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Multiplier, moderator, and reflector materials for advanced lithium–vanadium fusion blankets

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Abstract

The self-cooled lithium–vanadium fusion blanket concept has several attractive operational and environmental features. In this concept, liquid lithium works as the tritium breeder and coolant to alleviate issues of coolant breeder compatibility and reactivity. Vanadium alloy (V–4Cr–4Ti) is used as the structural material because of its superior performance relative to other alloys for this application. However, this concept has poor attenuation characteristics and energy multiplication for the DT neutrons. An advanced self-cooled lithium–vanadium fusion blanket concept has been developed to eliminate these drawbacks while maintaining all the attractive features of the conventional concept. An electrical insulator coating for the coolant channels, spectral shifter (multiplier, and moderator) and reflector were utilized in the blanket design to enhance the blanket performance. In addition, the blanket was designed to have the capability to operate at average loading conditions of 2 MW/m^2 surface heat flux and 10 MW/m^2 neutron wall loading. This paper assesses the spectral shifter and the reflector materials and it defines the technological requirements of this advanced blanket concept. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Spectral shifter and reflector materials are utilized in the high power density self-cooled lithium blanket design [1] to enhance the blanket performance and to eliminate the main drawbacks of this blanket concept. Liquid lithium is used as the tritium breeder and coolant to alleviate issues of coolant breeder compatibility and reactivity. Vanadium alloy (V–4Cr–4Ti) is utilized as the structural material because of its superior performance relative to the other vanadium alloys for this application. It has several attractive features including adequate thermal conductivity to accommodate high heat loads, good mechanical properties at high temperatures, high neutron fluence capability, low degradation under neutron irradiation, good compatibility with the blanket materials, low neutron absorption cross-section, low decay heat, low waste disposal rating, and adequate strength to accommodate the operating conditions.

The conventional self-cooled lithium–vanadium fusion blankets [2–4] have poor attenuation characteristics and energy multiplication for the DT fusion neutrons. A blanket thickness of about 1 m is required to recover the DT neutron energy, to generate adequate tritium fuel, and to reduce the energy deposition in the shield. This large blanket thickness has a negative impact on the total cost and the attractiveness of the fusion reactor.

Spectral shifter (multiplier and moderator) and reflector materials are incorporated in the blanket to reduce the required blanket thickness, to enhance the blanket energy multiplication factor and the blanket shielding capability, and to reduce the energy deposition in the shield. To achieve high surface heat flux capability for the first wall, a small lithium zone with adequate velocity is located between the spectral shifter and the first wall. This lithium coolant provides a direct heat transfer path for the surface heat flux that minimizes the maximum first wall temperature. However, the neutronics aspect of the design requires the spectral shifter (multiplier) material to be very close to the first wall to maximize the $(n, 2n)$ reaction rate. Beryllium, lead, and zirconium were considered because of their unique properties of good neutron multiplication and low

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neutron absorption. Previous studies for solid breeder blanket designs [5,6] concluded that beryllium is the top ranking material for enhancing the blanket performance. However, the health hazard associated with the beryllium dust during fabrication promoted this study to check the possibility of using other material for the self-cooled lithium–vanadium blanket concept. Ten materials are assessed as moderator and reflector materials. Neutronics, heat transfer, and hydraulics analyses were carried out in a parametric fashion to define the possible design window for each combination of multiplier, moderator, and reflector materials. These materials were assessed including the results from the parametric analyses to define the possible candidate materials that provide the maximum enhancement for the blanket performance.

A self-healing electrical insulator is required for the coolant channels to reduce the MHD pressure drop and to permit the blanket operation with low-pressure lithium coolant. This leads to a simple poloidal flow concept with reliable design and enhanced performance. The material combination of beryllium spectral shifter (multiplier) and titanium carbide spectral shifter (moderator) and reflector in this simple poloidal configuration provides a significant enhancement in the blanket performance. In addition, natural lithium is used to avoid extra cost related to the lithium enrichment process. Vanadium clad is used for the spectral shifter and the reflector materials with liquid metal bonding to minimize the maximum operating temperature of these materials. This bonding also provides a simple method to accommodate the material swelling due to neutron irradiation and the differential thermal expansion.

2. Spectral shifter materials

Neutron multiplier material is usually utilized for solid breeder blanket concepts to enhance its tritium breeding capability. In these concepts, the existence of the other elements in the lithium compound and the high volume fraction of the structural material result in a tritium breeding ratio of less than one. However, lithium has a good tritium breeding capability without neutron multiplier. In addition, the self-cooled blanket concept uses a low volume fraction of the vanadium structural material, which has insignificant impact on the neutron economy. These characteristics of the self-cooled lithium–vanadium blanket concept are responsible for its poor neutron attenuation performance, which necessitates a large radial blanket thickness to convert the energy of the DT fusion neutrons to sensible heat and to utilize the DT fusion neutrons for tritium production. Therefore, a spectral shifter is incorporated in this blanket concept to reduce the large mean free path of the DT fusion neutrons without significant energy loss through endothermic nuclear reactions and neutron loss through parasitic absorption reactions. The neutron multiplication function of the spectral shifter increases the tritium production from lithium-6 isotope, which compensates the tritium production loss from lithium-7 isotope because of the neutron spectrum softening. The tritium production from lithium-6 is through an exothermic reaction while it is endothermic reaction for lithium-7. Therefore, the blanket energy multiplication factor is increased because of the spectral shifter. In addition, the neutron spectrum softening enhances the performance of the reflector material, which results in less energy deposition in the shield. These changes significantly enhance the performance of the self-cooled lithium–vanadium blanket concept.

Several studies [5–7] assessed the neutron multiplier, the spectral shifter, and the energy converter materials for fusion blankets. Beryllium, bismuth, lead, and zirconium are the most promising multipliers excluding the fissionable materials. High $(n,2n)$ and low absorption cross-sections are the main factors to achieve the required nuclear performance. Lead and bismuth have similar multiplication performances. However, bismuth is excluded because it produces ^{210}Po. Zirconium has the lowest potential among the four materials. In addition, the zirconium absorption cross-section is the highest relative to the other three multipliers. The high melting temperatures of beryllium and zirconium permit the blanket to operate without phase change for these multipliers. Beryllium has a health hazard associated with its dust during fabrication that requires special handling procedure. In addition, the blanket design has to accommodate its swelling and the small amount of tritium produced during operation. Beryllium utilization in the blanket results in high values for both the energy multiplication factor and the tritium-breeding ratio. This performance is unique for beryllium relative to the other possible multipliers.

Lead has to operate in the liquid phase because of its low melting temperature to avoid volume change during start up and shut down. It produces ^{210}Po and ^{205}Pb. ^{210}Po is an α-emitter, which is produced from neutron irradiation of bismuth. Bismuth is a transmutation of lead by neutron capture and a natural impurity of lead. This requires on-line removal of polonium or its precursor bismuth to limit the ^{210}Po concentration in lead. ^{205}Pb is very long-lived isotope, which decays by electron capture. Zirconium produces ^{93}Zr and ^{93}Nb isotopes, which have very long half-lives. In addition, zirconium generates more decay heat relative to beryllium and lead.

In this study, a parametric analysis was performed to compare the performance of the self-cooled lithium–vanadium blankets with the different multiplier materials, beryllium, lead, and zirconium. Titanium carbide material was used as a reflector during this analysis. All zone dimensions were varied parametrically and the blanket performance parameters were observed. The tritium breeding results show that both beryllium and lead enhance the tritium production while zirconium reduces the blanket capability for tritium breeding. Beryllium does better than lead for improving the tritium breeding performance. In addition, beryllium improves significantly the blanket energy multiplication factor while lead does the opposite. This leads to the beryllium selection as the best spectral shifter (multiplier) for the self-cooled lithium–vanadium blanket. Zirconium reduces the tritium breeding capability of the blanket, which disqualifies its use as spectral shifter for this type of blankets. Beryllium does enhance the blanket shielding performance, which increases the attractiveness of the blanket concept. Also, lead and zirconium have the same effect. Therefore, lead is selected as the backup material for beryllium spectral shifter although lead has the disadvantages of low blanket energy multiplication factor and low melting point. The first three columns of Table 1 compare the blanket performance parameters with the three spectral shifter materials for the same blanket thickness.

3. Moderator and reflector materials

Moderator and reflector materials are used in the blanket to slow down the high-energy neutrons for absorption in the lithium breeder and to decrease the loss of neutrons from the blanket by scattering back many of those that have escaped. The best moderator or reflector material is consisting of elements of low-mass number with low absorption cross-sections. In addition, this material has to contribute to the energy multiplication in the blanket, which favors materials with exothermic nuclear reactions. Water is excluded from the system because of the use of liquid lithium. Beryllium is also excluded from this function because of the desire to reduce the total material cost. Ten materials are examined to select the most promising materials.

Carbon element has the lowest mass number possible to use and insignificant absorption cross-section, which improves the tritium breeding capability of the blanket. In addition, carbon has low activation characteristics. Carbide materials are considered for their carbon content and stability at high temperature. Copper is included because of its high thermal conductivity, which eases the thermal–mechanical design. The good shielding capability of tungsten promoted its consideration. The good fabrication characteristics, the low unit cost, and the existing database lead to the steel consideration. Calcium oxide was selected as reflector material for the conventional self-cooled lithium–vanadium blanket design [8] because it has low activation characteristics and low unit cost.

Table 1

Self-cooled lithium–vanadium blanket configuration with beryllium spectral shifter and different moderator/reflector materials

Multiplier material	Pb	Zr	Be	Be	Be	Be	Be	Be	Be	Be	Be	Be
Reflector material	TiC	TiC	TiC	C	316 Steel	W	Cu	Mn-steel	CaO	WC	ZrC	CaC_2
Beryllium thickness (m)	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Lithium thickness (m)	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Blanket thickness (m)	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
Blanket EMF[a]	1.06	1.27	1.35	1.26	1.39	1.03	1.43	1.48	1.25	1.05	1.37	1.42
Local TBR[a]	1.31	1.21	1.50	1.53	1.46	1.38	1.43	1.35	1.47	1.36	1.52	1.47
Shield energy fraction	0.041	0.034	0.029	0.080	0.024	0.006	0.015	0.030	0.071	0.003	0.033	0.081
Possible selection	Yes[b]	No[c]	Yes	No[d]	No[e]	No[f,g]	No[e]	Yes[f]	No[d]	No[f,g]	No[e]	No[d]
Multiplier ranking	2		1									
Reflector ranking			1					2				

[a] EMF (energy multiplication factor), TBR (tritium breeding ratio).

[b] Lead operates in liquid form.

[c] Poor performance, activation problem, and low tritium breeding ratio.

[d] Poor shielding performance.

[e] Reflector activation.

[f] High decay heat.

[g] High cost and low blanket energy multiplication.

Table 2
Main blanket performance parameters

Parameter	Value
Average surface heat flux (MW/m^2)	2
Average neutron wall loading (MW/m^2)	10
Blanket energy multiplication factor	1.33
Local tritium breeding ratio	1.32
Shield energy fraction	0.025
Blanket radial thickness (m)	0.57
Lithium enrichment	Natural
Lithium coolant inlet temperature (°C)	400
Lithium coolant outlet temperature (°C)	600
Max. vanadium temperature (°C)	754
Max. beryllium temperature (°C)	803
Max. titanium carbide temperature (°C)	866
Lithium coolant velocity (m/s)	
First wall coolant channel	6.06
Blanket channels	1.21
First wall lifetime for 1% strain (y)	27.2
Blanket thermal conversion efficiency (%)	43

The blanket performance was studied as a function of the zone dimensions for each material. The changes in the blanket performance parameters as a function of the zone dimensions are similar however the achieved level of performance depends on the selected moderator and reflector materials. Table 2 compares the blanket performance parameters for the different materials. Because of poor shielding performance, carbon, calcium oxide, and calcium carbide can be discarded. Steel, copper, and zirconium carbide are also eliminated because of activation and decay heat concerns. High cost and decay heat concerns discourage the use of tungsten and tungsten carbide. Among the other two materials, titanium carbide is the first choice. In addition to the good performance, it has attractive characteristics including good material stability and mechanical properties. Low activation manganese steel is the backup candidate although it has high decay heat.

4. Technological requirements

In the design of the advanced self-cooled lithium–vanadium blanket, beryllium spectral shifter (multiplier) and titanium carbide spectral shifter (moderator) and reflector were utilized. Neutronics, heat transfer, thermal hydraulics, and structure analyses were iterated to define the blanket geometrical configuration. In these analyses, several design guidelines were adopted to ensure a significant enhancement in the blanket performance. The reference average loading conditions are 2 MW/m^2 surface heat flux and 10 MW/m^2 neutron wall loading. The energy multiplication and the shielding capability of the blanket are maximized. The local tritium-breeding ratio is maintained above 1.3 to insure tritium self-sufficiency with natural lithium. Simple blanket configuration is emphasized to reduce the fabrication cost, to improve the blanket reliability, and to increase confidence in the blanket performance. The blanket thickness and the energy deposition in the shield are minimized to reduce the capital cost of the reactor system. Electrical insulator is utilized for the lithium channels to maintain low-pressure system and long lifetime for the blanket structure. The allowable temperature range of the vanadium structure is 400–800°C. The minimum temperature is intended to insure that the vanadium structure operates above the temperature at which significant irradiation embrittlement has been observed. The upper temperature is selected to provide adequate creep strength and to avoid high temperature helium embrittlement. The design iterations obtained a blanket with a total thickness of 0.57 m, which satisfies all the design guidelines and the loading conditions. Table 2 gives the main blanket performance parameters. The blanket design has a simple poloidal flow as shown in Fig. 1.

In this advanced blanket design, vanadium clad is used for the beryllium and the titanium carbide materials. Liquid metal (e.g. sodium) thermal bond is used to maintain acceptable maximum temperature for both materials. In addition, this liquid metal bond provides a simple method to accommodate the differential thermal expansion and the swelling due to neutron irradiation of both materials without impacting the blanket operation. Such technology was developed and used successfully for the fuel rods of the fast fission reactors, EBR-II, FFTF, and Fermi-1.

Electrical insulator is utilized for the lithium channels to maintain low-pressure system and long lifetime for the blanket structure. This technology is under development, where exploratory tests have demonstrated that a highly resistive calcium oxide coating can be formed on vanadium alloys. Also, self-healing characteristics have been demonstrated in preliminary experiments. Aluminum nitride coating is also under development for the same

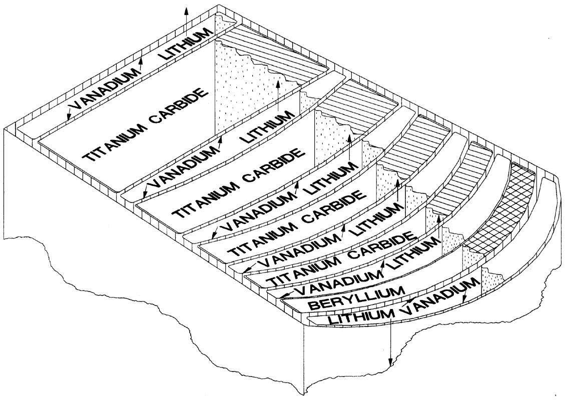

Fig. 1. Blanket sector cross-section.

function. Such coating materials are essential for this blanket concept to achieve an enhanced performance.

5. Conclusions

Spectral shifter (multiplier and moderator) and reflector materials were assessed for the self-cooled lithium–vanadium blanket concept. Beryllium spectral shifter (multiplier) and titanium carbide spectral shifter (moderator) and reflector are the top ranked materials for these functions. Vanadium clad was used for both materials with liquid metal thermal bond. Electrical insulator is utilized for the lithium channels to maintain low-pressure system and long lifetime for the blanket structure. These features result in an enhanced blanket performance including average loading conditions of 2 MW/m^2 surface heat flux and 10 MW/m^2 neutron wall loading, 600°C outlet lithium temperature for high thermal efficiency, and 0.57 m radial blanket thickness with good shielding performance.

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