High Performance PbLi Blanket

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Abstract — A novel blanket concept is described. The proposed design is a dual coolant concept based on ferritic steel as structural material using helium to cool the first wall. The temperature of the entire steel structure is maintained below the 550˚C limit. The breeding zone is cooled by circulating the liquid metal breeder to external heat exchangers. Flow channel inserts are employed in the poloidal liquid breeder ducts, serving both as electrical and thermal insulator between the flowing liquid metal and the steel structure. In this way, a liquid metal exit temperature of about 700˚C is achievable, allowing either an advanced Rankine steam cycle or a closed-cycle helium gas turbine (Brayton cycle) as power conversion system. A gross thermal efficiency of about 45% can be achieved with either system.

I. INTRODUCTION

Economically attractive magnetic fusion power reactors require high power density and high thermal conversion efficiency to offset the high capital cost. Previous power plant studies (*e.g.,* [1]) have established a minimum goal for the average neutron wall load of ≥ 3 MW/m^2 and a minimum thermal efficiency of the blanket system of ≥ 40%. It can be shown that this combination of high power density with sufficiently high efficiency in the power conversion system can **not** be achieved with solid breeder blankets irrespective of the structural material used, because the maximum breeder temperature of all candidate breeder materials would exceed specified limits.

Self-cooled lithium blankets with vanadium alloy as structural material allow for both high power density and high temperatures leading to high efficiency. However, they are generally ruled out for safety reasons if water is used in other components of the machine. For example, this causes a dilemma for a Low Aspect Ratio (LAR) tokamak employing a water-cooled centerpost. Safety concerns could be overcome by using the eutectic lead lithium alloy Pb-17Li instead of lithium. However, the heat transport properties as well as the compatibility with ferritic steels and vanadium alloys for this liquid metal are not as good as with lithium.

Giancarli et al. [2], proposed a self-cooled PbLi blanket based on a SiC/SiC composite as structural material. The electrical resistance of this composite material, which is basically a semiconductor, is expected to be high enough to keep the MHD pressure drop within tolerable limits.

The major issues not yet resolved for such a blanket concept include:

1. The large surface heat flux at the first wall requires a relatively high thermal conductivity of the SiC/SiC composite in order to avoid excessively large temperature differences across the wall, leading to intolerably high thermal stresses.

2. The rather large stresses in the containing walls caused by the static pressure and by the disruption forces acting on the liquid metal have to be reacted by the composite material, which has very low ductility.

3. The use of the SiC/SiC composite as the structural material for a large pressure vessel with a complicated form requires the development of new fabrication methods, especially novel joining techniques which are compatible with the liquid metal filling.

4. High temperatures of the lead-lithium coolant are required to achieve a sufficiently high thermal efficiency in the power conversion system. The compatibility of SiC with flowing Pb-17Li at temperatures up to 800˚C still has to be proven.

Most of these problems are avoided with the blanket concept described in this paper. The proposed design is a dual coolant concept similar to the one described in [3], based on ferritic steel as structural material using helium to cool the first wall. The temperature of the entire steel structure is maintained below the 550˚C limit. The breeding zone is cooled by circulating the liquid metal breeder to external heat exchangers. Flow channel inserts are employed in the poloidal liquid breeder ducts, serving both as electrical and thermal insulator between the flowing liquid metal and the steel structure. In this way, a liquid metal exit temperature of about 700˚C is achievable, allowing either an advanced Rankine steam cycle or a closed-cycle helium gas turbine (Brayton cycle) as power conversion system. A gross thermal efficiency of about 45% can be achieved with both systems.

II. DESCRIPTION OF THE BLANKET SEGMENT

A cross section of the blanket segment is shown schematically in Fig. I. The concept is characterized by a U-shaped first wall (FW) with helium cooling channels oriented in the radial/toroidal direction. This FW forms, together with the helium manifolds at the back side of the segment, a box containing the liquid metal breeder. A grid of steel plates inside this box creates large liquid metal ducts and, as an additional function, reinforces the FW box. Inside all liquid metal ducts, which are oriented in the poloidal direction, there are flow channel inserts made of silicon carbide. These inserts serve as electrical as well as thermal insulators between the flowing liquid metal and the steel structure. In addition to the first wall, the grid plates also are cooled by helium in order to keep the steel structure below 550˚C. The Pb-17Li enters the blanket at the bottom, flows upwards in the front row of parallel ducts, turns around at the top by 180˚ and flows down in the two parallel rows at the rear side of the blanket. The FW box is fabricated by diffusion welding and subsequent bending of the straight plates containing the milled coolant channels. A cross section of the FW is shown in Fig. II. The grid plates with smaller coolant channels are similar and also fabricated by diffusion welding.

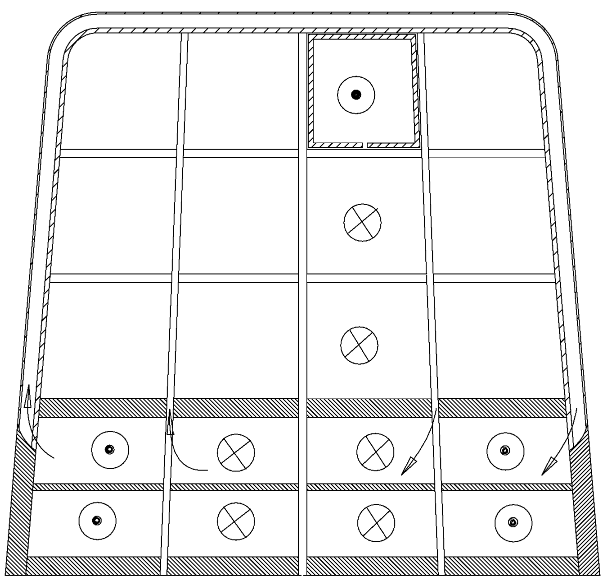

Fig. I. Outboard blanket cross-section

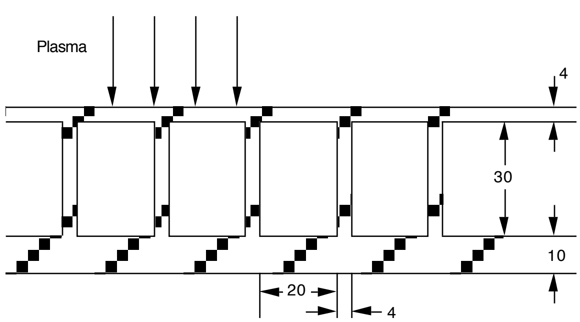

Fig. II. Cross section of the first wall box

The incoming helium at 350˚C first cools the FW and then the grid plates, where it is heated up to 500˚C. The helium flow is subdivided into two completely independent systems. The cooling channels in the FW as well as those in the grid plates are alternatively connected to one of the two systems in order to minimize the FW temperature increase in case of a Loss of Coolant Accident (LOCA) in one of the systems. Another benefit of the alternating flow directions is the more equal temperature distribution in the entire segment, resulting in lower thermal stresses.

The selected design of the helium cooling system is characterized by the following features:

1. Integrated manifolds. The helium manifolds are an integral part of the segment box. Separate welds are not required between each cooling channel and the manifolds, which is expected to increase reliability.

2. Multiple passes of the coolant through the FW. The total helium mass flow passes four times through the FW before it is used to cool the grid plates. This means, for example, that for a total temperature rise between helium inlet and outlet from 350˚C to 500˚C the highest helium bulk temperature in the FW is about 420˚C and the temperature increase in one pass is less than 20˚C. Another important result of this flow scheme is the possibility to use large coolant channels in combination with a high flow velocity, resulting in low bending stresses in the FW box caused by the liquid metal pressure.

3. Adjustment of the number of parallel channels per pass to the local power density and the helium bulk temperature. This increases the helium velocity and, consequently, the heat transfer coefficients in regions of potentially high structural temperatures, minimizing the maximum FW temperature.

4. Alternating flow direction in the FW coolant channels. The helium of the two cooling loops flows in opposite directions through the FW cooling channels. This leads to a symmetric temperature field in the segment box with lower thermal stresses.

5. Heat transfer at the FW enhanced by surface roughening. Artificial surface roughening at the FW enhances the heat transfer at the wall with the high heat flux. Since only one of four walls in a channel is roughened, the increase in pressure drop is marginal. This method results in lower structural temperatures and smaller temperature variations in the segment box.

6. Cooling the FW and stiffening grid plates in series. The power density is highest in the FW and decreases in the radial direction. Flowing in series means lower temperature in the FW and higher coolant temperatures in regions with lower power density, minimizing temperature differences in the segment structure. The flow in the grid plate manifolds is similar to that of the first wall.

III. BLANKET THERMAL-HYDRAULIC LAYOUT

A. Design Parameters

Parameters have been assumed for a preliminary layout of the blanket system. These parameters are summarized in Table I. First wall dimensions, grid plate dimensions, cooling channel size and spacing of the grid plates were estimated based on maintaining acceptable mechanical stresses in the structure in case the segment is pressurized to the full He pressure (plus static pressure of Pb-17Li) in the event of of a LOCA. The geometric design parameters are indicated in Figs.II and III.

Table I
Parameters Assumed for Thermal-Hydraulic Analysis

Average neutron wall load	4 MW/m^2
Average first wall heat flux	0.8 MW/m^2
Total energy multiplication in the blanket	1.4
Radial depth of the breeding zone	0.75 m
Toroidal width of a segment	1 m
Height of the blankets	20 m
Helium pressure	8 MPa
Helium inlet/FW outlet/blanket outlet temperature	350 / 420 / 500˚C
Pb-17Li in/outlet temperature	480˚C / 700˚C

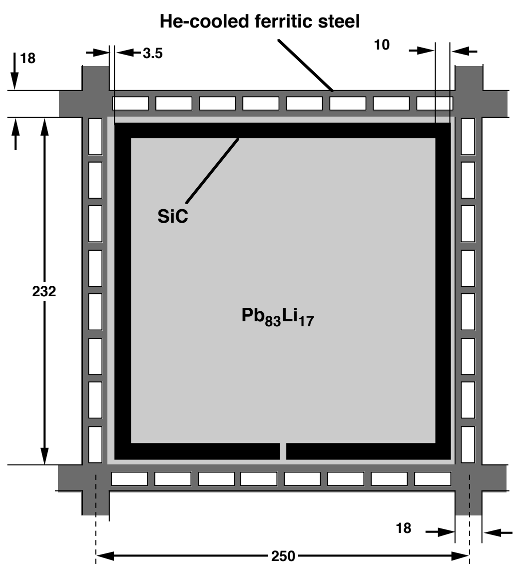

Fig. III. Configuration of a breeding zone cell.

B. Segment Power Distribution and Flow Rates

One segment of the blanket is assumed to be 1 m wide by 20 m high (representative of a highly-elongated plasma as found in LAR tokamaks). Therefore, with 4 MW/m^2 average neutron wall loading, the total volumetric heat generation is 112 MW. In the absence of detailed neutronics analysis, we assume the power deposition is roughly proportional to the volume fractions, so that 100 MW is deposited in the PbLi and 12 MW in steel. With 0.8 MW/m^2 average surface heat flux, an additional 16 MW is deposited in the FW. For the estimation of the heat fluxes through the 10 mm thick insulator plates the material properties listed in Table II are used.

The power distribution results shown in Table III require the coolant flow rates listed in Table IV.

Table II
Thermal Properties Used in the Analysis

Steel conductivity web thickness	25 W/m-K 4 mm
Pb-17Li conductivity thickness	15 W/m-K 3.5 mm
SiC conductivity thickness	4 W/m-K 10 mm
He heat transfer coefficient	2000 W/m^2-K
Pb-17Li heat trans. coefficient	1000 W/m^2-K
He heat capacity	5200 J/kg-K
PbLi heat capacity	190 J/kg-K

Table III
Power Distribution in Blanket Segment (MW)

Volumetric Heating in Pb-17Li in SS	112 100 12
Surface Heating	16
Heat Removed in He	
Surface heat	16
Volumetric heat in SS	12
Heat transferred from PbLi	7
TOTAL	36
Heat Removed in PbLi	
Volumetric heat in SS	100
Heat transferred to He	–7
TOTAL	93
Total Segment Power	**129**

Table IV
Coolant Flow Rates

Inlet He density	6.16 kg/m^3
Inlet He volume flow rate	8.3 m^3/s
Outlet He density	4.97 kg/m^3
Outlet He volume flow rate	10.3 m^3/s
PbLi volume flow rate	0.25 m^3/s

The mass flow rate of PbLi required to remove 100 MW of power is 2400 kg/s. Using a mass density of 9500 kg/m^3, the corresponding volume flow rate is 0.25 m^3/s. This leads to a PbLi velocity of 1.5 m/s in the four parallel channels in the front row.

C. Coolant Access Tubes

A characteristic feature of $Pb_{83}Li_{17}$ is its low tritium solubility. The resulting high tritium partial pressure can lead to intolerably high tritium permeation losses from the coolant access tubes and therefore generally requires additional permeation barriers. Another issue is the material for the outlet tubes for a PbLi temperature of 700˚C. There is no steel available allowing a temperature above 600˚C. To solve both problems, it is suggested to use concentric access tubes with the liquid metal flowing in the inner tube and helium in the annular gap. In this way helium with a temperature of 500˚C cools the liquid metal duct, especially if a thermal insulator is arranged inside the liquid metal tube. 15-mm thick SiC is proposed for this purpose. This design allows the use of steel for all access tubes. Tritium from the Pb-17Li in this case will not enter the building atmosphere but rather the helium coolant, where it can be recovered easily.

IV. POWER CONVERSION SYSTEM

The heat is removed from the blanket by two systems:

1. A helium loop with an inlet temperature of 350˚C and an outlet temperature of 500˚C
2. A liquid metal loop with an inlet temperature of 480˚C and an outlet temperature of 700˚C

This heat source can be used either for a Rankine cycle (steam turbine) or for a Brayton cycle (closed-cycle gas turbine). A gross thermal efficiency of at least 45% can be achieved with both power conversion systems based on the temperatures listed above. A closed cycle helium gas turbine process is chosen as a reference concept for the following reasons:

1. A steam turbine cycle has nearly no potential for further improvement of the efficiency. To achieve a value of 46%, already an advanced system with a steam pressure of 31 MPa and two reheats to 565˚C is required. A helium gas turbine cycle with a maximum pressure of 18 MPa can lead to the same efficiency at a maximum helium temperature of 650˚C. A rise of this temperature looks feasible and would increase the efficiency substantially.

2. Liquid metal/water heat exchangers are always a safety concern. Those concerns are mitigated by the use of the less reactive alloy Pb-17Li but the acceptance of liquid metal cooling can be greatly enhanced if the potential for a liquid metal/water reaction is avoided.

3. Tritium permeation losses from the Pb-17Li through the heat exchanger tube wall can be much more easily recovered from helium than from water.

4. There is much higher flexibility for the selection of structural materials for the components outside the irradiation environment if inert helium is used.

5. Liquid metal with a temperature of 700˚C requires the use of refractory metals in the heat exchanger. Those metals are always endangered by water leaks becoming a source of oxygen in the system. In a system without water in the high temperature components the helium can be purified to a much higher degree.

A total compression ratio of ~3 is required to allow for the relatively low helium temperature of 350˚ C. The temperature differences available in both systems will result in reasonable small heat transfer surface areas in both types of heat exchangers. For the case here having two different heat sources (He and Pb-17Li loops), a two stage lHX is required.

V. TRITIUM REMOVAL AND CONTROL

The tritium production in one segment with a total generated power of 140 MW is estimated to be 20 g/day. The liquid metal flow rate in one segment is 2400 kg/s. This means that the tritium concentration in the liquid metal is increased by about 0.1 wppb during one pass through the blanket. In a water-cooled blanket, the situation is completely different. There the liquid metal inventory is usually circulated 10 times per day. This means the tritium concentration increases by 20 wppb during one pass. This is a factor of 200 times higher than in the case of self-cooling where a bypass flow of about 0.5% would be sufficient if the same tritium concentration is tolerable. A higher bypass ratio would lead to a lower partial tritium pressure compared to a water-cooled Pb-17Li blanket.

Furthermore, the high PbLi temperature of 700˚C greatly enhances tritium extraction because at this temperature tritium is much more mobile than at 450˚C typical for water-cooled blankets. At this time, no attempt has been made to select a suitable extraction method. This must be done together with the selection of design and materials used for the heat exchanger.

VI. POTENTIAL PROBLEMS AND ISSUES

All of the numbers in this paper are rough estimates based on extrapolated values from similar concepts and partly on educated guesses. Thermal-hydraulic and thermal-mechanical analyses are particularly required to verify the dimensions chosen. Independent of the outcome of such analyses, the following more general issues should be addressed:

1. <u>Compatibility of SiC with Pb-17Li</u>. The maximum interface temperature between the two materials is below 700˚C. Tests at ISPRA have shown that the two materials are compatible at 800˚C under stagnant conditions. Tests in flowing Pb-17Li are underway there.

2. <u>Thermal Conductivity of SiC</u>. A thermal conductivity of at least 15 W/m-K is usually required to avoid excessively large temperature differences across the first wall. Contrary to this requirement, the maximum measured conductivity for the SiC/SiC composite at the relevant temperature is around 10 W/m-K, decreasing rapidly under neutron irradiation. For the design proposed here, the first wall heat flux does not pass through SiC, and a thermal conductivity as low as possible is required because the material serves here as an insulator. A value of 4 W/m-K has been used for the estimates. It should be possible to achieve such a low value with either high porosity or with the simplest 2-D composite.

3. <u>Electrical Resistance of SiC</u>. Measured resisivities for the SiC/SiC composite material are not available. MHD analysis of the French TAURO concept used a value of 0.2 Ω-cm which had been measured for solid SiC at 1000˚C [2]. Their finding was that the MHD pressure

drop in a duct with such a resisivity is tolerable. For comparison, the resisivity of ferritic steel at 500˚C is 95×10^{-6} ohm-cm and for Pb-17Li 130×10^{-6} Ω-cm. Pure alumina would have a resisivity of 10^6 Ω-cm at 1000˚C.

4. Strength and Fracture Toughness of SiC. Blanket designs based on the use of SiC/SiC as a pressure container have been criticized frequently because it has nearly zero ductility and is uncertain as a leak-tight container. Both aspects, the integrity under mechanical load and the leak tightness are much less important for the design proposed here because the SiC serves as an insulator only. Any mechanical loads by the coolant pressure are avoided by a pressure equalization between the flowing liquid metal and the stagnant zone at the outer side. Therefore, it may be possible to use solid SiC or at least the most simple 2-D composite to reduce cost decisively.

5. Activation of Pb-17Li by Neutron Irradiation. One main argument against the use of Pb-17Li blankets has been the radiotoxity of ^{210}Po. Investigations performed in Europe during the past five years, however, showed that this problem had been vastly overestimated. More precise neutronic data as well as more adequate calculation methods indicate ^{210}Po generation is orders of magnitudes lower than previously estimated. Release experiments of ^{210}Po from Pb-17Li proved that the release rates are not determined by the vapor pressure of Po but rather by the vapor pressure of a Po-Pb compound which is orders of magnitudes lower than that of the element itself. Both effects – the lower Po-210 generation and the lower release rates – led to the conclusion that ^{210}Po is no longer a significant safety issue. For a typical case, the contribution of ^{210}Po to the total dose to the public during a LOCA has been estimated to be less than 1%. The total release of radiotoxic materials was in any case so small that no evacuation of the public would be required.

6. Compatibility of Pb-17Li with Ferritic Steel. All the steel structure in the blanket segment and the steel wall of the liquid metal coolant tubes are thermally insulated from the flowing Pb-17Li by a SiC liner. There is a gap of stagnant Pb-17Li between the steel wall and the flowing Pb-17Li for pressure equalization. At this Pb-17Li/steel interface the temperature will be slightly higher than the local helium temperature. The helium cooling will be designed in a way that this coolant is heated up to the exit temperature in regions with the lowest power density to keep this over-temperature as low as possible. The highest steel temperature will occur, in any case, at the plasma facing surface.

   For self-cooled Pb-17Li blankets with a flow velocity of up to 2 m/s and ferritic steel as structural material, a maximum allowable interface temperature of 470˚C has been chosen, based on a corrosion rate of less than 20 µm/year. It is assumed that a limit about 50˚C higher can be allowed in the stagnant gap. If the corrosion at this temperature turns out to be too high or if thermal analyses show a higher interface temperature, the helium exit temperature can be lowered from 500˚C to 460-480˚C without causing large disadvantages.

7. Tritium Breeding Ratio. Self-cooled PbLi breeder blankets generally lead to the highest breeding ratios for a given reactor geometry. For a Dual Coolant Blanket with about the same geometry as proposed here, a TBR of 1.16 has been calculated with a 3-D Monte Carlo calculation including all openings and gaps. In the present concept, however, about 15% of the breeder is replaced by SiC. Scoping calculations [4] indicated that this change in composition can reduce the TBR by about 10 points. Therefore, more detailed neutronics analysis will be required after the overall geometry of the LAR-tokamak has been determined.

VII. CONCLUSIONS AND OUTLOOK

The blanket design proposed here can be used in tokamaks with water-cooled components because the Pb-17Li breeder material reacts only very mildly with water in case of leaks. The use of ferritic steel structural material with SiC inserts allows an average neutron wall load up to 4 MW/m^2, and can lead to a gross thermal efficiency in the power conversion system of about 45%. With a liquid metal exit temperature of 700˚C, either a Rankine cycle with a steam turbine or a Brayton cycle with a helium gas turbine can be used.

The helium-cooled first wall allows a surface heat flux up to 0.8 MW/m^2 without exceeding a temperature limit of 550˚C. High thermal conductivity is not required for the SiC, which serves as a thermal and electrical insulator only, without any mechanical load carrying functions. SiC, with an electrical resistance between that of steel and alumina, is not a real insulator but leads to a tolerable MHD pressure drop without requiring insulating coatings.

No serious feasibility issues have been identified, but a number of uncertainties remain. Potential problems are the impact of SiC on tritium breeding, the compatibility of SiC with flowing Pb-17Li and the corrosion of ferritic steel in stagnant Pb-17Li which may require a reduction of the helium exit temperature. Other issues include the selection of a suitable tritium extraction system and selection of suitable materials for the heat exchanger.

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