Nuclear Aspects of a Solid Wall Blanket Based on Advanced Ferritic Steel and Re-circulating Flibe

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Nuclear Aspects of a Solid Wall Blanket Based on Advanced Ferritic Steel and Re-circulating Flibe

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***Abstract*. Nuclear analysis was performed for a solid wall blanket concept that uses the nano-composited ferritic (NCF) steel alloy 12YWT as structural material with Pb as the neutron multiplier and Flibe (Li_2BeF_4) as the tritium breeder and coolant. With an enrichment of 40% ^{6}Li the overall tritium breeding ratio is expected to be ~1.16 and the blanket energy multiplication is 1.13. The peak structure dpa and helium production rates are 77.6 dpa/FPY and 955 He appm/FPY, respectively, implying a lifetime of ~3 FPY. The NCF structure dominates the total activity and decay heat. The Mo content in the NCF needs to be reduced from 0.02% to <0.01% for the structure waste to qualify as low level class C waste.**

I. Introduction

The Advanced Power Extraction (APEX) project has been exploring concepts for first wall and blanket designs with potential for enhancing the attractiveness of fusion energy systems [1]. An advanced solid wall blanket concept considered in the APEX project uses the nano-composited ferritic (NCF) steel alloy 12YWT as structural material with Pb as the neutron multiplier and Flibe (Li_2BeF_4) as the tritium breeder and coolant. It also uses an innovative re-circulating coolant scheme, which allows part of the coolant to be re-circulated in order to enhance the outlet temperature, and thus improve the power conversion cycle efficiency. The selected advanced ferritic steel alloy [2] has a maximum operating temperature of 800°C and is compatible with Flibe up to 700°C. The coolant outlet temperature at 681°C allows coupling with a helium-closed cycle power conversion system leading to a gross thermal efficiency of 47%. A cross section of an outboard blanket module at midplane is also shown in Fig. 1. Each first wall (FW) channel has a tube containing liquid Pb as the neutron multiplier. The FW assembly is followed by a large box, which is subdivided into side and back flow channels and the central channel [3]. In this paper, nuclear analysis is presented for this blanket design.

II. Neutronics Analysis

Neutronics calculations were performed to determine the relevant nuclear performance parameters for the blanket with lead multiplier. These include tritium breeding, nuclear heating, radiation damage, and shielding requirements. In addition, the design option with beryllium multiplier was analyzed and compared to the reference design. Table I gives the radial build used in the calculations. The material composition of each zone is listed. In the outboard (OB) side, the re-circulating blanket is followed by a 40 cm thick secondary blanket consisting of 94% Flibe and 6% NCF structure. Due to limited space, no secondary blanket is utilized in the inboard (IB) region. The ONEDANT module of the DANTSYS 3.0 discrete ordinates particle transport code system [4] was used to perform the calculations utilizing the FENDL-2 [5] nuclear data library. Both the IB and OB regions were modeled simultaneously to account for the toroidal effects. The results were normalized to the peak neutron wall loading values of 5.45 and 3.61 MW/m^2 in the OB and IB regions, respectively. The results of the neutronics calculations are summarized here.

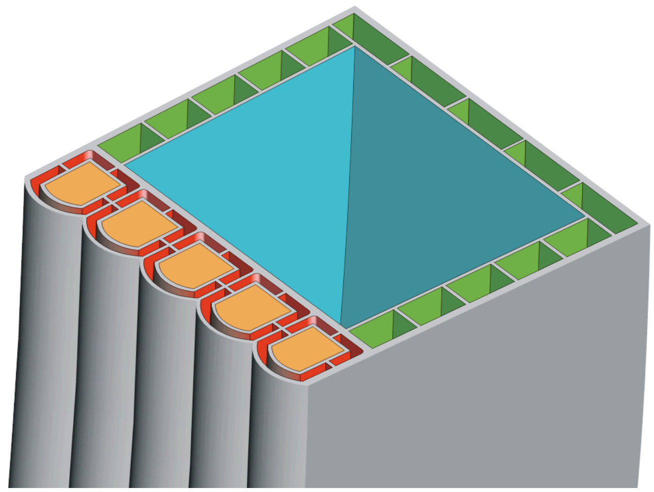

Fig. 1. Midplane cutaway of outboard module.

TABLE I
RADIAL BUILD OF THE REFERENCE BLANKET

Zone		Thickness	Volume fraction		
			Flibe	NCF	Pb
1	First wall	3 mm		1	
2	FW Flibe channel	10 mm	0.92	0.08	
3	Pb front wall	3 mm	0.2333	0.7667	
4	Pb mulitplier	40 mm	0.2333	0.18	0.5867
5	Pb back wall	3 mm	0.2333	0.7667	
6	Flibe channel + side wall	7 mm	0.92	0.08	
7	Flibe channel back wall	6 mm		1	
8	Flibe + side walls	199 mm	0.932	0.068	
9	Back wall	29 mm	0.6069	0.3931	
	Total	300 mm			

A. *Tritium Breeding*

Figure 2 shows the effect of enriching Li in ^{6}Li on the local OB tritium breeding ratio (TBR). The contributions from the re-circulating and secondary blankets are shown separately. Since the TBR has a flat peak in the enrichment range between 40 and 60%, an enrichment of 40% ^{6}Li is chosen. At this enrichment the secondary blanket contributes ~13% of the local OB TBR of 1.244. The results also indicated that the TBR is not very sensitive to the Pb zone thickness. Only ~3% enhancement in the TBR is achieved by increasing the Pb zone thickness from 4 to 8 cm. Assuming neutron coverage of 75% for the OB region, 15% for the IB region, and 10% for the divertor region, the overall TBR will be ~1.11 excluding breeding in the divertor region. Breeding in the divertor zone could add ~0.05 depending on the amount of Flibe used. Hence, we expect that tritium self-sufficiency can be realized in a fusion power plant employing the re-circulating blanket.

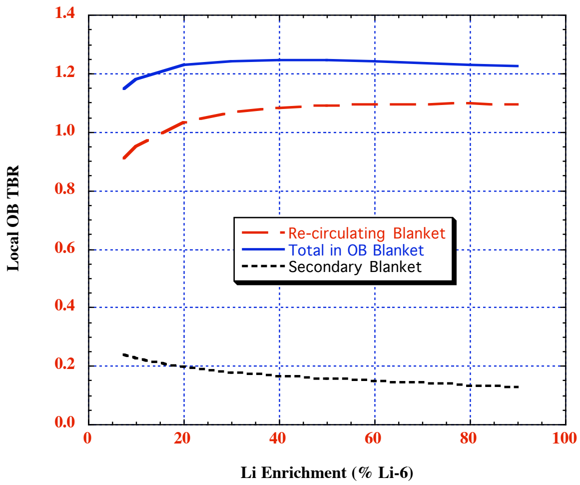

Fig. 2. Local TBR in OB region with re-circulating blanket.

B. Nuclear Heating

The total nuclear energy multiplication in the 30 cm thick re-circulating IB and OB blankets and 40 cm thick OB secondary blanket is 1.13. The OB secondary blanket contributes 4.5% of the total IB and OB nuclear heating. This corresponds to only ~3.7% of the total IB and OB thermal power that includes surface heating. Nuclear heating radial profiles in the different blanket components were determined for use in the thermal hydraulics analysis. The results are shown in Fig. 3 for a unit neutron wall loading. The total power generated from nuclear heating was calculated for the different zones of the blanket module using the average OB and IB neutron wall loading values of 4.6 and 2.8 MW/m^2, respectively, and a module height of 8 m. The results for the OB and IB modules are given in Table II. The surface heat flux adds 2.14 and 1.92 MW to the thermal power in the OB and IB first wall zones, respectively.

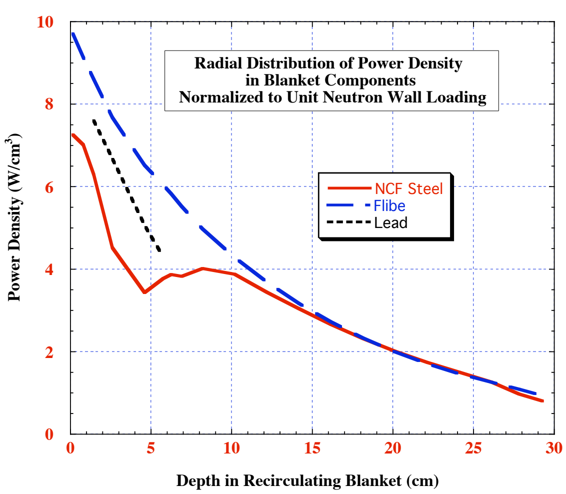

Fig. 3. Radial distribution of power density in blanket components.

TABLE II
POWER FROM NUCLEAR HEATING IN THE ZONES OF THE BLANKET MODULE

Zone	Power from Nuclear Heating (MW)	
	OB Module	IB Module
First wall	4.86	2.96
Side walls	1.14	0.69
Back wall	0.31	0.19
Central Flibe channel	4.88	2.97
Total	11.19	6.81

C. Radiation Damage

The peak OB dpa and helium production rates in the NCF structure are 77.6 dpa/FPY and 955 He appm/FPY. The corresponding values for the IB modules are 61.7 dpa/FPY and 719 He appm/FPY. Based on a radiation damage limit of 200 dpa, the lifetime of the re-circulating blanket is expected to be ~3 FPY. The peak cumulative end-of-life (30 FPY) dpa in the NCF structure of the OB secondary blanket is 60.3 dpa implying that it will be a lifetime component. Figure 4 shows the radial profile of the radiation damage in the structure of the re-circulating and secondary blankets at the OB midplane.

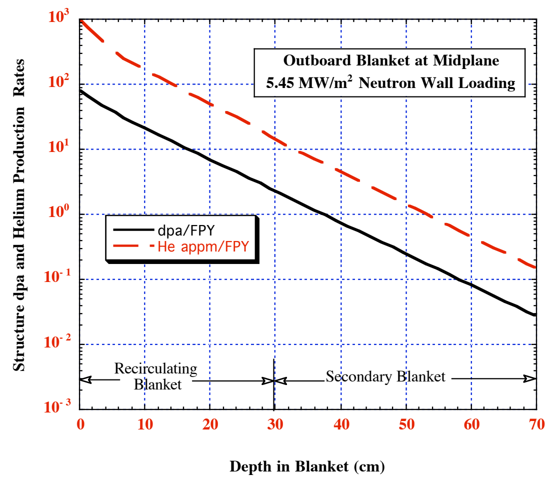

Fig. 4. Radial variation of structure damage at OB midplane.

D. Shielding Requirement

Calculations were performed to determine the radial build in both the IB and OB regions required to provide adequate shielding for the vacuum vessel (VV) and TF magnet coils. Table III lists the required radial build. This results in all VV and magnet radiation limits being satisfied. The peak end-of-life helium production in the VV is 0.4 appm allowing for rewelding. The peak values of end-of-life fast neutron fluence and insulator dose in the magnet are 2.4x10^{18} n/cm^2 and 4.4x10^9 Rads which are below the widely accepted limits of 10^{19} n/cm^2 for Nb_3Sn and 10^{10} Rads for polyimides.

TABLE III
RADIAL BUILD REQUIRED FOR ADEQUATE SHIELDING

	Outboard	Inboard
Re-circulating Blanket	30 cm	30 cm
Secondary Blanket	40 cm	0
Shield	10 cm	40 cm
Vacuum Vessel	30 cm	30 cm
TF Magnet	60 cm	60 cm

E. Impact of Using Be Instead of Pb

The option of replacing the liquid lead multiplier in the blanket by beryllium pebbles was considered. The radial build is similar to that given in Table I with the exception that the thickness of the multiplier region (zone 4) is reduced to 37 mm with 32.2% Flibe, 8% NCF, and 59.8% Be. Zones 3 and 5 include 100% NCF and the thickness of zone 6 is increased to 10 mm. The neutronics calculations with this radial build yield a local OB TBR of 1.322 out of which ~10% is contributed by the 40 cm thick secondary blanket. Excluding breeding in the divertor region, the overall TBR is estimated to be ~1.17. This is ~6% larger than that for the reference design with Pb multiplier. The total nuclear energy multiplication in the IB and OB 30 cm re-circulating blankets and OB secondary blanket is 1.24 compared to 1.13 with Pb. Total nuclear heating in the blanket is ~10% higher than in the case with Pb multiplier. The increase in heating occurs primarily in the front zone of the blanket. Nuclear heating in the first wall zone increases by ~28%. A critical issue associated with using Be in fusion blankets is the amount of tritium produced and retained in the beryllium. The total amount of tritium produced in the Be pebbles used in all IB and OB modules is 2.4 kg at end-of-life of the blanket (3 FPY). The tritium inventory will be much lower than the tritium production due to tritium permeation out of Be at the high Be temperatures.

III. Activation Analysis

Activation calculations were performed for the reference blanket design with Pb multiplier. The neutron flux used for the activation calculations was generated from the neutronics calculations. The activation analysis was performed using the activation code DKR-PULSAR2.0 [6]. The code combined the neutron flux with the FENDL/A-2.0 [7] cross section library to calculate the activity and decay heat as a function of time following shutdown. No impurities were included in either the NCF structure or molten salt breeder. The NCF structure is irradiated for 3 years, which is the predicted blanket lifetime. The residence time of the Flibe in the blanket varies for the different coolant channels with the largest being in the central Flibe channel. In the activation calculations the largest residence time of 24 seconds was used and the Flibe was assumed to spend 75% of the time unirradiated outside the blanket. Activation calculations for the stagnant liquid Pb assume that it remains in the blanket for the plant lifetime of 30 years.

A. Radioactive Inventory

Figure 5 shows the total activity generated in the IB and OB blanket modules. The results are given as a function of time following shutdown for the NCF structure, the Flibe breeder/coolant, and the Pb multiplier. The NCF structure activity is larger than the Flibe activity after a minute following shutdown. The Pb activity is much lower than that generated in the structure. The structure activity is dominated by Fe-55 ($T_{1/2}$ = 2.73 y) as shown in Figure 6. On the other hand, the Flibe activity is dominated by N-16 ($T_{1/2}$ = 7.13 s) for up to a minute after shutdown and by tritium ($T_{1/2}$ = 12.33 y) and F-18 ($T_{1/2}$ = 1.83 h) at intermediate times. Long-term activity is due to Be-10 ($T_{1/2}$ = 1.51x10^6 y).

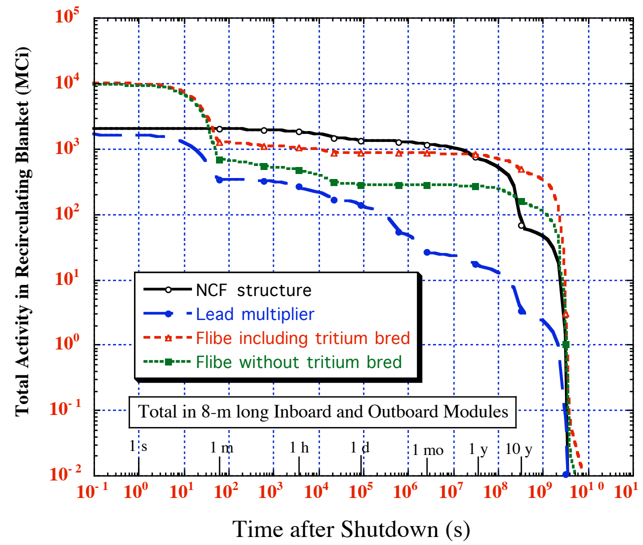

Fig. 5. Total activity in the blanket constituents.

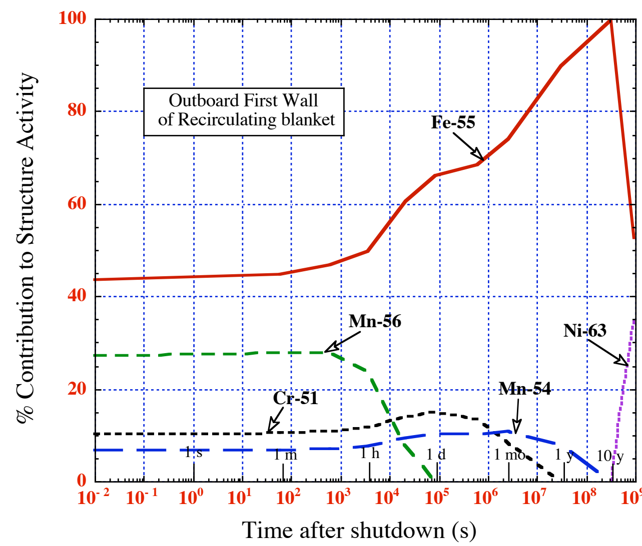

Fig. 6. Major radionuclides contributing to structure activity in outboard FW of the blanket.

B. Decay Heat

Figure 7 shows the total decay heat generated in the blanket. The results are given as a function of time following shutdown for the NCF structure, the Flibe breeder/coolant, and the Pb multiplier. The NCF structure decay heat is much larger than the Flibe decay heat after a minute following shutdown. The Pb decay heat is comparable to that generated in the Flibe between one minute and several hours following shutdown but is much larger at shutdown times up to one year. The structure decay heat is dominated by Mn-56 ($T_{1/2}$ = 2.578 hr) for several hours following shutdown with Mn-54 ($T_{1/2}$ = 312.12 d) dominating beyond that time. On the other hand, the Flibe decay heat is dominated by N-16 ($T_{1/2}$ = 7.13 s) for up to a minute after shutdown and by F-18 ($T_{1/2}$ = 1.83 h) in the next few hours. Decay heat in Flibe will be negligible beyond that time particularly if the bred tritium is removed.

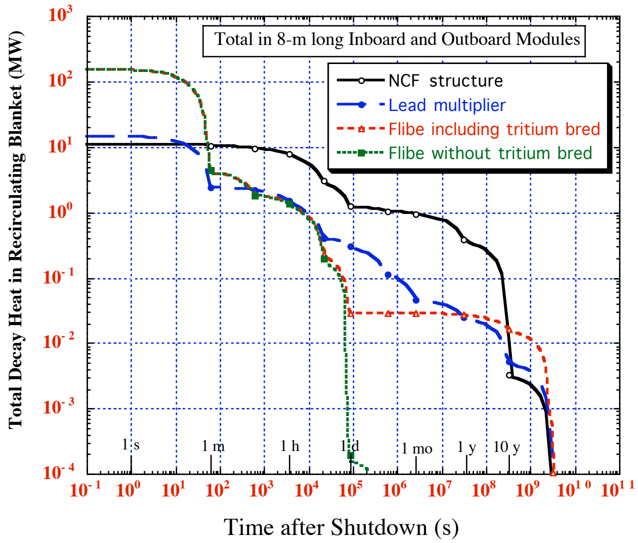

Fig. 7. Total decay heat in the blanket constituents.

C. *Waste Disposal Evaluation*

The radwaste classification of the different components was evaluated according to both the Nuclear Regulatory Commission (NRC) 10CFR61 [8] and Fetter [9] waste disposal concentration limits. Using Class C limits, a waste disposal rating (WDR) > 1 implies that the radwaste does not qualify for shallow land burial. The WDR values for the NCF structure are based.

The WDR for the NCF structure in the blanket is only 0.12 using the 10CFR61 limits and is contributed primarily by Nb-94 produced from transmutation of Mo. Using Fetter limits, the WDR is in the range 0.33-1.97 and is dominated by Tc-99 produced from Mo. The range in WDR reflects the range given by Fetter for the waste disposal limit of Tc-99. These values are based on compacted waste corresponding to crushing the solid waste before disposal and thus disallowing artificial dilution of activity. The results imply that the Mo content in the NCF structure needs to be reduced from 0.02% to less than 0.01% to ensure that the structure of the solid FW blanket qualifies as Class C low level waste. In addition, an attempt should be made to eliminate or limit concentrations of impurities such as Nb and Ag to levels less than about 1 wppm [10].

The WDR values for the Flibe breeders are very low and disposal as Class C low level waste is not an issue. The WDR for Flibe in the blanket is 0.042 with the 10CFR61 limits and 0.0006-0.006 with Fetter limits. Most of the contribution is from C-14 produced as a result of multiple neutron reactions with F. If the lead multiplier remains in the blanket for the 30 years of plant lifetime, the WDR based on Fetter limits will be 49 which is contributed by Bi-208. The WDR for Pb can be kept below 1 by slowly circulating the Pb and removing the produced Bi. A very small Pb flow rate, less than 1 cm^3/s, is required for a removal efficiency of 95%. Notice that slow circulation of the Pb multiplier is also required to remove other hazardous activation products such as Po-210.

IV. SUMMARY

Nuclear analysis was performed for a solid wall blanket concept that uses the nano-composited ferritic (NCF) steel alloy 12YWT as structural material with Pb as the neutron multiplier and Flibe (Li_2BeF_4) as the tritium breeder and coolant. Neutronics calculations were performed to determine the relevant nuclear performance parameters for the blanket. With an enrichment of 40% ^{6}Li the overall tritium breeding ratio is expected to be ~1.16 and the blanket energy multiplication is 1.13. Nuclear heating profiles were determined for the different components of the blanket and used in the thermal hydraulics analysis. The peak structure dpa and helium production rates are 77.6 dpa/FPY and 955 He appm/FPY, respectively, implying a lifetime of ~3 FPY. Calculations were performed to determine the radial build in both the inboard and outboard regions required to provide adequate shielding for the vacuum vessel and TF magnets. The NCF structure dominates the total activity and decay heat. The Mo content in the NCF needs to be reduced from 0.02% to <0.01% for the structure waste to qualify as low level class C waste. While the waste disposal rating (WDR) of the Flibe is well below unity, the Pb has to be circulated at a very small flow rate (<1 cm^3/s) to remove the generated ^{208}Bi and allow Pb disposal as low level waste.

ACKNOWLEDGMENT

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