Nuclear Analysis for a Flowing Li_2O Particulate Blanket Without Structural First Wall

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Nuclear Analysis for a Flowing Li_2O Particulate Blanket Without Structural First Wall

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Abstract

Neutronics and activation calculations have been performed for a Li_2O particulate blanket concept without structural first wall. The concept has the potential for achieving tritium self-sufficiency with a lifetime structure and reweldable vacuum vessel. It has attractive safety features resulting from the significant reduction in radioactivity and decay heat generation in the structural material.

1. Introduction

The Advanced Power Extraction (APEX) project was initiated to explore innovative concepts for blankets and other in-vessel components that can tremendously enhance the potential of fusion as an attractive and competitive energy source [1]. These concepts should have high power density handling capability, high power conversion efficiency, potential to achieve high availability, and safety and environmental attractiveness. An innovative concept to be explored utilizes Li_2O granular particulates flowing down the reactor chamber. This concept is referred to as the APPLE (Advanced Plasma-facing Particulate Li_2O Evaluation) concept. The APPLE concept is shown in Fig. 1. It eliminates the solid structural first wall (FW) allowing for handling a high surface heat flux and neutron wall loading and enhancing the lifetime of the structural material. The very low vapor pressure of Li_2O leads to high temperature operation with high power conversion efficiency. In addition, the concept has the advantages of reduced activation and high tritium breeding potential. A front layer of particulates falling unimpeded under the action of gravity removes the surface heat. At the entrance region to the blanket, a SiC baffle is used to direct the Li_2O flow toward the inboard and

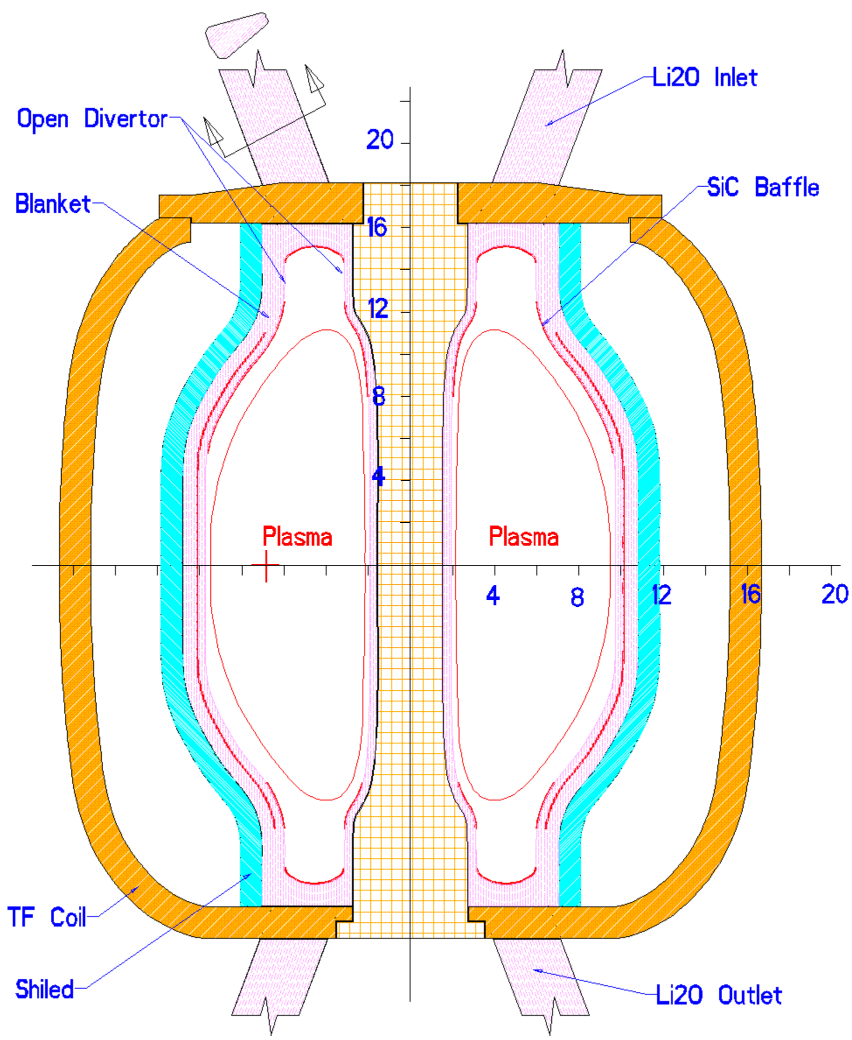

Fig. 1. Schematic of the APPLE concept.

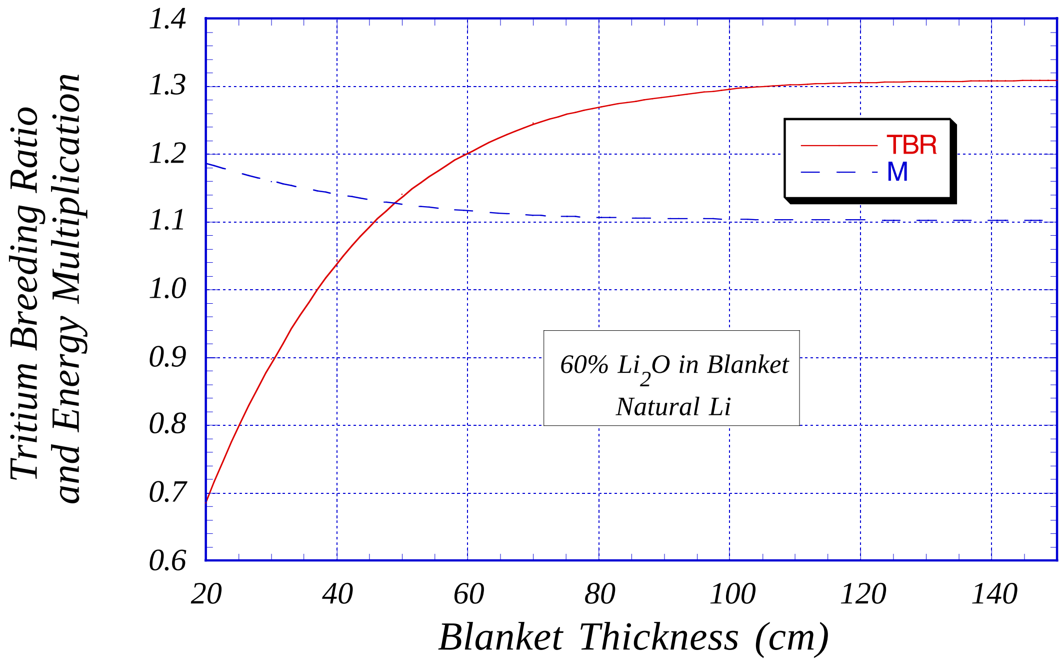

Fig. 2. Impact of blanket thickness on local TBR and energy multiplication.

outboard regions. The blanket region is separated from the front layer by SiC walls. In the blanket, the Li_2O particulates flow at a lower velocity so that the Li_2O will exit at reasonably uniform temperature. The SiC walls and baffles do not contain pressure and are not structural members.

SiC and Li_2O are selected because of their high temperature capabilities. The total partial pressure over Li_2O is 10^{-5} torr at 1000˚C, which is judged to be acceptable by the plasma. Therefore, the Li_2O temperature is limited to below that temperature limit. The flow of the particulates inside the blanket is not free flow, but restricted by an opening at the bottom of the blanket regime to maintain the required velocity and packing fraction. The velocity is controlled so that the exit temperature from the blanket region will also be at 1000˚C. Since the flow in the blanket is not free flow, but a flow controlled by an opening at the bottom of the blanket, high packing fraction can be obtained. Both radiation and contact cooling by the particulates will cool the SiC wall. The maximum SiC temperature is estimated to be 1500˚C. The shield is cooled by low temperature water. Water leakage toward the blanket is not a safety issue. The water reactivity with the blanket materials, and the impact on further operation of this blanket, is not different from any other blanket. In this paper, the nuclear performance features of the concept are analyzed.

2. Calculational procedure

Neutronics and activation calculations have been performed for the APPLE concept. The local nuclear parameters were determined using a one-dimensional (1-D) model in which both the inboard (IB) and outboard (OB) regions are modeled simultaneously to properly account for the toroidal geometrical effects. The plasma facing layer is 5 cm thick with Li_2O at 30% packing. It is followed by a 0.5 cm thick SiC separation wall. The Li_2O in the blanket has a packing fraction of 0.6. The

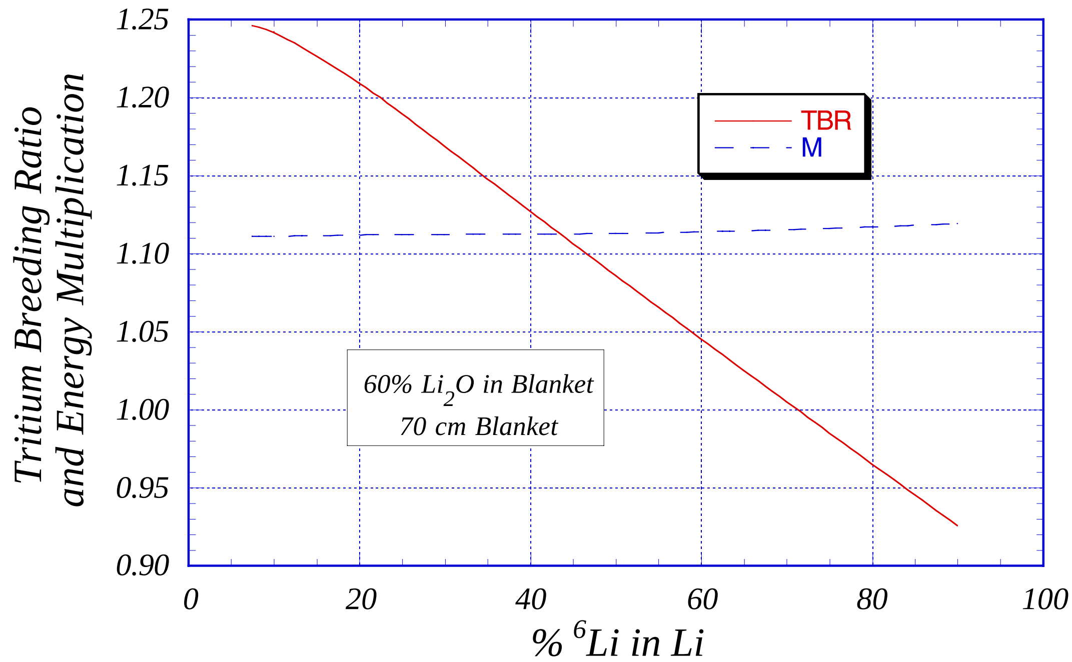

Fig. 3. Effect of lithium enrichment on local TBR and energy multiplication.

shield consists of 80% steel and 20% H_2O. The vacuum vessel (VV) is made of two steel sheets each 5 cm thick sandwiching a 30 cm thick shielding zone made of 80% steel and 20% H_2O. While 316SS was used in the neutronics calculations, both 316SS and low activation ferritic steel were considered in the activation analysis. The results were normalized to OB and IB wall loadings of 10 and 7 MW/m^2, respectively. The local neutronics results were coupled with the appropriate coverage fractions to estimate the overall parameters. The neutronics and shielding calculations were performed using the ONEDANT module of the DANTSYS 3.0 [2] discrete ordinates particle transport code system along with nuclear data based on the FENDL [3] evaluation. The activation analysis was performed using the activation code DKR-PULSAR2.0 [4] with the FENDL/A-2.0 data library [5].

3. Blanket optimization

The impact of blanket thickness on the local tritium breeding ratio (TBR) and energy multiplication (M) was investigated. The results in Fig. 2 show that the TBR increases with blanket thickness reaching a maximum value of 1.3. On the other hand, M decreases slightly (<8%) with increasing blanket thickness, reaching a minimum value of 1.1. The results are for natural lithium in the Li_2O. The effect of enriching Li in ^6Li is shown in Fig. 3. It is clear that enriching the Li results in a significant decrease in TBR and negligible increase in M. Therefore, natural Li is used in the reference APPLE design.

In addition to breeding tritium and multiplying the fusion energy, the Li_2O particulate blanket in the APPLE concept is required to reduce the damage rate in the structural material of the shield to allow it to be a lifetime component. The peak damage rate in the shield depends on the blanket thickness.

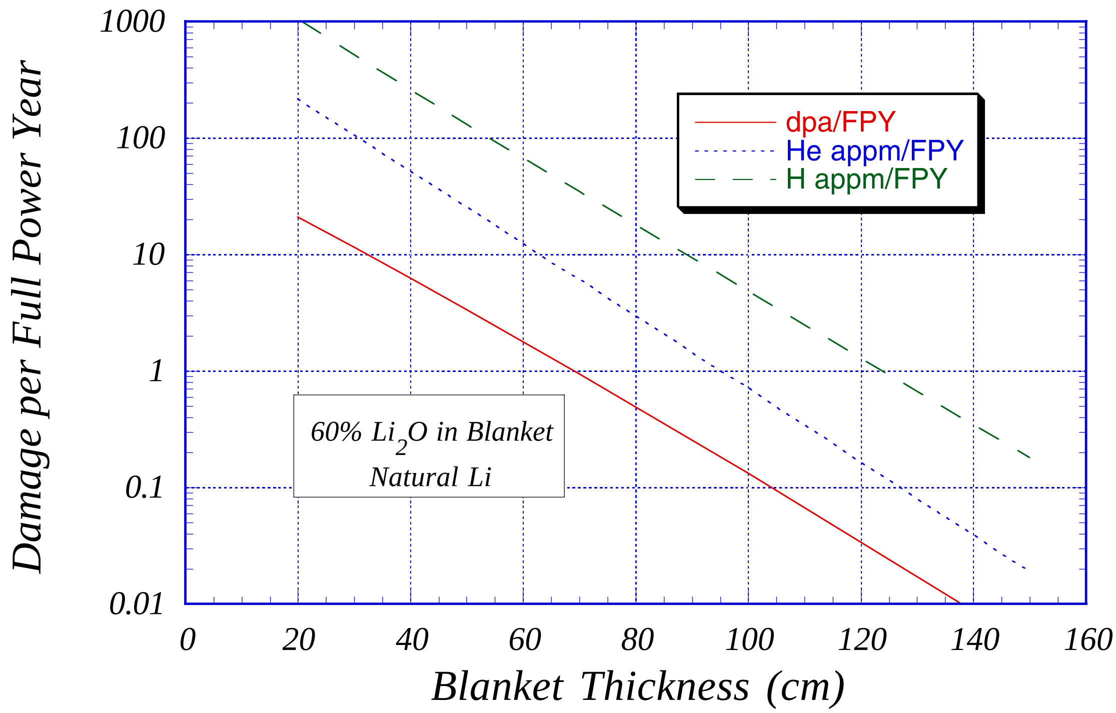

Fig. 4. Impact of blanket thickness on peak damage and gas production rates in the steel structure of the shield.

Figure 4 gives the impact of blanket thickness on the peak damage and gas production rates in the shield structure. The steel damage and gas production rates decrease by an order of magnitude for each 35 cm of blanket thickness. Assuming 30 full power years (FPY) of plant life and a 200 dpa damage limit for the steel structure, a minimum blanket (Li_2O at 60% packing fraction) thickness of 40 cm is required for the structure to be a lifetime component. Based on these results, the IB blanket thickness in the reference design is taken to be 40 cm. On the other hand, with the less constrained space on the OB side, a 75 cm thick OB blanket is utilized in the reference design to enhance the overall tritium breeding potential. Notice that any further increase in blanket thickness results only in a modest TBR increase as shown in Fig. 2.

4. Tritium breeding and energy multiplication

The local TBR and M values obtained in the reference design are given in Table 1. The results are shown for both the IB and OB regions. Only 3.2% of nuclear heating in the OB region is deposited in the water-cooled shield and VV. In the IB side, the shield and VV contribute 15.4% of the nuclear heating. The overall TBR and M depend on the neutron coverage fractions (NCF) of the regions surrounding the plasma and the blanket thickness in each region. The relative NCF for the IB and OB regions varies significantly with the aspect ratio. In APEX, neutron coverage fractions of 75%, 15%, and 10% for the OB, IB, and divertor regions, respectively, were assumed corresponding to an aspect ratio of 2.5. The local TBR and M values were combined with these neutron coverage fractions to determine the overall TBR and M. The blanket thickness in the divertor region is assumed to be 40 cm similar to that in the IB region. The overall TBR is estimated to be 1.215. The OB, IB, and divertor regions contribute 76.2%, 14.3%, and 9.5%, respectively. The overall energy multiplication

Table 1. Local TBR and M in the reference APPLE design.

	Inboard	Outboard
Blanket Thickness (cm)	40	75
Local TBR	1.158	1.233
Local M	1.166	1.099

Table 2. Nuclear heating and damage rate in the SiC separation wall.

	Inboard	Outboard
Peak Nuclear Heating (W/cm^3)	54.9	75.0
Peak dpa Rate (dpa/FPY)	72.8	93.1
Peak He Prod. Rate (He appm/FPY)	7310	10438

is estimated to be 1.116. 93.6% of the nuclear heating is deposited as high grade heat in the Li_2O particulate blanket.

5. Nuclear heating and radiation damage

The peak power density and damage rate values in the SiC separation wall are given in Table 2. The results are given for the IB and OB regions. Both the atomic displacement and helium production rates are given. The damage rates are high and frequent replacement will be needed. Notice that the SiC baffles and separation walls do not contain pressure and are not structure members. The lifetime for these non-structural components is not defined. The baffles and separation walls in the APPLE concept are designed for quick replacement.

The steel structure of the shield located behind the Li_2O particulate blanket experiences lower nuclear heating and damage rate due to neutron attenuation in the blanket. Table 3 gives the peak power density and radiation damage values in the steel structure at the back of the blanket. The results are given for both the IB and OB regions. Nuclear heating and radiation damage values in the OB region are much lower than in the IB region due to the larger attenuation in the thicker OB blanket. The peak cumulative atomic displacement damage after 30 FPY plant life is less than the 200 dpa limit considered for steel structure. This implies that the steel structure at the back of the Li_2O particulate blanket in the APPLE concept is expected to be a lifetime component.

6. Vacuum vessel and magnet shielding

The VV is located behind the shield. For the VV to be reweldable, the cumulative helium production in the structure should not exceed 1 He appm. The shield thickness needed to reduce the peak helium production in the VV to less than 1 He appm after 30 FPY plant life was determined. Adequate VV

Table 3. Peak nuclear heating and radiation damage in the steel structure.

	Inboard	Outboard
Peak Nuclear Heating (W/cm^3)	14.9	4.3
Peak dpa rate (dpa/FPY)	5.54	0.87
Peak end-of-life dpa @ 30 FPY	166.2	25.9
Peak He Prod. Rate (He appm/FPY)	42.6	5.5
Peak end-of-life He appm @ 30 FPY	1277	163

Table 4. Peak VV neutronics parameters.

	Inboard	Outboard
Peak Nuclear Heating (mW/cm^3)	10	11
Peak end-of-life dpa	0.09	0.10
Peak end-of-life He appm	0.40	0.42

shielding is provided using a 40 cm thick OB shield and a 55 cm thick IB shield. The shield is assumed to consist of 80% steel and 20% H_2O. Table 4 gives the peak neutronics parameters for the VV in both the IB and OB regions. The results clearly indicate that the VV is reweldable.

Adequate shielding must be provided for the superconducting magnets such that their performance is not degraded by neutron and gamma irradiation. The component most sensitive to radiation is the organic insulator because of possible degradation in mechanical strength. Radiation damage could also affect the critical properties of the superconductor and the resistivity of the copper stabilizer. In addition, magnet nuclear heating that is removed by cryogenic liquid helium should be limited. We will assume that the magnet radiation limits are similar to those adopted in the ITER design [6]. These are end-of-life fast neutron fluence of 10^{19} n/cm^2, end-of-life dose to the insulator of 10^9 Rads, $6x10^{-3}$ end-of-life dpa to Cu stabilizer, and 1 mW/cm^3 peak nuclear heating. Table 5 gives the peak radiation effects in the magnet located behind the 40 cm thick VV. It is clear that all magnet radiation limits are satisfied.

7. Radial build for the reference design

The OB radial build that satisfies requirements for steel structure lifetime, VV reweldability, and superconductor magnet shielding is 155 cm (75 cm blanket, 40 cm shield, and 40 cm VV). In the IB region, the total radial build is 135 cm (40 cm blanket, 55 cm shield, and 40 cm VV). This radial build is shown in Fig. 5. This configuration also allows for tritium self-sufficiency with the overall TBR estimated to be 1.215.

Table 5. Peak magnet neutronics parameters.

	Inboard	Outboard	Design Limit
Peak Nuclear Heating (mW/cm^3)	0.028	0.027	1
Peak end-of-life Fast Neutron Fluence, E> 0.1 MeV (n/cm^2)	$8.5x10^{17}$	$8.0x10^{17}$	10^{19}
Peak end-of-life Dose to Epoxy Insulator (Rads)	$8.3x10^{8}$	$7.1x10^{8}$	10^{9}
Peak end-of-life dpa to Cu Stabilizer	$4.3x10^{-4}$	$4x10^{-4}$	$6x10^{-3}$

Table 6. Class C WDR.

Zone	Lifetime (FPY)	WDR (Fetter)	WDR (10CFR61)
SiC baffle/separation wall	2	0.275	0.02
IB shield	30	0.648	0.144
IB VV	30	$4.54x10^{-3}$	$1.92x10^{-4}$
OB Shield	30	0.46	0.057
OB VV	30	$4.39x10^{-3}$	$1.86x10^{-4}$

8. Activity and decay heat

Activation analysis was performed for the APPLE concept. The impact of replacing 316SS (20 appm Nb impurity) by low activation ferritic steel was assessed. The analysis used the ORNL low activation ferritic steel (LAFS) 9Cr-2WVTa with 0.5 wppm Nb as a structural material [7]. While nearly identical short-term activities are obtained in the two alloys, the long-term activity is reduced by more than two orders of magnitude when the LAFS is used. The LAFS is used in the reference design. Comparing the structure activity with and without the Li_2O particulate blanket indicates that the short-term activity that affects decay heat and off-site dose from accidental release is reduced by a factor of ~40 due to the attenuation of the neutron flux in the blanket. On the other hand, the long-term activity, which affects the radwaste classification, is fluence dependent. Hence, the reduction in long-term activity is not as significant since the structure is used for the whole reactor life (30 FPY) while in a conventional solid wall design, the FW/blanket structure is replaced after ~ 2 FPY.

Thick (cm)	Li_2O @ 30% p.f.	SiC wall	Li_2O @ 60% p.f.	Shield 80% Steel 20% H_2O	Steel	VV 80% Steel 20% H_2O	Steel
IB	5	.5	34.5	55	5	30	5
OB	5	.5	69.5	40	5	30	5

Fig. 5. Radial build for the reference APPLE design.

Activation analysis was performed for the reference APPLE concept. The SiC baffles and separation walls were assumed to be replaced every 2 FPY. On the other hand, the shield and VV were assumed to last for 30 FPY. Figures 6 and 7 show the specific activity and decay heat values induced in the different components as a function of time following shutdown. The ORNL LAFS produces an acceptable level of radioactivity after shutdown. The IB and OB shields dominate the overall activity and decay heat induced in the structure. $^{55}Fe(T_{1/2} = 2.7$ yr), $^{185}W(T_{1/2} = 75.1$ day), and $^{187}W(T_{1/2} = 23.9$ hr) are the main contributors to the induced radioactivity during the first few weeks following shutdown. $^{55}Fe(T_{1/2} = 2.7$ yr) and ^{54}Mn dominate the induced activity at intermediate periods following shutdown. The long-term radioactivity (between one and 10 years) is mostly generated by the $^{63}Ni(T_{1/2} = 100$ yr) and $^{60}Co(T_{1/2} = 5.27$ yr) isotopes.

9. Waste disposal ratings

The radwaste of the different components of APPLE were evaluated according to both the NRC 10CFR61 [8] and Fetter [9] waste disposal concentration limits (WDL). The waste disposal rating (WDR) is defined as the sum of the ratio of the concentration of a particular isotope to the maximum allowed concentration of that isotope taken over all isotopes and for a particular class. Using Class C limits, a WDR > 1 implies that the radwaste does not qualify for shallow land burial. The calculated WDR values are given in Table 6. The results are given for compacted wastes. According to Fetter limits, all components would qualify for disposal as low level Class C waste. The source for the WDR of the SiC is the $^{26}Al(T_{1/2} = 7.3 \times 10^5$ yr) isotope produced by the ^{28}Si (n,t) reaction. On the other hand, $^{192m}Ir(T_{1/2} = 240$ yr), and $^{94}Nb(T_{1/2} = 20{,}000$ yr) are the dominant contributors to the WDR for all other components. They are produced by nuclear interactions with the iridium, niobium and molybdenum impurities. According to the 10CFR61 limits, all components also would qualify for disposal as low level Class C waste. Except for the WDR of the SiC baffles, which is dominated by the $^{14}C(T_{1/2} = 5730$ yr) isotope, the WDR for all other components is dominated by contribution from the ^{94}Nb isotope.

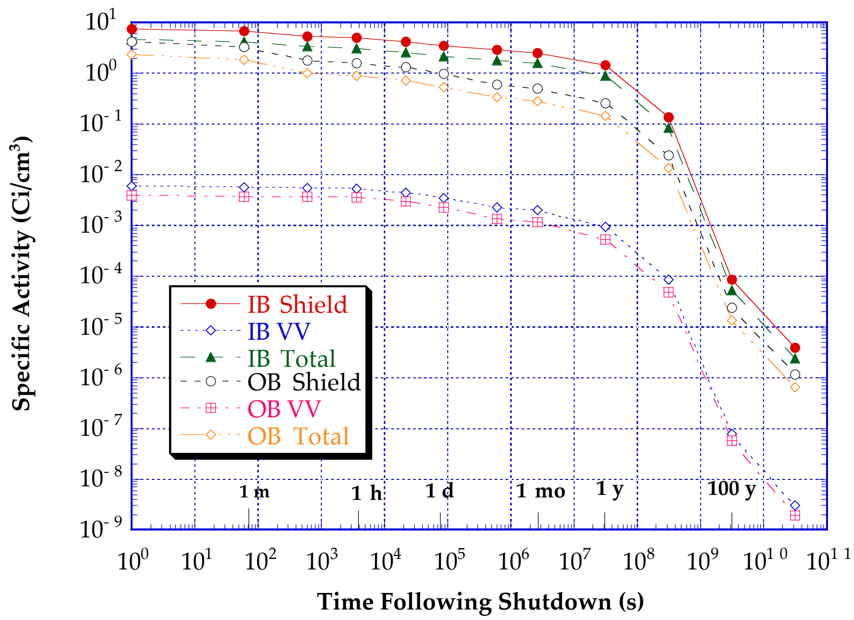

Fig. 6. Activity induced in the different components as a function of time following shutdown.

10. Summary and conclusions

Neutronics calculations have been performed for the APPLE concept using a neutron wall loading of 10 MW/m^2. Steel structure is used in the shield and vacuum vessel. The Li_2O in the blanket has a packing fraction of 0.6. A minimum blanket thickness of 40 cm is required for the steel structure to be a lifetime component. The radial build that satisfies requirements for steel structure lifetime, VV reweldability, and superconductor magnet shielding was determined. The achievable overall TBR was estimated to be >1.2 taking into account the difference in blanket thickness in the regions surrounding the plasma. Although the steel structure and VV are lifetime components, the SiC baffles and separation walls, which are not structure members, experience a large damage rate and are designed for quick replacement. More than an order of magnitude reduction in decay heat and activity results from placing the structure behind the Li_2O particulate blanket. Using low activation ferritic steel structure behind the Li_2O particulate blanket allows for near surface burial of the radwaste.

It is concluded that the Li_2O particulate blanket concept without a structural first wall has the potential for achieving tritium self-sufficiency with lifetime structure and reweldable vacuum vessel. It has attractive safety features resulting from the significant reduction in radioactivity and decay heat generation in the structural material.

Acknowledgement

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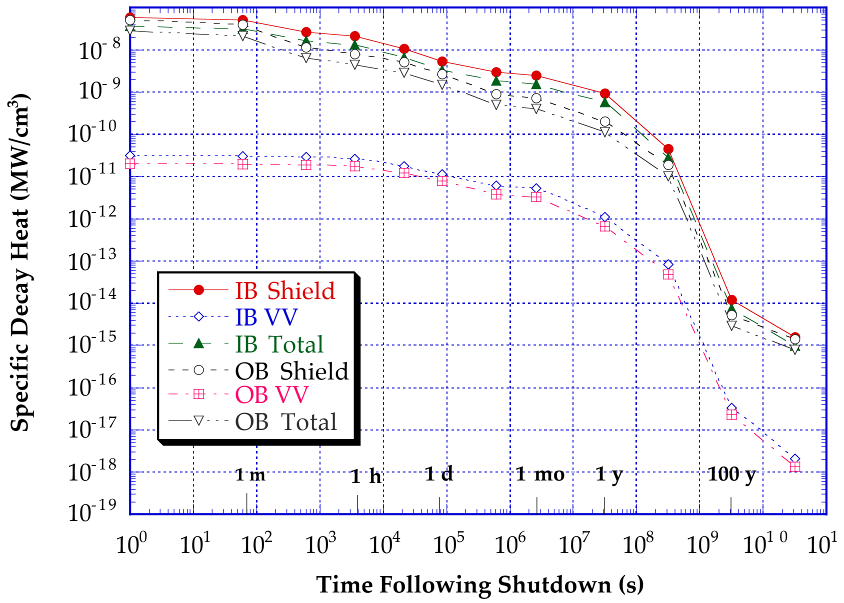

Fig. 7. Decay heat induced in the different components as a function of time following shutdown.

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