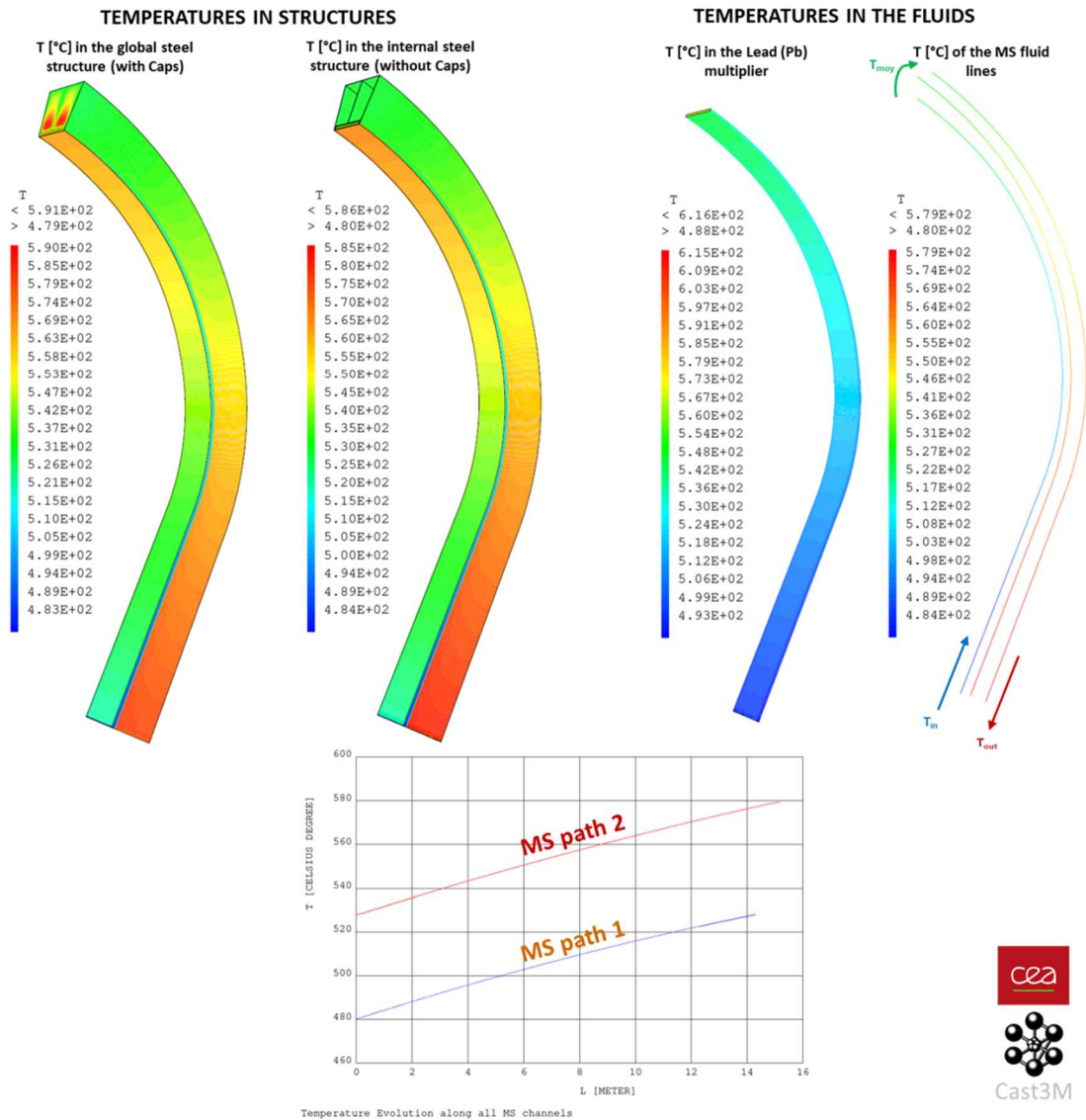


Fig. 3. Thermal and thermo-hydraulic results via the FE model of the BCMS BB outboard segment (for the CLiK MS)

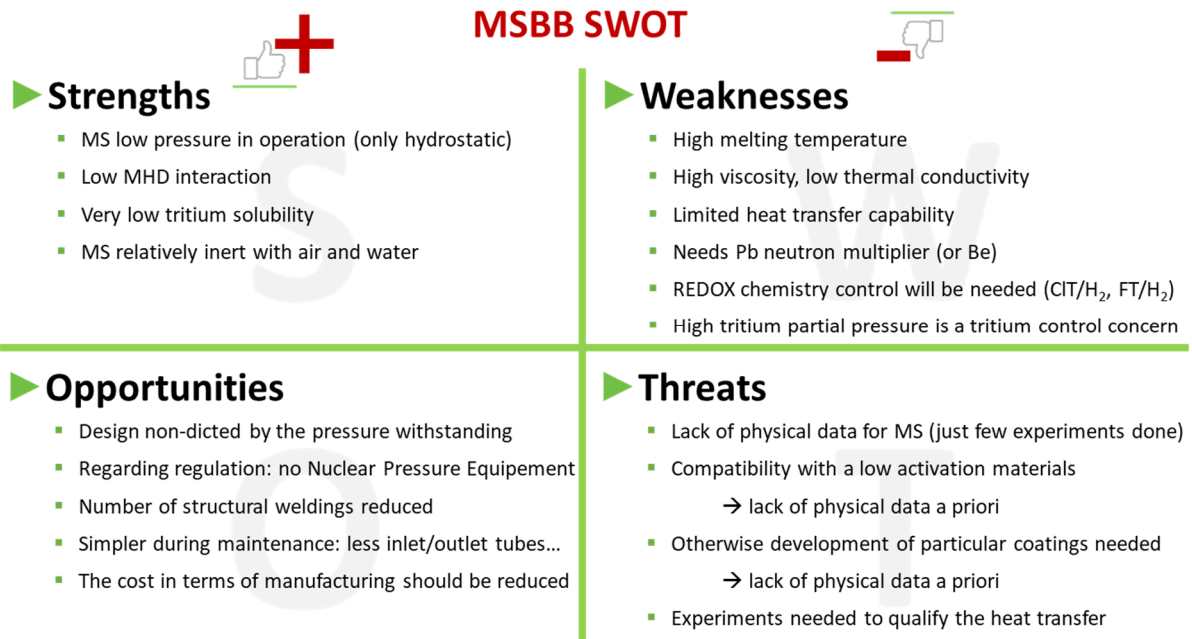


Fig. 4. Molten Salt Breeding Blanket Strengths, Weaknesses, Opportunities and Threats (SWOT)

6. Advantages and drawbacks

BCMS BB have several advantages, which lead to their investigations. As the MS is not pressurized during operation, high requirements associated to Nuclear Pressure Equipment (ESPN / PED) could be relaxed. Moreover, the MS Magnetohydrodynamic (MHD) flow is low and the losses of calories are low too. Besides, BCMS BB have identified drawbacks such as the material compatibility and the MS chemistry control during irradiation. Note that more details are given in [34].

Furthermore, the Fig. 4 summarizes via a SWOT, the Strengths, the Weaknesses, the Opportunities and the Threats of such BCMS BB. The stakes of using MS appears substantial and the challenges are high.

7. Conclusions and perspectives

To summarize, several points can be noted:

- Firstly, four promising MS are compared via the nuclear analyses of the BCMS BB: FLiBe, FLiPb, CILiPb and CILiK. Regarding the nuclear results, the FLiBe MS fulfils all criteria regarding nuclear quantities (in particular, TBR = 1.28) but its MP temperature (460°C) is high and Alloy-N or coating on an advanced ferritic-martensitic steel is needed to protect the structural material. FLiPb, CILiPb and CILiK (TBR = 1.18) are promising but a neutron shielding must be developed to protect the VV and the TFC. However, only few data exists for FLiPb and CILiPb salts. Future works should address decommissioning and wastes classification.

- Secondly, for the thermal and thermo-hydraulic analyses, the study has been conducted with two MS: FLiBe and CILiK. With the CILiK MS, the maximum temperature in the PM2000 (Fe-19Cr ODS) structure is reached in the top zone with a hot spot at 591°C. The global segment ΔP are 0.040 MPa which is very encouraging and the PP needed for cooling the BCMS BB is 3.7% of the total fusion power which is not high. With the FLiBe MS, the maximum temperature is 40°C higher in the FW for an alike global thermo-hydraulic response.

Nonetheless, this article gives perspectives regarding neutronic, thermo-hydraulic analyses and design options. It could be considered using it in support to other future R&D studies regarding other physical aspects, which are listed here regarding major technical aspects:

- Chemistry: MS chemistry ‘building’, MS characterization (because of the lack of literature), chemistry control of the chosen MS, MS tritium extraction (and associated processes), MS detritiation;
- Material: material compatibility in the BB, structural material developments (ODS steel, advanced EUROFER, SiC_f/SiC or a mixed structure) or choices (e. g. PM2000), potential coatings developments (barrier against corrosion by the MS);

- Balance of Plant (BoP): BoP analyses with this BB concept, efficiency analysis, pumping technologies;
- Waste: nuclear waste generated (regarding the DEMO specifications).

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References

- [1] G. Federici et al., An overview of the EU breeding blanket design strategy as an integral part of the DEMO design effort, *Fusion Engineering and Design* 141 (2019) 30–42.
- [2] B. N. Sorbom et al., “ARC: A Compact, High-Field, Fusion Nuclear Science Facility and Demonstration Power Plant with Demountable Magnets,” *Fusion Eng. Des.*, 100, 378 (Nov. 2015).
- [3] C.P.C Wong et al., “Assessment of first wall and blanket options with the use of liquid breeder” *Fusion Science and Technology*, April 2005.
- [4] W. R. Grimes et al., “Molten Salts as Blanket Fluids in Controlled fusion reactors” ORNL-TM-4047, 1972.
- [5] S. Malang, et al., “Comparison of lithium and the eutectic candidate liquid metal breeder materials lead-lithium alloy, two for self-cooled blankets”, *Fusion Engineering and Design* 27 (1995) 399-406.
- [6] European Pressure Equipment Directive 2014/68/EU of 15 May 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of pressure equipment. <https://eur-lex.europa.eu/legalcontent/EN/TXT/?uri=CELEX:32014L0068>.
- [7] R. Boullon et al., The DEMO Helium Cooled Lithium Lead “advanced-plus” Breeding Blanket: Design improvement and FEM studies, *Fusion Engineering and Design* Volume 146, Part B, September 2019, Pages 2026-2030
- [8] D. Rapisarda et al., Status of the engineering activities carried out on the European DCLL, *Fusion Engineering and Design* Volume 124, November 2017, Pages 876-881
- [9] I. Fernández-Bergeruelo et al., Remarks on the performance of the EU DCLL breeding blanket adapted to DEMO 2017, *Fusion Engineering and Design* Volume 155, June 2020, 111559
- [10] S. Cantor et al. “Viscosity and Density in Molten BeF₂ – LiF solutions” the *Journal of chemical physics* volume 50 number 7.
- [11] Charles Forsberg et al., Fusion Blankets and Fluoride-Salt-Cooled High-Temperature Reactors with Flibe Salt Coolant: Common Challenges, Tritium Control, and Opportunities for Synergistic Development Strategies Between Fission, Fusion, and Solar Salt Technologies, *Nuclear Technology*. DOI: 10.1080/00295450.2019.1691400
- [12] RCC-MRx, Design and Construction Rules for

- Mechanical Components of Nuclear Installations, AFCEN, 2018.
- [13] Y. De Carlan et al, Microstructural and mechanical characterization of thin ODS plates, CEA Report, DEN/DANS/DMN/SRMA/LA2M/NT/2018-3759/A
- [14] PLANSEE, Dispersion-Strengthened High-Temperature Materials Catalogue, PM1000, PM2000, PM 2000 – grain classes 4 and 6.
- [15] 2017 Generic DEMO MCNP model with SDEF card IDM ref 2MF7SQ.
- [16] TRIPOLI-4 Project Team, TRIPOLI-4 Version 8 User Guide, CEA-R-6316, Feb (2013) <http://www.oecd-nea.org/tools/abstract/detail/nea-1716/>.
- [17] U. Fischer et al., Required, achievable and target TBR for the European DEMO, *Fus. Eng. Des.* 155 (2020) 111553.
- [18] R. Serrano-Lopez et al., “Molten salts database for energy applications” *Chemical Engineering & Processing*.
- [19] S. Watanabe et al., “Structural investigation on lead fluoride-lithium fluoride at various compositions and temperatures *Journal of Nuclear Material* 344 (2005) 104-108.
- [20] M. Ablanov et al., “Solubility of hydrogen fluoride in the molten LiF-PbF₂” *Journal of Nuclear Materials* 258±263 (1998) 500±504.
- [21] Physical Properties Data Compilations Relevant to Energy Storage. I. Molten Salts: Eutectic Data, NSRDS-NBS 61, Part I.
- [22] H. Ohno et al., “Structural Analysis of Some Molten Materials by X-ray Diffraction” Part 5. LiCl, PbCl₂ and their Mixtures, *J. Chem. Soc., Faraday Trans. 1*, 1978, 74.
- [23] Physical Properties Data Compilations Relevant to Energy Storage II. Molten Salts: Data on Single and Multi-Component Salt Systems NSRDS-NBS 61 Part II.
- [24] Physical Properties Data Compilations Relevant to Energy Storage I. Molten Salts: Eutectic Data NSRDS-NBS 61 Part I.
- [25] P. Fellner et al., of the molten system LiCl-NaCl-KCl, *Chem. zvesti* 34 (3) 330-334 (1980).
- [26] F. A. Hernández et al, Consolidated design of the HCPB Breeding Blanket for the pre-Conceptual Design Phase of the EU DEMO and harmonization with the ITER HCPB TBM program, Volume 157, August 2020, 111614
- [27] Fast spectrum Molten Salt Reactor Options, ORNL/TM-2011/105.
- [28] Physical Properties Data Compilations Relevant to Energy Storage. II. Molten Salts: Data on Single and Multi-Component Salt Systems – NSRDS US – National Bureau of Standards – pages 224 to 242.
- [29] M.R. Gilbert, T. Eade, C. Bachmann, U. Fischer, N.P. Taylor, Waste assessment of European DEMO fusion reactor designs, *Fus. Eng. Des.* 136 (2018), pp. 42-48.
- [30] D. F. Williams, Assessment of Candidate Molten Salt Coolants for the NGNP/NHI Heat-Transfer Loop, 2006.
- [31] Cast3M. <http://www-cast3m.cea.fr>
- [32] A. Venturini et al., Literature review of PbLi alloys properties, LM-D-R-262, 27/04/2017.
- [33] J.P. Holman, *Heat Transfer* (Mc Graw Hill).
- [34] R. Boullon et al., Advanced blankets investigation for DEMO test facility & neutronic support on driver blankets report 2019, EUROFUSION Report ENR-PRD.BB-WP2-T004-D001 (BB-2.1.1-T011-D001)