Assessment of the Activation, Decay Heat,and Waste Disposal of a Dual Coolant Lithium Lead Test Blanket Module for ITER

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***Abstract*— The U.S. is proposing a test blanket module (TBM) to be placed in half of the three dedicated test ports of ITER. The TBM is based on the dual coolant lithium lead (DCLL) blanket concept. Conventional ferritic steel (F82H) is used as the structure of the first wall (FW), the two breeder channels, the back plate, the inlet/outlet piping, and the shield plug. Two separate cooling circuits are employed: helium is used to cool the FW and blanket structure while the Pb-17Li is used as a coolant and breeder mainly in the two breeder channels. SiC flow channel inserts (FCI) are used to thermally and electrically isolate the flowing Pb-17Li from the relatively low-temperature structure. A 2 mm thick beryllium layer is used as a plasma facing material on the FW area (1.25 m^2) subjected to 0.78 MW/m^2 neutron wall load. In this paper, we present results pertaining to the radioactive inventory and decay heat levels at shutdown and at several post-irradiation times following the pulsed operation scheme of ITER.**

Keywords-neutronics; ITER; test blanket module; dual coolant lithium lead; radioactivity; decay heat

I. INTRODUCTION

A test blanket module (TBM) is under development by the U.S. and is planned to be placed in a vertical half of one of the three test blanket ports in ITER (see Fig. 1). The TBM is based on the dual coolant lithium lead (DCLL) blanket concept in which helium under 8 MPa pressure is used to cool the first wall (FW) and blanket structure whereas Pb-17Li eutectic (with 90%Li-6 enrichment) is circulated poloidally in two back channels to both remove heat and breed tritium in these zones [1]. The low-activation ferritic steel [2], F82H, is used as the structural material. To thermally isolate the relatively high temperature Pb-17Li breeder from the FW region, a flow channel insert (FCI) of thickness 0.5 cm is used as a liner in all the LiPb channels and it also acts as an electrical insulator to mitigate MHD effects. The TBM is 64.5 cm wide and 194 cm high. A stainless steel frame cooled with water will house the two vertical TBM, as shown in Fig. 1. The total radial depth of the TBM is 41.5 cm, including a 0.2 cm thick beryllium front liner which acts as a plasma facing component (PFC) and a 17 cm thick back wall. A 30.7 cm thick manifold zone follows the back plate and houses the inlet/outlet piping system. A separate 128 cm thick 316SS/H_2O shield plug is used behind the TBM. In this paper, we present the anticipated radioactivity and decay heat level in each component of the TBM following the pulsed operation scheme planned in ITER. The results cited here are needed for further safety evaluation of the operation of the DCLL TBM under ITER operational environment. Other relevant information such as tritium production, nuclear heating, and shielding performance can be found in a companion paper [3].

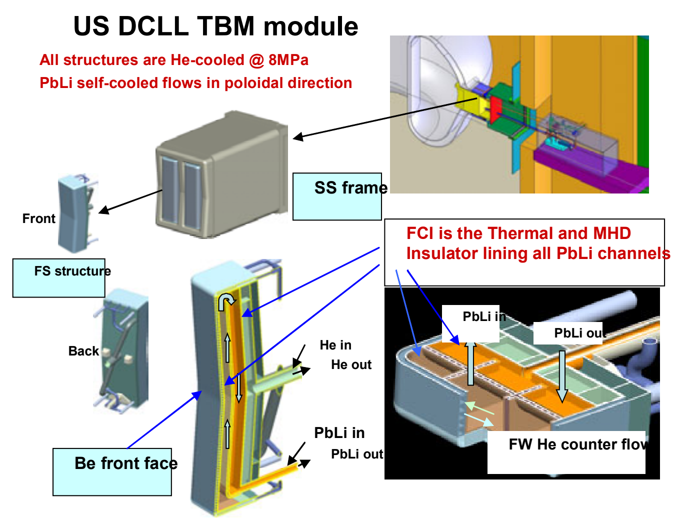

Figure 1. Relative location of the test module in the test port, transporter location and module cross-section sketch.

II. CALCULATION PROCEDURE

The radioactivity inventory and decay heat in the DCLL TBM were assessed at shutdown and at several post-irradiation times using a one-dimensional (1-D) model in which the inboard (IB) of ITER was simulated at the mid-plane and the TBM was considered to occupy the outboard (OB) region. In this model, the IB of ITER basic machine was approximated with a 1 cm thick beryllium front layer, a 2 cm thick copper heat sink layer (70% Cu-ITER grade, 20% H_2O, 10% 316SS-lw), a 53 cm thick ITER shielding blanket (75% 316SS-lw, 25% H_2O), and a 1 m-thick vacuum vessel (75% 316SS-lw, 25% H_2O). The IB front Be tile is located at a radial distance of 3.56 m while the Be PFC layer of the TBM is located at a radial distance of 8.5 m from the center of the torus. The material composition and radial build described in Table I was used in modeling the OB. The manifold zone and the shielding plug were placed behind the TBM. For the latter, we assume that it consists of the conventional ferritic steel F82H structure (used instead of 316SS) and water with a volume ratio of 3:1.

TABLE I. RADIAL BUILD AND COMPOSITION USED IN THE CALCULATION

Zone Description	Thick (mm)	% Be	% FS	% LL	% SiC	% He
PFC layer	2	100	0	0	0	0
Front wall of FW	4	0	100	0	0	0
FW cooling channel	20	0	17	0	0	83
Back wall of FW	4	0	100	0	0	0
SiC insert 1	5	0	8.1	0	80	11.9
Front breeding channel	70	0	8.1	75.7	4.3	11.9
SiC insert 2	5	0	8.1	6.1	73.9	11.9
Flow divider plate	15	0	54.8	6.1	0.4	38.7
SiC insert 3	5	0	8.5	6.1	73.3	12.1
Back breeding channel	110	0	8.5	74.7	4.7	12.1
SiC insert 4	5	0	8.5	1	78.4	12.1
Back wall	170	0	62.8	1	0.2	36
Total	**415**					

The 1-D discrete ordinates code, ANISN [4], was used to calculate the neutron flux in the 1-D toroidal model described above along with a multigroup cross-section library based on FENDL-2 data [5]. The flux in turn was used as input to the activation code, DKR-PULSAR [6], to calculate the radioactivity and decay heat levels at shutdown and at 11 post-irradiation times up to 1000 years. The activation/decay data library of FENDL-2 was used in the calculation [7]. The impurities (wppm) considered for F82H structure are as follows: Co^{59} 33.916, Nb^{93} 3.99, Mo 69.806, Pd 0.1796, Ag 0.1596, Cd 0.0499, Eu 0.0499, Dy 0.0499, Ho^{165} 0.0499, Er 0.0499, Os 0.01995, Ir 0.0499, and Bi^{209} 0.0499. For Pb-17Li, they are: Na^{23} 1.839, K 1.226, Ca 1.839, Cu 2.044, Ag 10.22, Sb 3.066, Bi^{209} 40.88. For SiC, they are: Sc^{45} 0.0016, Cr 0.518, and Fe 3.626. Natural isotopes for a given material are also included since transmutation rates are difference in each isotope.

In the following, the integrated activity (Ci) and decay heat (MW) are estimated for a TBM of 64.5 cm toroidal width, 194 cm poloidal height and 200.5 cm radial depth. The 1-D results are multiplied by a modification factor of $\theta / 2\pi$ where θ=64.4/850 is the angle, in radians, subtended by the FW of the TBM. The assumptions made are as follows:

(1) The TBM is assumed to be placed in the test port for the entire mission of ITER operation during the 1st phase (10 years), starting from the beginning of the low duty D-T phase (5th year) when the 14.1 MeV neutrons are generated. It is envisioned that 3-4 types of TBM will be utilized for testing, namely the Electromagnetic/Structural (EM/S) TBM, the Neutronics (NT) TBM, the Thermofluid/MHD TBM, and the Integrated (I) TBM. These TBMs are utilized for different periods according to a proposed test plan. Therefore, they are subjected to differing machine operation conditions (no neutrons during the H-H phase up to the 3rd year, and D-D operation in the 4th year). We assume that neutron fluence starts to build up from the 5th year to the 10th year when it reaches a value of 0.3 MWa/m^2. Without replacement for the TBM during this period (as assumed in the present analysis), the results reported here give upper conservative estimates for the activation and decay heat levels in the TBM.

(2) The 500 MW pulses are assumed to be generated one after another. Their number is calculated by dividing the full-power-year (FPY) operation that corresponds to a fluence limit of 0.3 MWa/m^2 by 400 s. For an average NWL of 0.57 MW/m^2 in ITER, we get 0.526 FPY and the number of pulses is 41494. Each pulse is assumed to be 400 s full flat top followed by 1800 s dwell time.

(3) The structure and SiC inserts are irradiated during a pulse and allowed to decay during the 1800 dwell time. This is repeated 41494 times.

(4) For the Pb-17Li breeder, in addition to the above irradiation scenario, within each pulse, it is irradiated for 36 s and not irradiated for 20 s (out of the reactor). The total Pb-17Li transit time is 56 s. The in-and-out time is estimated from the volume of the Pb-17Li in the TBM and coolant loop (~0.42 m^3), the nominal Pb-17Li volumetric flow rate (~7.74x10^{-3} m^3/s) and the volume of the TBM (~28 m^3). Thus, the number of transit (cycles during an effective 500 s pulse) is 500/56 ~9 cycles.

III. RADIOACTIVE INVENTORY

Table II gives the total radioactive inventory in the TBM (Ci) at shutdown and its breakdown by material and zone. A total of 2.44 MCi is attained with a contribution of 0.75 MCi from the structure, 1.54 MCi from Pb-17Li and 0.15 MCi from SiC insert, respectively. The larger contribution from Pb-17Li is due to the generation of the Pb-207m isotope ($T_{1/2}$=0.805 s). It is generated from the Pb-208(2,2n) and Pb-206(n,γ) reactions. This isotope decays quickly which makes the F82H structure the main contributor to the total activity inventory thereafter. For example, the activation level one minute after shutdown is 0.74 MCi with a contribution of 0.61 MCi from structure (82.4%), 0.02 MCi from Pb-17Li (2.7%) and 0.11 MCi from SiC (14.9%). The activation in the back breeding channel is the largest due to its large radial width (11 cm). The total activation and the contribution from each material are depicted in Fig. 2 for various times after shutdown. It is clear that the total activation inventory is dominated by the contribution from the structure for all times. A few minutes after shutdown, the activation level in the Pb-17Li breeder is ~2 orders of magnitude lower than the level in the structure. Due to its relatively smaller volume, the activation inventory in the SiC insert is ~2-6 orders of magnitude lower than the level in the structure (and total), as shown in Fig. 2.

The total activation in the F82H structure and the contribution from each zone (as we proceed outwards in the radial direction) are shown in Fig. 3. The total activation inventory stays at a level of ~0.7 MCi for ~ 1 hr and drops slowly thereafter. The level is ~0.1 MCi after 1 year and is ~0.01 MCi after 10 years. The inventory declines rapidly after this time frame and reaches a value of ~1 Ci after 100 years. This is an extremely low level and therefore it imposes no concerns with regard to disposing the activated materials of the TBM.

With regard to the breakdown of the total inventory in the structure, it is shown in Fig. 3 that the contribution from the shield is dominant up to ~ 1 day after shutdown when the contribution from the structure in the back breeder channel starts to be the largest. The activation in the back plate is also large. To be noted that the activation inventories in the 1st and 2nd wall (0.4 cm thick) are comparable but they are less than those attainable in the shield, the back breeder channel, and the back plate. This illustrates the importance of accounting for the activation in zones other that the FW when assessing the total radioactive inventory in the TBM (blanket in general).

TABLE II. RADIOACTIVITY INVENTORY IN THE TBM AT SHUTDOWN (CI) AND CONTRIBUTION FROM EACH MATERIAL AND ZONE

Zones	Material			Sum
	F82H	Pb-17Li	SiC	
First wall	7.645E+04			7.645E+04
FW cooling channel	5.440E+04			5.440E+04
Second wall	5.454E+04			5.454E+04
SiC-insert	4.770E+03		6.298E+04	6.775E+04
Breeding channel 1	3.573E+04	1.053E+06	2.973E+04	1.118E+06
SiC-insert	1.523E+03	3.746E+03	2.267E+04	2.794E+04
Divider plate	2.765E+04	1.004E+04	3.292E+02	3.802E+04
SiC-insert	1.265E+03	2.978E+03	1.792E+04	2.216E+04
Breeding channel 2	1.459E+05	4.641E+05	1.469E+04	6.247E+05
SiC-insert	4.916E+02	1.472E+02	5.956E+03	6.595E+03
Back plate	1.050E+05	2.248E+03	2.418E+02	1.075E+05
Piping zone	2.324E+04	1.317E+03	1.509E+02	2.471E+04
Shield	2.196E+05			2.196E+05
Total	7.506E+05	1.538E+06	1.547E+05	***2.443E+06***

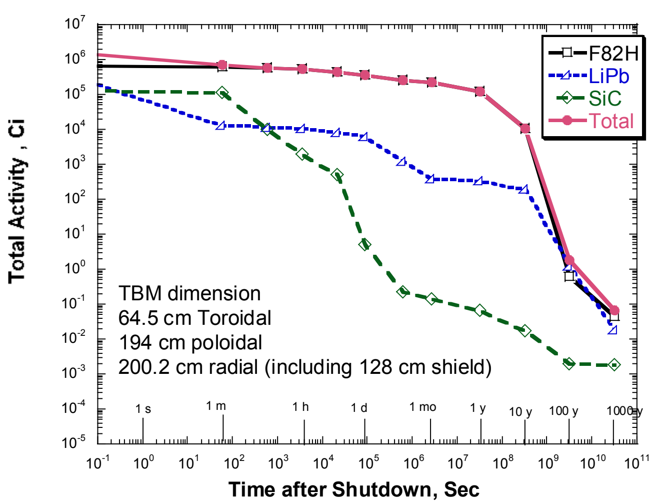

Figure 2. Total activity generated in the test blanket module and contribution from each material.

The total radioactive inventory in the Pb-17Li breeder and the contribution from each zone are shown in Fig. 4. It drops rapidly from ~1.5 MCi at shutdown to ~0.01 MCi in one minute due to the decay of the Pb-207m isotope. It stays at that level up to 1 day. After 1 month from shutdown, the activation drops to 500 Ci. It continues to stay at that value up to 10 years when it drops sharply to a level of 1 Ci at 100 year. This inventory includes the activation from the tritium that is generated in the TBM. This inventory is dominated from contribution from the front and back breeder channels. Activation levels of ~ 2-3 orders of magnitude lower are attainable in the back plate, the divider plate, and the piping zone.

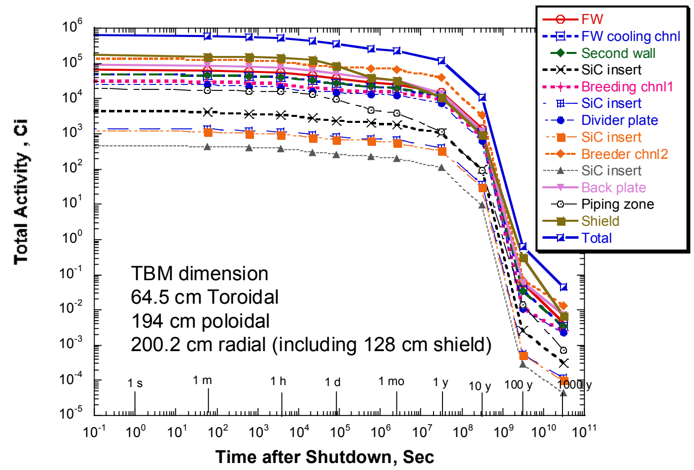

Figure 3. Total activity in the F82H structure and contribution from each zone.

As shown in Fig. 2, the total radioactive inventory in the SiC insert stays at a level of 0.1 MCi for ~ 1 min, then it drops to a level of ~8 Ci after 1 day and to ~0.08 Ci after 1 year and is due mainly to the Fe impurity. At 100 y, the inventory is extremely low (~0.002 Ci).

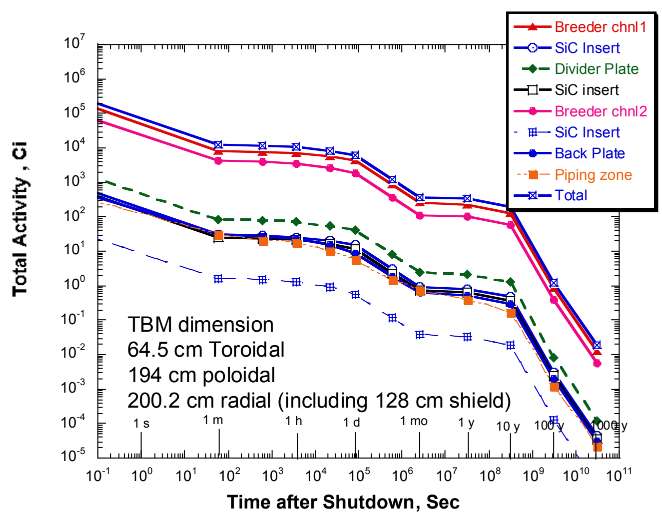

Figure 4. Total activity in the Pb-17Li breeder and contribution from each zone.

IV. DECAY HEAT GENERATION

The total decay heat at shutdown is given in Table III where the contribution from each zone in the TBM is shown. Also shown is the separate contribution from the structure, the Pb-17Li breeder and the SiC insert. At shutdown, the total decay heat is ~0.022 MW with a contribution of 0.004 MW, 0.015 MW, and 0.003 MW from F82H, Pb-17Li, and SiC, respectively. The large contribution from Pb-17Li is due to the production of the Pb-207m isotope which drops rapidly after shutdown, as discussed earlier, and after 1 minute the decay heat reaches a low value of ~0.006 MW.

TABLE III. DECAY HEAT IN THE TBM AT SHUTDOWN (MW) AND CONTRIBUTION FROM EACH MATERIAL AND ZONE

Zones	Material			Sum
	F82H	**Pb-17Li**	**SiC**	
First wall	4.241E-04			4.241E-04
FW cooling channel	3.074E-04			3.074E-04
Second wall	3.133E-04			3.133E-04
SiC-insert	2.776E-05		1.156E-03	1.184E-03
Breeding channel 1	2.178E-04	1.004E-02	5.445E-04	1.080E-02
SiC-insert	9.466E-06	3.573E-05	4.133E-04	4.585E-04
Divider plate	1.719E-04	9.571E-05	5.996E-06	2.736E-04
SiC-insert	7.884E-06	2.840E-05	3.259E-04	3.622E-04
Breeding channel 2	9.046E-04	4.421E-03	2.655E-04	5.591E-03
SiC-insert	2.973E-06	1.401E-06	1.056E-04	1.100E-04
Back plate	5.897E-04	2.134E-05	4.131E-06	6.152E-04
Piping zone	1.087E-04	1.246E-05	2.395E-06	1.236E-04
Shield	9.566E-04			9.566E-04
Total	4.042E-03	1.466E-02	2.823E-03	***2.152E-02***

The total decay heat and the contribution from each material for several post-irradiation times are shown in Fig. 5. From a fraction of an hour up to ~100 years after shutdown, the total decay heat is attributed to the contribution from the structure. The decay heat levels after 1 hour, 1 day, 1 year, 10 years, and 100 years are, $3.5x10^{-3}$ MW, $1x10^{-3}$ MW, $1x10^{-4}$ MW, $2x10^{-6}$ MW, and $7x10^{-10}$ MW, respectively. The decay heat generated in the Pb-17Li breeder is ~2-3 orders of magnitude lower for all times after a few minutes following shutdown while the attainable level in the SiC insert is 2-6 orders of magnitude lower than the level in the structure.

The decay heat generated in the FW is not the major contributor to the total decay heat, as is the case for the total activation inventory. This is shown in Fig. 6 where it is apparent that the contribution from the structure in the shield, the back breeder channel, and the back plate is dominant. The contribution from the structure in the FW, FW cooling channel, and the second wall is next followed by the contribution from the structure in the front breeder channel, the divider plate and the piping zone.

The total decay heat generated in the Pb-17Li breeder and the contribution from each zone is depicted in Fig. 7. The decay heat after 1 hour, 1 day, 1 year, 10 years and 100 years after shutdown are ~$3x10^{-5}$ MW, ~$1x10^{-5}$ MW, ~$9x10^{-8}$ MW, $1x10^{-9}$ MW, and $3x10^{-10}$ MW, respectively. The decay heat generated in the front and back breeder channels are the largest among the other zones. The decay heat generated in the divider plate zone is about two orders of magnitude lower than the values in these channels.

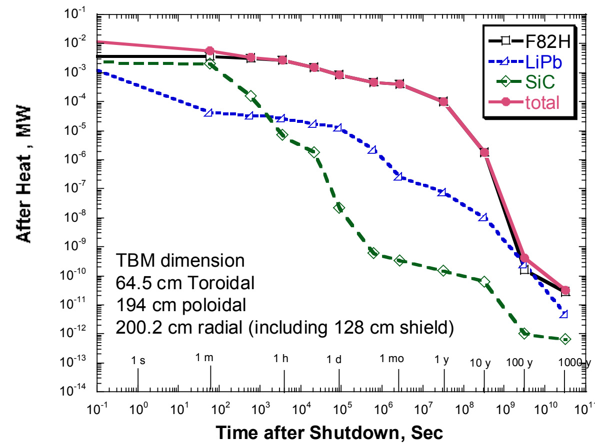

Figure 5. Total afterheat generated in the test blanket module and contribution from each material.

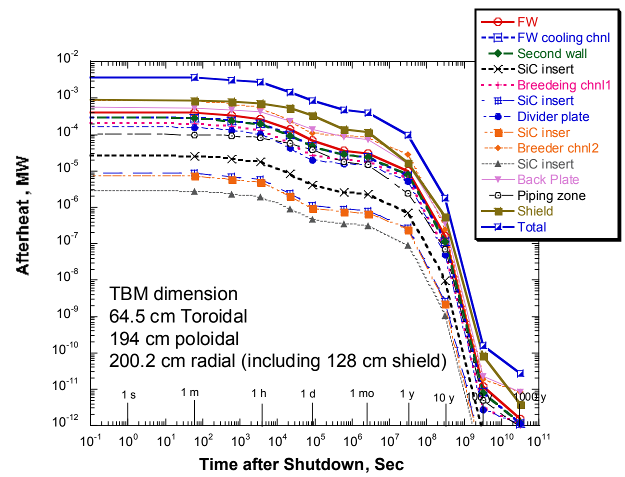

Figure 6. Total decay heat in the F82H structure and zone contributions.

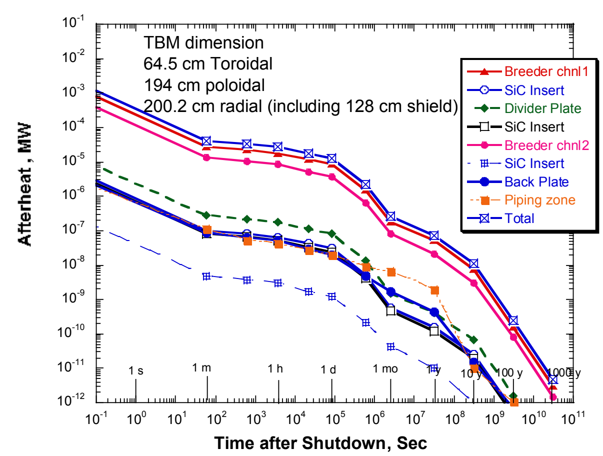

Figure 7. Total after heat in the Pb-17Li breeder and contribution from each zone.

The total decay heat generated in the SiC inserts is larger than the decay heat generated in the Pb-17Li breeder for few minutes after shutdown, as shown in Fig. 5. It drops sharply thereafter and reaches very low values. After 1 hour, 1 day, 1 year, 10 years, and 100 years following shutdown, these values are $1x10^{-5}$ MW, $2x10^{-8}$ MW, $1x10^{-10}$ MW, $8x10^{-11}$ MW, and $1x10^{-12}$ MW, respectively. These values are insignificant and impose no safety concerns.

V. Radwaste Assessment

The waste disposal rating (WDR) depends on the level of the long-term activation. For the F82H structure, Nb-94 ($T_{1/2}$=$2.03x10^4$ y), Mn-53 ($T_{1/2}$=$3.7x10^6$ y), Ni-59 ($T_{1/2}$=$7.5x10^4$ y), and Nb-91 ($T_{1/2}$=$6.8x10^2$ y) are the main contributors. In Pb-17Li, the main contributor to the long-term activation is the Pb-205 isotope ($T_{1/2}$=$1.52x10^7$ y) while the C-14 isotope ($T_{1/2}$=5730 y) and the Be-10 isotope ($T_{1/2}$=$1.51x10^6$ y) are the main contributors in the SiC insert. The radwaste classification of these materials was evaluated according to the Nuclear Regulatory Commission (NRC) 10FR61 [8] and Fetter [9] waste disposal concentration limits. The limits given are based on the assumption that all solid components are crushed before being disposed (no voids). Components having WDR >1, according to Class C limits, do not qualify for shallow land burial.

The WDR values for F82H structure, the Pb-17Li breeder, and the SiC insert are $6.9x10^{-3}$, $2.9x10^{-9}$, and $7.3x10^{-14}$, respectively, based on the NRC limits. The corresponding WDRs based on Fetter limits are $1.3x10^{-2}$, $8.7x10^{-3}$, and $2.1x10^{-4}$, respectively. Although the Fetter limits are generally more conservative, the values are still much lower than unity and therefore these materials are qualified for shallow land burial according to the Class C limits.

VI. Summary

The total radioactive inventory (Ci) in the DCLL TBM at shutdown is relatively small (2.44 MCi) and drops rapidly within a minute to reach a level of ~0.7 MCi due to the decay of the Pb-207m isotope. It stays at that level for ~1 hr and drops slowly thereafter. The level is ~0.1 MCi after 1 year and is ~0.01 MCi after 10 years. The inventory is almost entirely due to the activation of the F82H structure in the TBM, and in particular, to the structure in the back breeder channel, the back plate, and the shield. A few minutes after shutdown, the activation level in the Pb-17Li breeder is ~2 orders of magnitude lower than the level in the structure, even with the inclusion of the activation of the tritium bred while the activation in the SiC insert is ~2-6 orders of magnitude lower.

At shutdown, the total decay heat is as low as ~0.022 MW. After the decay of the Pb-207m isotope, the total decay heat is attributed mainly to the structure. The total decay heat after 1 hour, 1 day, 1 year, 10 years, and 100 years is $3.5x10^{-3}$ MW, $1x10^{-3}$ MW, $1x10^{-4}$ MW, $2x10^{-6}$, and $7x10^{-10}$ MW, respectively. These are extremely low values and impose no safety concerns. As is the case for the radioactive inventory, the decay heat generated in the FW is not the major contributor to the total decay heat. The decay heat generated in the Pb-17Li breeder is ~2-3 orders of magnitude lower for all times after few minutes following shutdown while the attainable level in the SiC insert is 2-6 orders of magnitude lower than the level in the structure.

The waste disposal rating (WDR) depends on the level of the long-term activation. For the F82H structure, Nb-94, Mn-53, Ni-59, and Nb-91 are the main contributors. In Pb-17Li, the main contributor is the Pb-205 isotope. The C-14 isotope and the Be-10 isotope are the main contributors in the SiC insert. The WDR values for F82H structure, the Pb-17Li breeder, and the SiC insert according to the conservative Fetter limits are $1.3x10^{-2}$, $8.7x10^{-3}$, and $2.1x10^{-4}$, respectively. They are thus much lower than unity and therefore these materials are qualified for shallow land burial according to the Class C limits.

Acknowledgment

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