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NEUTRONICS PERFORMANCE OF HIGH-TEMPERATURE REFRACTORY ALLOY HELIUM-COOLED BLANKETS FOR FUSION APPLICATION

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Abstract

Among the concepts considered in the Advanced Power Extraction (APEX) study is the He-cooled refractory metal FW and blanket concept. Refractory metals exhibit high operating temperature and can offer good capability for withstanding high power density operation that is the focus of the APEX study. In this paper, we assess the impact of using various refractory metal on the nuclear heating profiles across the blanket and power multiplication, PM, and on the tritium breeding profiles and tritium breeding ratio, TBR. The refractory metals considered with liquid lithium breeder are W, TZM, and Nb-1Zr. The impact of Li-6 enrichment on these profiles and on TBR and PM is also assessed. Comparison of these nuclear characteristics is also made to other liquid breeder (Flibe and Li-Sn). Because the moderation power of these breeders to neutron energy varies among them, the damage to the structure is different with various structure/breeder combinations. The damage parameters (DPA, helium and hydrogen production) at key locations are also compared to the corresponding values in the thick liquid FW/Blanket concept; an innovative design concept under consideration within the APEX study.

1. Introduction

The APEX Study [Abdou 1] focuses on developing innovative concepts capable of efficiently extracting high power density from blanket subjected to high neutron wall load (>10 MW/m2) and the associated high surface heat load (>2 MW/m2). This stems from the fact that, as currently stands, the average core power density in present fusion reactors design is much lower than that in fission rectors (~0.4 MW/m^3 in ITER for example vs. ~240 MW/m^3 in LMFBR). The proposed concepts must also satisfy other functional requirements such as: (1) tritium breeding at the rate required to satisfy tritium self-sufficiency, (2) tritium extraction and processing, and (3) radiation protection. The other challenging issues in these concepts are reducing components' failure rate and increasing plant availability.

Among the concept considered is the helium-cooled refractory metal FW/Blanket concept. Alloys of refractory metal such as tungsten, molybdenum, vanadium, and titanium exhibit high operating temperature and thus most suitable for high power density (HPD) operation regime. The objective of this paper is to evaluate the heating rate profiles and power multiplication, PM, when various candidate refractory alloys are deployed with lithium as the breeder. Tritium production rate (TPR) and tritium breeding ratio (TBR) are also assessed as function of Li-6 enrichment to optimize the design for maximum breeding potential. Comparison is also made to the breeding capability of other liquid breeders, namely, Flibe (Li_2BeF_4) and Li-Sn (25:75). The Li-Sn eutectic has the advantage of having low vapor pressure (to reduce plasma contamination) and has recently been proposed for fusion application [Sze 2]. In addition, we also assess the damage indices, expressed in terms of DPA, helium, and hydrogen production rates at several key locations, including the vacuum vessel (V.V.) and TF coil case with various refractory metals and breeders and comparison is made to the liquid FW/Blanket concept [Youssef 3, Ying 4]. For information on the operating temperatures/pressures and other relevant design parameters of the present concept, the reader is referred to [Wong 5] and [Zinkle 6].

2. Calculational Model

For the purpose of this parametric investigation, the 1-D calculational model shown in Fig. 1 is used in the analysis. Liquid lithium with tungsten structure and helium coolant is used as the reference case. The volume fraction of materials in each zone is given in Table I. The variation of volume fraction shown is the result of variation in the size of tubing for the liquid breeder and the helium coolant at various locations [Wong 5]. The FW facing the plasma is 2.2 cm-thick and is cooled with helium followed by a solid wall (module wall) of 0.2 cm-thick. The blanket zones vary in thickness as 1.5 cm, 1.8 cm, and 3.7 cm while the tube zones are 1.3 cm-thick. The total blanket thickness is ~57 cm, followed by the transitional zone (23 cm-thick, 30%He,70% structure), the plenum zone (40 cm-thick, 60%He, 40% structure), and the shield (10 cm-thick, 20%He, 80% structure). In all cases, the V.V. is made of 2 cm-thick outer walls with an internal 26 cm-thick zone consists of 60:40 316SS:Water. The calculations are performed with the ANISN transport code [Engle 7] along with 46-21 multi-group library based on FENDL-1 database [Paschenko 8].

3. Results and Discussion

3.1 Tritium Breeding and Effect of Structural Material

The best local TBR performance is with W and Li breeder. The TBR increases with Li-6 enrichment and start to saturate at a value of ~1.43 when Li-6 enrichment is ~35%. . It reaches an optimal value of ~ 1.45 at ~50% Li-6 enrichment. Neutrons slowed down by the W structure are get absorbed mainly by Li-6 via Li-6(n,α) reactions. Even at natural Li-6 enrichment (TBR<1), most of the contribution to TBR is from Li-6 (T6). This is also apparent from Fig. 2 which shows the tritium production rate (TPR) profiles across the breeding zone for the case with 35%Li-6 enrichment (reference case).

Using TZM and Nb-1Zr results in ~ 4% and ~15% decrease in TBR, respectively (35%Li-6, TZM: TBR ~1.37; Nb-1Zr: TBR ~1.21). The contribution from Li-7 to the local TBR (T7) is ~0.2 among various structural materials and the reduction in TBR is mainly due to reduction in the contribution from Li-6 (T6, see Fig. 3). The T6 is the largest with W while T7 in relatively the largest with TZM.

3.2 Nuclear Heating and Effect of Structural Materials

Smeared nuclear heating rate, P_{ho}, is defined as the average power deposition rate at a particular location in a given zone when the materials given in Table I are homogenized in the calculation for that zone. Heterogeneous rates, P_{htj}, for a particular material j, are those obtained when the volume fraction of that material, F_j is taken into consideration ($P_{htj} = P_{hoj}/F_j$).

In the W/Li system, the largest smeared heating rate occurs at the front module wall and is ~90 w/cc for an average wall load of 10 MW/m2, as shown in Fig. 4. Neutron heating dominates the total heating rate in the blanket zones due to absorption in the Li-6. Gamma heating is the dominant contributor in the zones that have large structure constituent. The approximate heterogeneous heating rate in the breeder itself is shown in Fig. 5. The maximum heating rate is ~50 w/cc.

In the blanket zones, W structure gives the highest heat deposition rates. The values with TZM are lower but comparable to the W case. As shown in Fig. 6, the smeared heating rates in the tube zones (32% structure, 47% He, 21% Li) when either TZM or Nb-1Zr is used are comparable but they are a factor of 1.5 lower compared to the W case (more gammas in this case). The maximum heating rates in the TZM (or Nb-1Zr) structure is ~40 w/cc, which is a factor of 2.2 lower than with the W structure.

3.3 Nuclear Characteristics of Other Breeders

3.3.1 Tritium Breeding

Two other liquid breeders are considered, namely, Flibe and Li-Sn, with tungsten structure. Figure 7 shows the TBR and power multiplication, PM, as a function of the Li-6 enrichment. The TBR is low (0.25) for Li-Sn with natural Li but it increases rapidly with increasing Li-6 enrichment and reaches a value of ~ 1.15 at 90% Li-6 enrichment. Clearly the "local" TBR value obtained from 1-D calculations is still marginal and tritium self-sufficiency can not be granted if penetrations and coverage fraction of the blanket is taken into consideration. In Flibe case, The situation is improved where TBR shows a steady increase with Li-6 enrichment (~0.45 at natural Li and ~ 1.21 at 90%Li-6). The same concern still holds for the Flibe, i.e., breeding appears to be marginal. The Li breeder shows the largest TBR.

As noted, the TBR in Li and Flibe increases with Li-6 enrichment due to the presence of the solid FW in the He-Cooled FW/B concept. This wall tends to slow down high-energy neutrons via inelastic scattering and they end up being absorbed in Li-6 via Li-6(n,α) reactions. This is in contrast to the GMD thick liquid FW/B concept in which TBR decreases with Li-6 enrichment [Youssef 3]. In this latter concept, no structural material is present in the front liquid layer and the large amount of Li-7 improves the neutron economy via Li-7(n,n'α)t reactions and therefore the TBR is the largest at natural Li enrichment.

3.3.2 Power Multiplication

The power multiplication, PM, is the largest in the Li-Sn case (PM ~1.4 at natural Li enrichment). This is advantageous from the viewpoint of improving the thermal cycle and its efficiency but the Li-Sn breeder, even at 90%Li-6, has a marginal TBR. Generally, the PM decreases slightly with Li-6 enrichment. At natural Li, PM is ~1.22 (Li), ~1.40 (Li-Sn) and ~1.07 (Flibe). The PM is the lowest with the Flibe breeder (~1.02) which is disadvantageous with comparison to Li-Sn.

The large PM with the Li-Sn breeder is due to the large Sn(n,γ) reaction rate, which generates larger gamma-ray flux. The gamma heating is the main contributor to the total heating in the system as can be seen from Fig. 8 which depicts the total power deposited per unit height (w/cm) in the poloidal. Here a comparison is made between Li and Li-Sn. Still Li-Sn gives larger power deposition rate than Li (by a factor of 1.15 at 35% Li-6 enrichment.). In addition, the contribution from gamma heating with the Li-Sn breeder is always larger than the contribution from neutron heating, but decreases with Li-6 enrichment. At 90%Li-6 enrichment, the contributions from gamma heating and neutron heating are comparable. As for Li case, the contribution from neutron heating is dominant above ~10%Li-6 enrichment.

3.4 Damage Parameters and Effect of Structural materials

The impact of using various refractory metal as structure on the damage parameters at various locations has been assessed with Li breeder (35%Li-6). At 10 MW/m2 wall load, the DPA rate at the FW is 56.3, 89.0, and 55.5 DPA/FPY with W, TZM, and Nb-1Zr structure, respectively. Tungsten shows the lowest DPA rate across the blanket/shield system. The TZM shows the highest damage rate at the FW while Nb-1Zr has a low rate at the FW but the values resume the TZM values at deeper locations (see Fig. 9). If the 200 DPA is used as the upper limit for damage before replacement is needed, the FW/blanket will be replaced every 3.6 years with W and Nb-1Zr structure and every 2.2 years with TZM structure.

The helium production rate at the FW is 21.8, 384.1, and 372.8 appm/FPY with the W, TZM, and Nb-1Zr, respectively. The tungsten shows the lowest helium production rate. At the FW, its value is more than an order of magnitude less than TZM and Nb-1Zr cases (~2 orders of magnitude at back locations see Fig. 10). The helium production rates in TZM and Nb-1Zr are similar due to the similarity in their cross sections, as can be seen from Fig. 11. The hydrogen production rate at the FW is 78.4, 3008.9, and 2052.7 appm/FPY with W, TZM, and Nb-1Zr, respectively. The profiles have features similar to those shown in Fig. 10.

The damage parameters in the V.V. walls (316SS) located behind the shield (not optimized) and the TF coil casing (316SS) have also been estimated (see Table II). The DPA rates in V.V. are 0.009, 0.07, and 0.06 DPA/FPY, with W, TZM, and Nb-1Zr structure, respectively, i.e. the damage with W is a factor of ~7 lower than the values with other structures. The accumulated DPA over the plant lifetime (30 years) are 0.3 DPA (W) and ~2 DPA (TZM, Nb-1Zr) which are below the 200 DPA limit for replacement. This makes the V.V. a lifetime component. On the other hand, the He-4 production rates at the V.V. walls are ~0.1, ~0.6, and ~0.4 appm/FPY. The damage with W structure is a factor of ~6 and 4 lower than with the TZM and Nb-1Zr structure, respectively. However, the accumulated helium over 30 years is larger than the 1 appm limit to make the V.V. reweldable. Generally, the damage parameters with the TZM are larger than with the Nb-1Zr structure.

The DPA rate, helium and hydrogen production rates at the FW with the tungsten structure are 56 DPA/FPY, 22 appm/FPY, and 78 appm/FPY, respectively. The corresponding values in the thick liquid FW/Blanket concept [Youssef 3] at the backing FW are 3.6 DPA/FPY, 21 appm/FPY, and 85 appm/FPY, respectively. Thus the DPA rate at the FW is a factor of ~16 larger in the helium-cooled concept. However, the helium and hydrogen production rates are comparable in the two concepts. Also, these damage parameters are comparable at the V.V. and the magnet casing.

3.5 Damage Parameters and Effect of Type of Breeder

The damage parameters were also estimated with Flibe (90% Li-6 enrichment) and Li-Sn (90%Li-6 enrichment). These parameters are similar at the FW and Module Wall among the three breeders. This is expected since the breeders are present behind these walls. However, the damage parameters at the V.V. and TF Coil casing are larger by a factor of 6-10 with the lithium breeder than with the Flibe breeder. On the other hand, these parameters are larger by a factor of 1.3-2.7 with the Li-Sn breeder than with the Flibe breeder. This shows that the liquid lithium is the least effective material in attenuating the nuclear field at the V.V. and TF while the Flibe is the most effective material in reducing the damage at these locations.

4. Conclusions

In the helium cooled refractory metal FW/Blanket concept under investigation in the APEX study, the best TBR performance is achieved with the tungsten structure and Li breeder. The TBR increases with Li-6 enrichment and saturates at a value of ~1.43 (~35%Li-6). Using TZM and Nb-1Zr results in ~ 4% and ~15% decrease in TBR, respectively. The TBR is low (0.25) for Li-Sn with natural Li but it increases rapidly with increasing Li-6 enrichment and reaches a value of ~ 1.15 at 90%Li-6. Clearly this "local" TBR value is still marginal and tritium self-sufficiency can not be granted. In the Flibe case, the situation is improved and TBR shows a steady increase with Li-6 enrichment (~0.45 at natural Li-6 and ~ 1.21 at 90%Li-6). The same T self-sufficiency concern still holds for the Flibe. In contrast to the liquid FW/B concepts studied in APEX, the TBR in Li and Flibe increases with Li-6 enrichment due to the presence of the solid FW in the He-Cooled FW/B concept. The max heating rate in the W structure is ~ 90 W/cc and is ~50 w/cc in the breeder zones (10 MW/m2 wall load). The heating rates when either TZM or Nb-1Zr is used are comparable but are a factor of 1.5 lower compared to the W case. The power multiplication, PM, is the largest in the case of Li-Sn breeder due to the large Sn(n,γ) reaction rate, which generates larger gamma-ray flux. This is advantageous from the viewpoint of improving the thermal cycle and its efficiency but the Li-Sn breeder, even at 90%Li-6, has a marginal TBR. The TBR could be increased by including a beryllium multiplier zone and/or reducing neutron absorption is Sn, possibly by enriching Sn (among its 10 natural isotopes) in its natural isotope Sn-119 [Youssef 9]. The damage in the FW and elsewhere in the system is the lowest when tungsten is used as the structural material. Also, the damage to the vacuum vessel is the least when Flibe is used as the breeder due to its superior moderation to neutrons energies.

Figure Captions

Figure 1: The Radial Build of the He-Cooled Refractory FW/Blanket Concept (1-D Cylindrical Model)

Fig. 2: Profiles of Tritium Production Rate across the Blanket Region and Contribution from T6 and T7 (W Structure- 35%Li-6)

Fig. 3: Profiles of Tritium Production Rate from Li-6 (T6) for Various Structural Materials

Fig. 4: Total Nuclear Heating Rate Profiles across the Blanket, Transitional Zone, Plenum, and Shield System (W/Li : Structure/Breeder)

Fig. 5: Profiles of the Total Heterogeneous Nuclear Heating Rates in the Breeder and Contribution from Neutrons and Gamma Heating (W/Li System, 35%Li-6 enrichment)

Fig. 6: Profiles of the Total Nuclear Heating Rates across the FW and Front Part of the Blanket for Various Structural Materials

Fig.7: The Tritium Breeding ratio, TBR, and Power Multiplication, PM, as a Function of Li-6 Enrichment for Several Breeders.

Fig. 8: Total Power Deposited in the FW/Blanket/Shield System per Unit Height as a Function of the Li-6 Enrichment

Fig. 9: The DPA Profiles across the Blanket, Transitional Zone, Plenum, and the Shield for Various Structural Materials

Fig. 10: The Helium Production Profiles across the Blanket, Transitional Zone, Plenum, and the Shield for Various Structural Materials

Fig. 11: The Helium Production Cross Section of Several Structural Materials

Table I: Volume Fraction of Materials in Various Zones

Zone Name	Structure	Breeder	Coolant (helium)
First Wall	0.167	-	0.831
Module Wall	1.0	-	-
Blanket Zone 1	0.013	0.975	0.04
Tube Zone 1, 2, 3, 4	0.32	0.215	0.465
Blanket Zone 2	0.022	0.924	0.054
Blanket Zone 3	0.031	0.902	0.067
Blanket Zone 4	0.04	0.879	0.081
Blanket Zone 5	0.05	0.856	0.094
Transitional Zone	0.7	-	0.3
Plenum Zone	0.4	-	0.6
Shield Zone	0.8	-	0.2

Table II: Damage Parameters with Various Structural Materials at Key Locations

Location	DPA/FPY		
	W	TZM	Nb-1Zr
FW	56.3	89.1	55.5
Module Wall	50.3	81.8	51.6
V.V. Case	0.009	0.07	0.06
SCM Case	$7x10^{-5}$	$8x10^{-4}$	$4x10^{-4}$
Cu-Stabilizer	$1x10^{-6}$	$1x10^{-5}$	$5x10^{-6}$
	He-4 Production (appm/FPY)		
FW	21.8	384.1	372.8
Module Wall	18.5	341.8	324
V.V. Case	0.096	0.64	0.43
SCM Case	$5x10^{-4}$	0.005	0.003
	H Production (appm/FPY		
FW	78.4	3009	2053
Module Wall	66.6	2671	1782
V.V. Case	0.09	0.89	0.30
SCM Case	0.001	0.01	0.004

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