LONG-TERM ACTIVATION AND TRITIUM GENERATION OF FLOWING LITHIUM-LEAD UNDER PROLONGED IRRADIATION IN FUSION POWER PLANTS

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Lithium-lead is a candidate tritium-generating material in conceptual designs of magnetic fusion power plants. Its prolonged utilization, ultimately during the entire lifetime of such a facility, has the potential to minimize amounts of active waste and improve the economic performance. Limits to a prolonged use are production of long-lived radioactive waste and depletion of lithium and reduction of the tritium production rate to levels where self-sufficiency is compromised. The methodology and calculations performed to estimate the transmutation of LiPb following its prolonged irradiation in two of the models in the European Power Plant Conceptual Study are presented. It is shown that no waste requiring permanent disposal is expected regardless of the irradiation length. Time-dependent tritium generation is discussed: Lithium replenishment seems unavoidable, but depletion rates are found to be lower than assumed in the design. The effect of the LiPb flow pattern in the irradiation history proves to be crucial in order to support these results.

KEYWORDS: *activation, tritium breeding, radioactive waste*

I. INTRODUCTION

Eutectic lithium-lead ($Li_{17}Pb_{83}$, hereinafter LiPb) is considered in blanket concepts of tokamak fusion power plants to generate tritium fuel on site. It provides good tritium yield under typical fusion neutron spectra, removal techniques are known, it is chemically stable and compatible with structural materials, and if sufficiently stagnant, magnetohydrodynamic pressure drops are negligible. Four models in the European Power Plant Conceptual Study[1,2] (PPCS) use this material, some even exploiting its liquid nature for the design of primary cooling systems. During the PPCS environmental analyses, conservative estimations of the activation inventory and categorization of the active material arising from the operation of these plants were performed.[3] They assumed the LiPb being stagnant and replaced after each one of the five blanket and 10 divertor cycles, as scheduled in a maintenance regime sketched in Fig. 1, providing 25 full-power years operational lifetime and high availability.[4] Irradiation cycles are thus classified in just three categories: (a) for the divertor, (b) for blankets and other in-vessel components, and (c) for the rest.

Blanket and divertor service lifetimes are limited by the radiation damage and transmutation suffered by structural, breeder, and armor materials, which compromise the thermomechanical performance of the component and the benign safety and environmental impact of the facility. Given its liquid nature, however, LiPb is not constrained by radiation damage effects. If neutron activation proves not to be an issue, reutilization becomes a feasible and attractive alternative to its replacement at the end of each cycle, reducing the amount of active material requiring disposal. PPCS data show that LiPb amounts used are considerable; masses required for the operation of the different concepts during one cycle (i.e., 5 yr for blankets, 2.5 yr for divertors) are shown in Table I. If this material is replaced after just one cycle irradiation, five or ten times these figures are needed over the plant's lifetime; were the initial amounts used throughout the entire operational life, up to 80% of the LiPb waste from the blankets and 90% from the divertor would not be produced. Reduced breeder requirements and waste production lead to reduced costs and a less demanding decommissioning.

A scoping study was carried out to estimate the long-term activation and the potential for reutilization of LiPb in a typical fusion power plant, aiming at obtaining useful information for the design of maintenance schemes,

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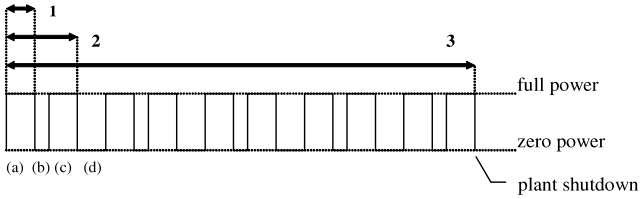

Fig. 1. PPCS maintenance scheme: (a) 2.5 yr at full-power operation, (b) 2 months for inspections and divertor replacement, (c) 2.5 yr at full-power operation, and (d) 10 months for inspections and replacement of divertor, blanket, and other in-vessel components (planned availability = 85.7%).

LiPb processing systems, and management strategies. To cover both near-term and advanced scenarios, the study focused on PPCS plant models A (PMA) and D (PMD) using water-cooled LiPb (WCLL) and self-cooled LiPb (SCLL) blanket concepts, respectively.[4] From a radiological point of view, the limit to a prolonged irradiation is the generation of waste requiring permanent storage (permanent disposal waste), as adopted by the European Fusion Programme. Activation of LiPb under prolonged irradiation in the blankets of PMA and PMD and in the divertor of the latter was studied using the FISPACT code and EAF nuclear data libraries.[5,6] Information on LiPb amounts, cooling loops, tritium systems and neutron distribution was gathered from PPCS documentation and analyses[4] and used to elaborate irradiation histories for this material covering the entire lifetime of the plants. These histories provided estimations of contact dose rate, decay heat, and clearance index for comparison with PPCS waste criteria, which define boundaries for the following categories: nonactive waste (NAW), simple and complex recycling material (SRM and CRM), and permanent disposal waste (PDW). The actual limits, listed in Table II, were chosen following revision of current procedures and practices in the nuclear industry.[7]

TABLE I

LiPb Masses in the PPCS Concepts

PPCS Plant Model	LiPb Mass (tonne)
A	8717
C	5350
D	
Blanket	2709
Divertor	1120
AB	6930

TABLE II

Fusion-Activated Material Classification Criteria Adopted in the PPCS

Active Material Classification	Contact Dose Rate (mSv h^{-1})	Decay Heat Rate (W m^{-3})	Clearance Index
PDW	>20	>10	
CRM	2 to 20	1 to 10	
SRM (hands-on recycling)	<2 (<0.01)	<1	
NAW			<1

From an operational point of view, lithium depletion and subsequent decrease in the tritium production rate is also a limiting factor. In principle, however, due to its liquid nature and continuous flow through cooling or detritiation loops, it is possible to conceive the addition of lithium on-line, as it depletes. This is an advantage over solid breeders such as pebble beds. Using PPCS neutron transport results, illustrative calculations were performed to ascertain lithium depletion rates and replenishment requirements.

II. MODELING THE IRRADIATION OF FLOWING LiPb

Several considerations were taken into account when developing approximations to the irradiation history using the FISPACT code. Primarily, the LiPb is irradiated differently in different parts of the plant. PPCS analyses found that neutron flux and spectra vary significantly within the structures of the power plant: Figure 2 shows those at the front and rear of the WCLL and SCLL blankets of the PPCS models, and Fig. 3 at the front and rear of the divertor of model D. Specific features of the plants, such as the layout of cooling and tritium removal systems, also affect the irradiation history. In PMA the LiPb is nearly stagnant and only a slow purge to a detritiation system exists to enable tritium recovery (~0.06 m^3/s). In both the blanket and divertor of PMD, the LiPb is continuously flowing at a considerable speed (~0.8 m^3/s); the LiPb in this blanket generates tritium but also transports heat to exchangers in four cooling loops embracing one-fourth of the torus each. The LiPb in the divertor circulates in a separate loop.

In any case, it is not realistic to assume the LiPb is static in a particular zone and exposed to the same neutron flux during a whole cycle: on the contrary, its circulation results in the mixing of all the LiPb in the loop. Consequently, an average volume element of LiPb is exposed to different neutron spectra and flux levels at and during different times as it travels around the plant structures.

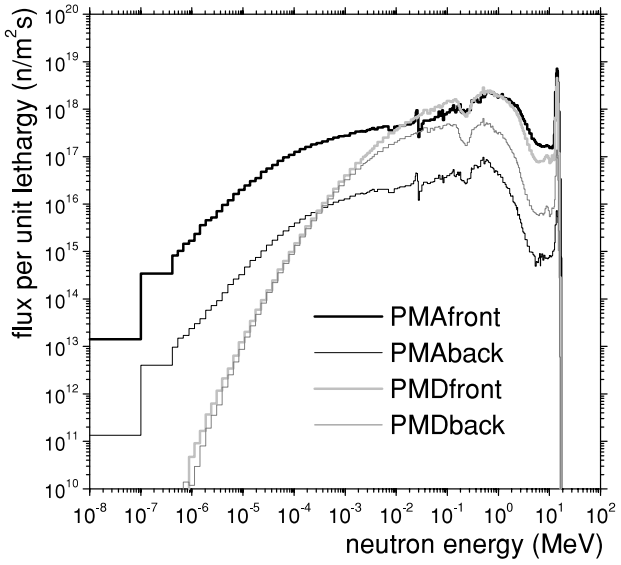

Fig. 2. PPCS blanket neutron spectra (flux per unit lethargy, n/m^2 s) at different radial locations of the outboard midplane of PMA and PMD blanket concepts.

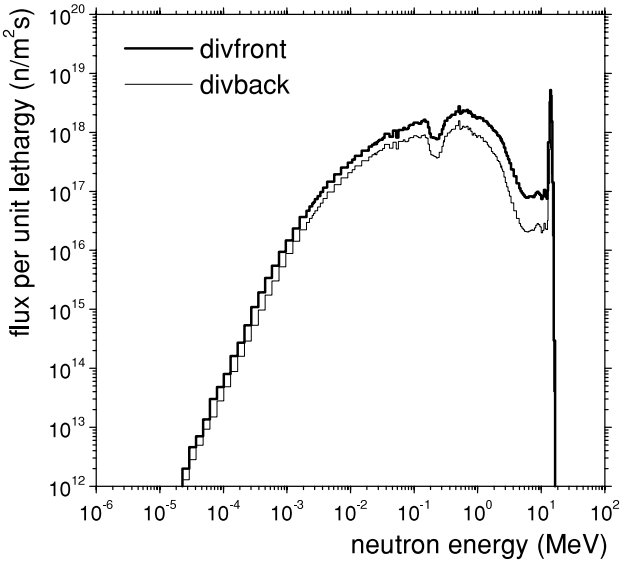

Fig. 3. PPCS plant model D divertor front and rear neutron spectra (flux per unit lethargy, n/m^2 s).

II.A. Modeling the Irradiation History

Nuclear inventories are governed by a set of coupled differential equations describing the rate of change with time of a nuclide under irradiation:

$$\frac{dN_i}{dt} = -N_i(\lambda_i + \sigma_i \pi) + \sum_{j \neq i} N_j(\lambda_{ij} + \sigma_{ij}\phi) + S_i \ , \quad (1)$$

where

i, j = subscripts representing nuclide species

λ = radioactive decay constant

σ = microscopic reaction cross section

S = source

ϕ = neutron flux.

Inventory codes are designed to deal with this set of equations using various numerical solvers. The $\sigma\phi$ products are in fact integrals over the energy range, treated as sums over purpose-specific multigroup formats by these codes, for reasons of computing speed and portability. In the case of long-lived nuclides, for which λ_i and depletion via neutron reactions are negligible compared with their generation rate and furthermore this generation is due only to reactions with neutrons, the solution to Eq. (1) is simply

$$N_i \cong \sum_{j \neq i} N_j \sigma_{ij} \int \phi(t)\, dt \ , \quad (2)$$

assuming that neither N_j nor σ_{ij} varies with time. Under these conditions the amount of nuclei of species i, N_i, generated in the LiPb under irradiation, and consequently the activity and related radiological quantities, are approximately proportional to the total neutron fluence received by an average volume element of LiPb during a cycle. If the material is static, the fluence is simply $F = \phi \cdot t$. In reality, however, the neutron flux varies continuously with time as the LiPb flows along the circuits. Inventory codes are typically not able to deal with continuous time variations of the neutron spectra. Some are built to account for pulsed flux variations in inertial fusion conditions and have been applied in magnetic studies.[8] FISPACT can simulate any series of discrete time variations in the neutron flux and spectra, a feature that was employed to approximate the irradiation history of flowing LiPb in this study. Using values of flux and spectra at several positions in the PPCS plant models, the total neutron fluence was made to depend on the neutron spectra and the time spent in the regions of the blanket and divertor associated with each one of those positions, and the integral was transformed into a sum of discrete values:

$$F = \int \phi \cdot dt = \sum_n \phi_n t_n \ , \quad (3)$$

where ϕ_n and t_n represent the neutron flux and time spent in a particular region n; hence,

$$N_i \cong \sum_n \left(\sum_{j \neq i} N_j \sigma_{ij} \phi_n t_n \right) \ . \quad (4)$$

A LiPb volume element traveling around circuits, blanket, and divertor modules will pass through regions of different neutron flux and spectra in a random order and at random times. But on average, if the flow rate is assumed to be constant and uniform throughout the different regions, the total time spent in one of them, t_n, during a whole cycle t_{tot}, will depend on the fraction of the total volume that this region represents:

$$t_n = \frac{v_n}{v_{tot}} t_{tot} \quad . \tag{5}$$

Using Eq. (5) to calculate the time the LiPb spends under neutron flux ϕ_n, irradiation histories can be developed, assuming during each cycle the LiPb is irradiated sequentially with spectra ϕ_1 during a time t_1, then with spectra ϕ_2 during a time t_2, and so on. The code calculates N_i and related quantities for every nuclide species i. This is the basis of the so-called *sequential* method, illustrated in Fig. 4, which is a modification of that proposed in Refs. 9 and 10 for the modeling of constant-flux, pulsed irradiations.

An alternative modeling method exists, easier to implement in the inventory code, the basis of which arises by combining Eqs. (4) and (5). In this case the total fluence, and therefore the activation of an average LiPb volume element due to the nuclide i, is given by

$$F = \int \phi \cdot dt = \sum_n \frac{v_n}{v_{tot}} \phi_n t_{tot} = \sum_n \frac{v_n}{v_{tot}} F_n^{tot} \quad , \tag{6}$$

$$N_i \cong \sum_n \frac{v_n}{v_{tot}} \left(\sum_{j \neq i} N_j \sigma_{ij} F_n^{tot} \right) \quad , \tag{7}$$

and

$$A_i = \lambda_i N_i \cong \sum_n \frac{v_n}{v_{tot}} A_{n,i}^{tot} \quad , \tag{8}$$

where F_n^{tot} and $A_{n,i}^{tot}$ are the fluence and activity of nuclide i in a particular region n for a whole blanket/divertor cycle. Summing over nuclide species i, the average long-term activation (and related quantities) of the LiPb can be approximated by the volume-weighted sum of the activation in the different regions, calculated assuming that the LiPb is irradiated here during the whole cycle. This is the basis of the *volume-weighted sum* approximation to the irradiation history of LiPb flow.

The assumptions made to derive these approximations imply that their validity is limited to long-term activation, and only short-lived nuclei will be underestimated. But since the interest of this study focused on levels of activity and related radiological quantities at waste disposal timescales (several decades to 100 yr), short-lived nuclei do not have any significance and this limitation is not restrictive. The volume-weighted sum method, however, has a further limitation: It is valid only if N_j in Eq. (2) is a nucleus present in the original composition of the material being irradiated, i.e., if N_i is generated in single-step reactions. For nuclei generated via multiple step reactions, further ϕ terms appear in Eq. (2) and linearity with the neutron fluence disappears. The effect of this is difficult to ascertain; however, it can be seen that in any case it conservatively overestimates the amount of those nuclei. As a consequence of the time spent in a region being not the total but a fraction of it, the activity is reduced. If the relationship with ϕ is linear, as for single-step-generated nuclides, the activity will be linearly reduced, but if it is quadratic, cubic, etc., as for nuclides generated via multiple steps, the activity will be reduced accordingly. A linear decrease conservatively envelopes any other possible decrease rate of the activity. Calculations were performed using both methods to allow for comparison, using data and results from neutron transport analyses of the PPCS study.

II.B. Cooling and Tritium Recovery Systems

PPCS analyses made use of the HERCULES code[11] to build computational models of the tokamak plant geometry in an automatic fashion. The models are divided into layers and sectors, as shown in Fig. 5: One poloidal sector within one radial layer defines a cell, and each cell is filled with a mixture of materials according to the design. A few, worst-case cells were selected and their neutron spectra made representative of entire sections of the components. Conservatively, all selected cells had maximum neutron flux in their respective regions, e.g., midplane cells in the case of the blanket, as shown in the Fig. 5. Both PMD blanket cooling and PMA tritium

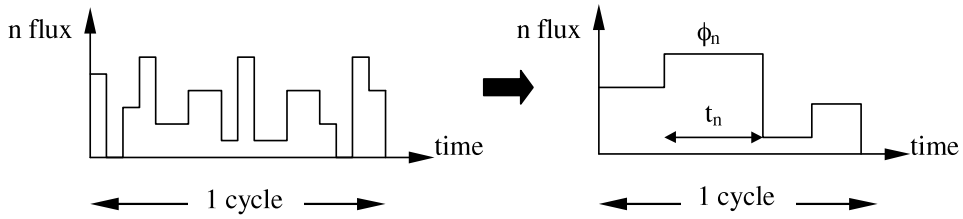

Fig. 4. Redistribution of a random irradiation of a LiPb volume element (left) into periods of constant flux (right), as used in the sequential method.

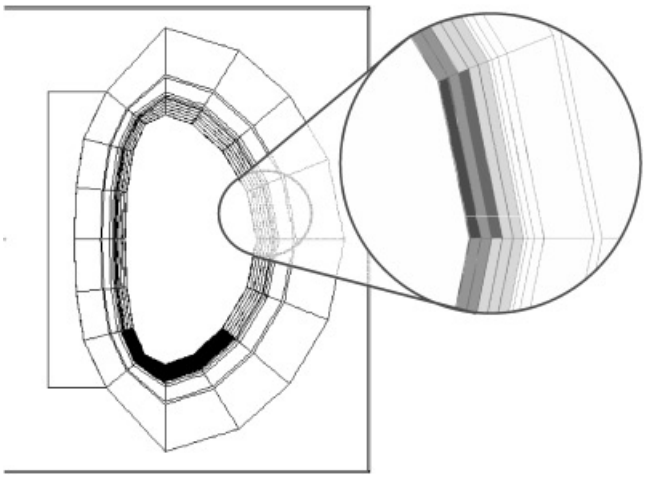

Fig. 5. Poloidal cross section of the HERCULES model for PPCS PMA, and detail of the radial buildup at the outboard midplane. Midplane cells represent entire semipoloidal sections of the blanket. Black cells correspond to the divertor.

removal loops are designed to collect LiPb from a series of inboard and outboard modules, so representative cells were chosen for various inboard and outboard semipoloidal sections. Pipes, heat exchangers, and other circuit volumes outside the blanket and divertor, where the LiPb is not irradiated, were also accounted for. The cooling loop of the PMD divertor was assumed to be completely detached from the blanket, and therefore calculations were conducted separately for blanket and divertor loops.

III. ACTIVATION AND WASTE CATEGORIZATION RESULTS

Irradiation histories were developed using the methodology previously described and PPCS neutron spectra, assuming 5.50 GW of fusion power for PMA and 2.46 GW for PMD. The optimized LiPb elemental composition of the PPCS study was used, shown in Table III. Natural isotopic abundance was assumed throughout except for lithium, enriched to 90% in ^{6}Li according to design values.

Histories developed using the sequential irradiation method explored the potential for reutilization of the LiPb in (a) the PMA blanket loops, (b) the PMD blanket loops, and (c) the LiPb in the PMD divertor loop. Since the order of the irradiation sequence affects the results, although significantly only for short-lived nuclei, sequences were conservatively devised starting in the regions of lower neutron flux and following an increasing flux order. Tritium extraction, essential for the adequate functioning of the plant, was accounted for using FISPACT commands to remove hydrogen isotopes from the inventory to a certain extent at the end of each irradiation. Values up to 99% were found in the literature for efficiency of detritiation systems,[12] but 90% was considered a more conservative value. Results of contact dose rate, decay heat generation, and clearance index were compared with PPCS criteria. The categorization of the LiPb waste following this comparison is summarized in Tables IV and V.

Regardless of the number of irradiation cycles, no LiPb is suitable for clearance after 50 or 100 yr of cooling: All this material has to be treated as active waste, but the categorization results vary significantly with the

TABLE III

LiPb Elemental Composition

	Weight Percent		Weight Percent		Weight Percent		Weight Percent		Weight Percent		Weight Percent
H	1.00E−02[a]	P	1.00E−02	Cu	4.00E−03	Ru	1.00E−02	Ce	1.00E−02	Ta	2.02E−04
He	1.00E−02	S	1.00E−02	Zn	1.00E−03	Rh	1.54E−03	Pr	1.00E−02	W	1.00E−02
Li	6.80E−01	Cl	8.54E−03	Ga	3.55E−03	Pd	1.00E−02	Nd	2.52E−03	Re	1.00E−02
Be	1.00E−02	Ar	5.70E−03	Ge	1.00E−02	Ag	5.00E−04	Sm	1.85E−04	Os	1.00E−02
B	1.00E−02	K	9.90E−05	As	5.70E−03	Cd	5.00E−04	Eu	5.00E−05	Ir	1.52E−03
C	1.00E−02	Ca	8.46E−03	Se	1.00E−02	In	2.22E−03	Gd	1.00E−02	Pt	5.41E−03
N	4.34E−04	Sc	1.97E−03	Br	1.83E−03	Sn	5.00E−04	Tb	1.02E−04	Au	8.26E−03
O	1.00E−02	Ti	1.00E−02	Kr	1.00E−02	Sb	1.03E−03	Dy	2.16E−03	Hg	1.00E−02
F	1.00E−02	V	9.86E−02	Rb	1.00E−02	Te	1.00E−02	Ho	5.00E−05	Tl	1.00E−02
Ne	1.00E−02	Cr	1.00E−02	Sr	1.00E−02	I	1.00E−02	Er	1.00E−02	Pb	9.87E+01
Na	1.00E−02	Mn	4.53E−03	Y	6.04E−03	Xe	1.00E−02	Tm	1.89E−03	Bi	4.30E−03
Mg	1.00E−02	Fe	1.00E−03	Zr	1.00E−02	Cs	5.00E−05	Yb	1.00E−02	Th	5.00E−05
Al	1.00E−02	Co	5.00E−05	Nb	5.00E−05	Ba	1.00E−02	Lu	1.00E−02	U	5.00E−05
Si	1.00E−02	Ni	2.00E−04	Mo	1.39E−03	La	1.00E−02	Hf	1.23E−03		

[a]Read as 1.00×10^{-2}.

TABLE IV

LiPb Waste Categorization 50 yr After Plant Shutdown

	Blanket Cycles									
	1		2		3		4		5	
PMA blanket LiPb	CRM		CRM		CRM		PDW		PDW	
PMD blanket LiPb	CRM		CRM		CRM		CRM		PDW	
PMD divertor LiPb	CRM	CRM	CRM	CRM	CRM	CRM	CRM	CRM	CRM	CRM
Divertor cycles	1	2	3	4	5	6	7	8	9	10

TABLE V

LiPb Waste Categorization 100 yr After Plant Shutdown

	Blanket Cycles									
	1		2		3		4		5	
PMA blanket LiPb	SRM		CRM		CRM		CRM		CRM	
PMD blanket LiPb	SRM		CRM		CRM		CRM		CRM	
PMD divertor LiPb	SRM	SRM	SRM	CRM	CRM	CRM	CRM	CRM	CRM	CRM
Divertor cycles	1	2	3	4	5	6	7	8	9	10

irradiation and cooling times. After 50 yr following plant shutdown, all LiPb is CRM when irradiated only once. Before transforming it into undesirable PDW, PMA blanket LiPb can be reused twice, PMD blanket LiPb three times, and PMD divertor LiPb indefinitely. The situation after 100 yr of cooling is quite different: No LiPb is PDW in any of the cases, despite the number of cycles under irradiation. After only one cycle, all LiPb in both plants is SRM, which is less hazardous and cheaper to recycle. The LiPb in the blankets becomes CRM after being irradiated a second cycle. The LiPb in the PMD divertor, however, is CRM only after the fourth irradiation. If complex recycling after 100 yr is acceptable under the existing regulatory framework, the same LiPb could be reused throughout the entire life of the plant in both PMA and PMD.

These results show that a choice in the LiPb usage strategy arises: Dispose of the LiPb as SRM and get new supplies every cycle or, on the contrary, prolong the irradiation of the original material at the expense of transforming it into CRM. Figure 6 illustrates this choice for PMA: results of the active material categorization accounting for the LiPb flow in the irradiation history, for two different scenarios, are compared with previous PPCS results, which assumed static irradiation.[3] The first scenario assumes that the LiPb is replaced with new material after irradiated during only one cycle, and the second that the initial LiPb is used during the entire operational life. In the first case the total amount of waste remains the same as in the original calculations (1.33×10^5 tonnes), although with the flow irradiation modelling the LiPb is now SRM and no CRM is generated any more. In the second one there is still LiPb being CRM, but the total amount of waste is reduced by ~28% (down to 9.26×10^4 tonnes).

Irradiation histories following the volume-weighted sum method were also developed and used in FISPACT, and results at 50 and 100 yr after shutdown were compared with those obtained using the sequential method. As expected, the volume-weighted approximation consistently overestimated the values of activity and related quantities compared to the results of the sequential method. Figure 7 illustrates this effect, presenting the difference in contact dose rate values of both methods after 100 yr. The trend is for this difference, and the overestimation, to increase with the irradiation time, and this increase appears to be well fitted by a quadratic form. Analysis of the dominant species, in Fig. 8, shows that as expected, the few dominant nuclei responsible for the long-term contact dose rate that are generated via two-step reactions are responsible for this difference, in particular, ^{207}Bi generated via $^{209}\mathrm{Bi}(n,2n)^{208}\mathrm{Bi}(n,2n)^{207}\mathrm{Bi}$. The main pathways for other long-lived dominant nuclides are all single-step reactions: $^{151}\mathrm{Eu}(n,\gamma)^{152}\mathrm{Eu}$, $^{153}\mathrm{Eu}(n,\gamma)^{154}\mathrm{Eu}$, and $^{109}\mathrm{Ag}(n,2n)^{108m}\mathrm{Ag}$. Fluctuations from the quadratic form arise due to small traces of the activity being generated via reactions with more than two steps.

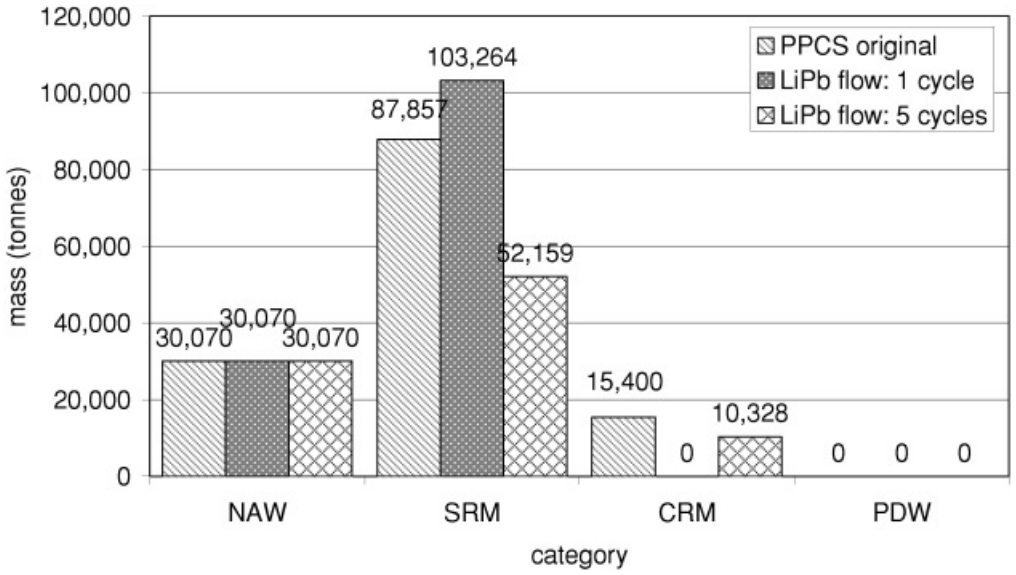

Fig. 6. PMA waste amounts per category for three different LiPb cycle scenarios.

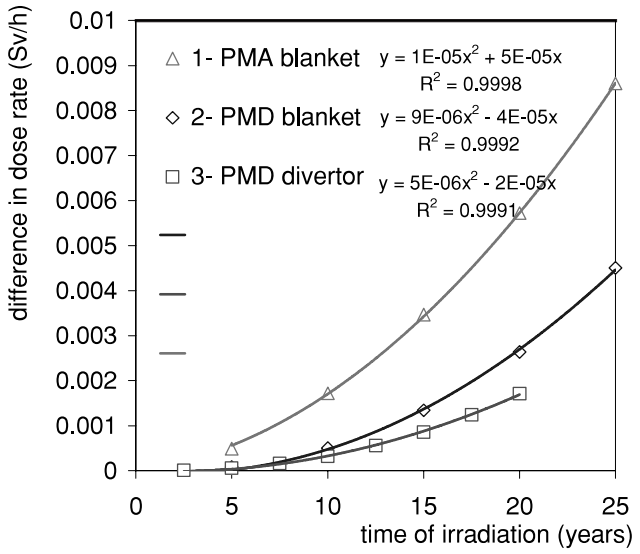

Fig. 7. Difference in results of contact dose rate after 100 yr between the volume-weighted and sequential methods, in Sv/h.

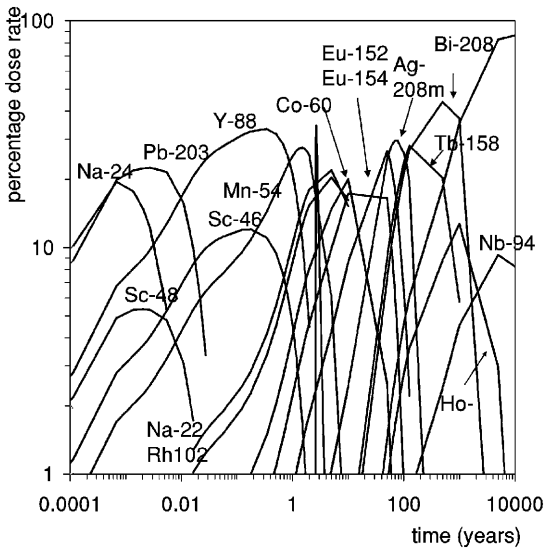

Fig. 8. Dominant nuclide contributions to the total contact dose rate of LiPb irradiated in the blanket of PMD.

IV. TIME-DEPENDENT TRITIUM GENERATION

Even if environmental issues are not a limiting factor, prolonged utilization of the tritium-generating material during several cycles is challenged by lithium depletion. PPCS concepts were designed to guarantee self-sufficiency until the end of one blanket cycle, and then assume the replacement of LiPb with new material at full lithium content. Therefore, in principle, tritium breeding rates (TBRs) will not be adequate when irradiating the same LiPb for longer unless lithium replenishment is provided. Accounting for the flowing nature of the LiPb in the lithium depletion rate, however, it is found that the useful life of LiPb as breeder can be extended as well. The flow and mixing of all LiPb has a positive effect in lengthening its tritium production capability or, if on-line replenishment is provided, in reducing the requirements of enriched lithium.

Tritium balance is also governed by Eq. (1), but in this case an approximate analytical treatment is possible.

Tritium is produced mainly via two reactions with lithium nuclei: $^6\mathrm{Li}(n,\alpha)\mathrm{T}$ and $^7\mathrm{Li}(n,n'\alpha)\mathrm{T}$, the first one particularly dominant under typical fusion spectra. The subscript j in Eq. (1) thus corresponds to ^{6}Li or ^{7}Li in this case. Ignoring tritium depletion and allowing again for a discretization of the neutron flux in the spatial domain, the tritium production rate can thereby be approximated by the sum of the rates of each reaction in a series of regions:

$$\frac{dT}{dt} = \sum_n \sum_j N_{nj} R_{nj} \ , \tag{9}$$

where

N_{nj} = ^{6}Li or ^{7}Li nuclei density in n'th region

R_{jn} = rate per unit density of the tritium generating reaction of nuclei j in region n (i.e., $\sigma_j \phi_n = R_{nj}$).

The total TBR is then

$$\mathrm{TBR} = \sum_n \sum_j \mathrm{TBR}_{nj} = \frac{1}{T_{use}} \sum_n \sum_j N_{nj} R_{nj} \ , \tag{10}$$

where T_{use} is the consumption rate in the plasma. An expression for the depletion of the lithium isotopes can also be obtained from Eq. (1). Being stable nuclei present in the original composition, and assuming that replenishing reactions and nuclear decay are negligible for ^{6}Li and ^{7}Li,

$$N_{nj} = N_{nj0} e^{-R_{nj} t} \ , \tag{11}$$

where the subscript 0 represents initial conditions. Assuming those same reactions in lithium are responsible for all tritium generation *and* lithium depletion, it is possible to write the time variation of the tritium generation as

$$\mathrm{TBR}(t) = \sum_n \sum_j \mathrm{TBR}_{nj0} \cdot e^{-R_{nj} t} \ . \tag{12}$$

Equation (12) is valid, under all the assumptions made to derive it, when the breeder is static and constantly receiving the same neutron flux in the n'th region. However, as noticed during the irradiation modeling, the LiPb is flowing through different neutron environments as it travels around the circuits. Assuming constant and uniform LiPb flow again, Eqs. (4) and (5) apply to Eq. (12) to represent that the depletion of N_j in a volume element of LiPb depends on the neutron fluence and that the fluence is the sum of discrete fluences rather than an integral of a continuous function of time. If this is so, Eq. (12) becomes

$$\mathrm{TBR}(t) = \sum_n \sum_j \mathrm{TBR}_{nj0} \cdot \exp\left(-\sum_k \frac{v_k}{v_{tot}} R_{kj} t \right) \ . \tag{13}$$

In summary, if the breeder is static, as in plant models using pebble bed blanket concepts, lithium is depleted under constant flux in each region of the blanket, but when it is uniformly flowing through regions of different neutron flux levels, it depletes according to an averaged fluence. Spatial discretization of the neutron flux is convenient again in order to approximate the otherwise continuous and smooth time variation by a volume-weighted sum and to use the results of the PPCS neutronic analyses where radial/poloidal profiles of $^6\mathrm{Li}(n,\alpha)\mathrm{T}$ and $^7\mathrm{Li}(n,n'\alpha)\mathrm{T}$ reaction rates were obtained.[11] Calculations of the time dependence of the total TBR were performed using those in Eqs. (10), (12), and (13). Since these are single-step reactions, the restriction to the volume-weighted approximation mentioned in the previous section does not apply to the tritium generation and lithium depletion processes.

Results are shown in Fig. 9, where the limit TBR $>$ 1.0 is used as representative of self-sufficiency. In PMA this is extended to ~9.5 irradiation years, nearly two blanket cycles instead of the one assumed in the design and confirmed by the calculations for static breeder using Eq. (12) (lighter lines). The great variation in flux levels throughout the blanket circuits, and particularly its radial attenuation, strongly diminishes lithium depletion and extends the useful life of the breeder. A similar effect is obtained for PMD: The LiPb flow is beneficial here too, extending the time during which TBR $>$ 1.0 up to ~15 yr. Since neutron flux levels do not vary as much as in PMA, this is now due to the flow of the LiPb through ex-vessel

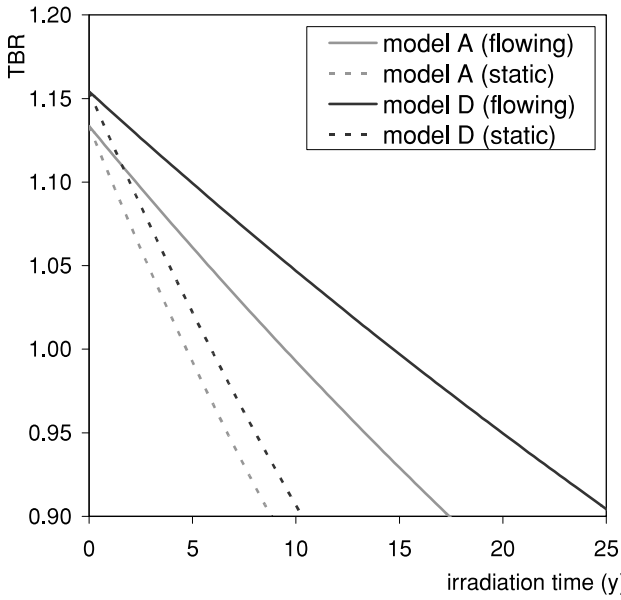

Fig. 9. Time variation of the tritium breeding ratio in PMA and PMD according to Eqs. (12) (lighter lines) and (13) (darker lines).

regions of the circuits where flux levels are negligible, representing approximately half of the total volume.

The TBR > 1.0 condition is, however, not enough to guarantee self-sufficiency in the plant and has only illustrative purposes. Other factors need to be accounted for, such as tritium decay and losses during its processing in the fuel systems. Given its half-life, some of it can be stored while production exceeds consumption and used when the situation is opposite. A more detailed analysis using existing formulation[13] is desirable, but out of the scope of this study.

V. DISCUSSION

A scoping study has been performed to estimate the long-term activation and time-dependent tritium generation of LiPb in typical tokamak fusion power plants, such as those in the European PPCS program. The long-term radiotoxicity of LiPb under fusion irradiation appears to depend almost entirely on activation products of impurities in lead (Eu, Bi). Using the radiological criteria adopted in the PPCS, the LiPb in the blankets and divertor of PMA and PMD does not require permanent disposal after 100 yr of decay, regardless of the length of its irradiation in such devices. The implication is that the same LiPb could be used during the entire lifetime of the plants. At this same timescale, the LiPb in PMA and PMD blankets is in the simple recycling category for only one cycle irradiation, whereas that in the divertor of the latter is such for up to three cycles. Longer irradiation transforms it into material requiring complex recycling mechanisms. Economic and other criteria may apply to decide which strategy to follow. It is found that the LiPb flow is particularly favorable in the case of PMA to achieve adequate tritium generation during longer irradiation, the useful life of the LiPb being extended in both PMA and PMD. Lithium replenishment seems, however, unavoidable.

It was assumed throughout the study that discrete spatial values of the neutron flux can approximate its smooth, continuous time variation, which enabled the use of PPCS results on radial/poloidal neutron spectrum profiles and $^{6}\mathrm{Li}(n,\alpha)\mathrm{T}$ and $^{7}\mathrm{Li}(n,n'\alpha)\mathrm{T}$ reaction rates. Two different methods were devised to model the irradiation history of the LiPb flow. The sequential method adequately predicts the long-term activity, whereas the volume-weighted method systematically overestimates nuclei generated in multiple-step reactions. Reference 10 suggests the inclusion of a few pulses at the end of a continuous, equivalent, steady irradiation history in order to account for short-lived nuclei in pulsed irradiations. Given the random nature of the flow, the great variability of the neutron flux, and the interest in long-term activity, it is difficult and not so desirable to find an equivalent scheme for the sequential method developed here.

Cautious extrapolation to PPCS plant models other than those considered here is possible. Neutron spectra and circuits layout of plant model C, based on a dual-coolant blanket concept (DCLL), are relatively similar to PMD, and therefore nearly the same behavior and results are expected. Model AB, based on a helium-cooled LiPb blanket concept[2] has LiPb loops similar to those of PMA, but its neutron behavior, however, is quite different; particularly regarding radial attenuation in the blanket. This undermines the advantages of the LiPb flow in this plant model.

Provided suitable recycling routes for LiPb exist, its reutilization during the entire operational life of fusion plants based on this material seems possible if Li replenishment is provided. Required amounts, however, are minimal, since it accounts for just 0.68% of the total LiPb mass and only a fraction of it is depleted generating tritium each cycle. This is an advantage over the complete replacement of the breeder at the end of each maintenance cycle.

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