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ACTIVATION ANALYSIS FOR THE AQUEOUS SELF-COOLED BLANKET AND SHIELD OF ITER

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ABSTRACT

Activation analysis was performed for the outboard (o/b) and inboard (i/b) blanket and shield of ITER. The options of using PCA or Tenelon were assessed. The o/b blanket and shield qualify as class C LLW. If Tenelon is used, it qualifies as class A waste. The i/b shield by itself qualifies as class C waste only if Tenelon is used. If PCA is used, then class C qualification can be realized if the i/b and o/b shields are disposed of together. The total amount of ^{14}C produced in the coolant is 4650 Ci for $LiNO_3$ and 54 Ci for LiOH. The Be/SS/W i/b shield results in a decay heat much less than that in an all W shield. Under adiabatic heat-up conditions, the PCA structure can withstand a LOCA and after one day the temperatures do no exceed 700°C.

INTRODUCTION

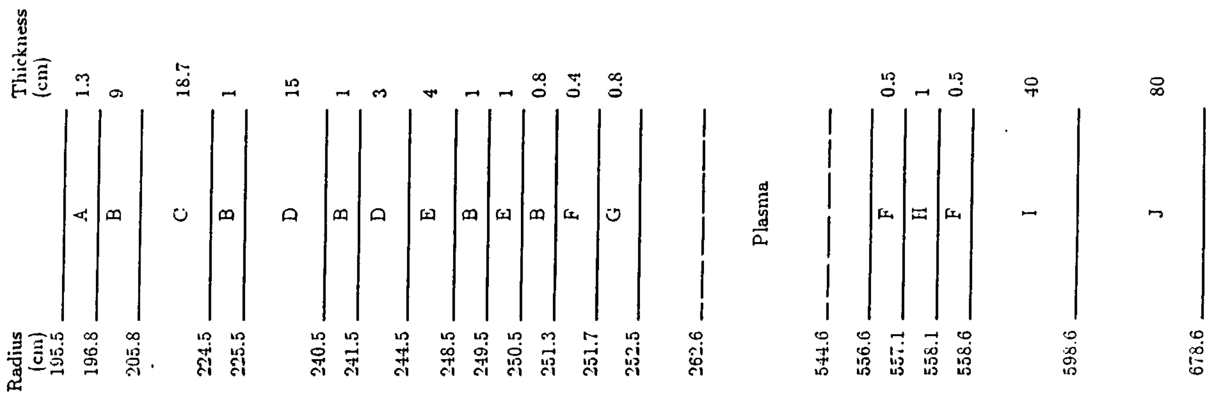
An aqueous lithium salt blanket and shield has been developed for an early compact version of the International Thermonuclear Experimental Reactor (ITER). The reactor has a major radius of 4 m and an aspect ratio of 2.86. It produces 631 MW of fusion power leading to average and peak neutron wall loadings of 1.15 and 1.91 MW/m^2, respectively. The outboard aqueous self-cooled blanket and shield design utilizes pebble beds of beryllium and steel through which an aqueous Li salt solution flows. LiOH and $LiNO_3$ dissolved in the water coolant at concentrations of 5 g/100 cm^3 and 16 g/100 cm^3, respectively, were considered. The lithium is enriched to 90% ^{6}Li. The inboard shield and the divertor zone shield are cooled also by the aqueous Li salt solution. This design achieves tritium self-sufficiency while providing adequate magnet protection.

The inboard shield thickness in ITER is constrained to 0.55 m with a peak neutron wall loading of 1.47 MW/m^2 at the midplane. An efficient inboard tungsten-based shield cooled with the $H_2O/LiNO_3$ aqueous solution was designed for TIBER-II.[2] Although tungsten provides excellent magnet protection, its high specific decay heat, particularly in the front layers of the shield caused some concern in case of a Loss of Coolant Accident (LOCA) with air or cover gas circulation required to dissipate the decay heat.[3] With this in mind an attempt was made to reduce the amount of W in the inboard shield of ITER and locating it in low neutron flux zones. The shield optimization study resulted in the ITER inboard shield being configured in 3 main layers: a 0.05 m Be layer, followed by a 0.18 m steel layer, then a 0.18 m W layer.[4] Five coolant channels, each 0.01 m wide, are distributed across the shield with a 0.1 m thick layer of the aqueous solution at the back of the shield.

In this paper, the activation analysis performed for the outboard and inboard blanket and shield will be presented. The options of using PCA and the low activation austenitic steel Tenelon will be assessed. The activity produced in the coolant will be calculated and results compared for the two candidate Li salts. The U.S. waste disposal ratings (WDR) for the structural material will be presented. The thermal response of the blanket and shield materials to LOCA and LOFA will be determined utilizing the decay heat results.

CALCULATIONAL PROCEDURE

A one-dimensional toroidal cylindrical geometry model, that includes both the outboard and inboard blanket and shield has been used in the calculations. The radial build used in the calculations is shown in Fig. 1. The one-dimensional discrete ordinates neutron transport code ONEDANT[5] was used to generate the neutron flux in the different zones of the blanket and shield. The neutron flux was then utilized in the activation calculations performed using the DKR-ICF code[6] and the ACTL library.[7] Both the austenitic steel alloys PCA and the low activation manganese steel Tenelon are considered. The elemental compositions of these alloys are those reported in the BCSS study.[8] The results for the inboard and outboard regions are normalized to the appropriate neutron wall loadings. 2.9 full power years (FPY) of reactor operation are used in the calculations.



A	99.7% PCA	F	100% PCA
B	95.6% Aq. soln, 4.1% PCA	G	90% C, 10% PCA
C	82.7% W alloy, 15% PCA, 2% Pb	H	100% Aq. soln.
D	97.7% PCA, 2% Pb	I	61.13% Be (0.9 d.f.), 2.12% PCA, 36.75% Aq. soln.
E	82.7% Be (0.9 d.f.), 15% PCA, 2% Pb	J	64.37% PCA, 35.63% Aq. soln.

Fig. 1. Radial build used in neutronics and activation calculations.

ACTIVITY AND BIOLOGICAL HAZARD POTENTIAL (BHP)

The total activity in the inboard (i/b) and outboard (o/b) blanket and shield as a function of time following shutdown is shown in Fig. 2 for the case with Tenelon. The results are given per cm height at the reactor midplane and are normalized to the peak neutron wall loadings for the i/b and o/b regions of 1.47 and 1.91 MW/m^2, respectively. The inboard activity is higher than the outboard activity up to ~ 5 days following shutdown. In this period the inboard activity is dominated by ^{187}W($T_{1/2}$ = 23.9 h) and ^{56}Mn($T_{1/2}$ = 2.6 h). In the period between 5 days and 10 years, the outboard activity is higher with ^{55}Fe($T_{1/2}$ = 2.7 y), ^{60}Co($T_{1/2}$ = 5.27 y) and ^{54}Mn($T_{1/2}$ = 313 d) being the main contributors. In the inboard region during this period most of the activity is contributed by ^{185}W($T_{1/2}$ = 75.1 d) in addition to ^{60}Co, ^{55}Fe, and ^{54}Mn. The inboard activity is higher than the outboard activity after 10 years with dominant contributions from ^{63}Ni($T_{1/2}$ = 100 y), ^{59}Ni($T_{1/2}$ = 80,000 y), ^{93m}Nb($T_{1/2}$ = 13.6 y), and ^{14}C($T_{1/2}$ = 57.30 y). The results for the case with PCA show a similar trend.

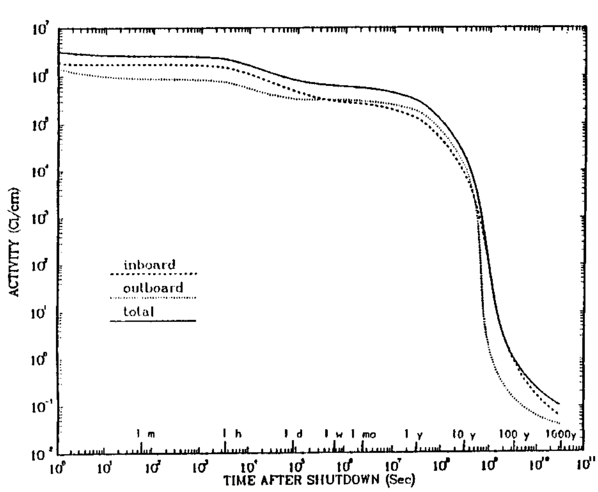


Fig. 2. Activity per cm height at reactor midplane using Tenelon.

A comparison between the total activity produced in the i/b and o/b regions (excluding the coolant) in cases with Tenelon and PCA is shown in Fig. 3. The activity in the blanket and shield using Tenelon is higher than that obtained using PCA up to ~ 8 hours following shutdown mainly due to the contribution of ^{56}Mn($T_{1/2}$ = 2.6 h). The Tenelon activity drops sharply below that for PCA after 10 years due to the decay of ^{54}Mn($T_{1/2}$ = 313 d). Taking into account the height for the i/b and o/b blanket and shield and normalizing to the average i/b and o/b wall loadings of 1.05 and 1.5 MW/m^2, respectively, the total activity in the blanket and shield at shutdown is 1561 MCi with Tenelon and 1130 MCi with PCA. The total activity drops by an order of magnitude in about one year following shutdown.

The biological hazard potential (BHP), given in terms of the amount of air required to dilute the isotopic concentration to the maximum permissible concentration has been calculated. The results obtained for the BHP in general show similar variation with time after shutdown as obtained for the activity. Comparing the total BHP values for the blanket and shield in the cases with Tenelon and PCA indicates that the

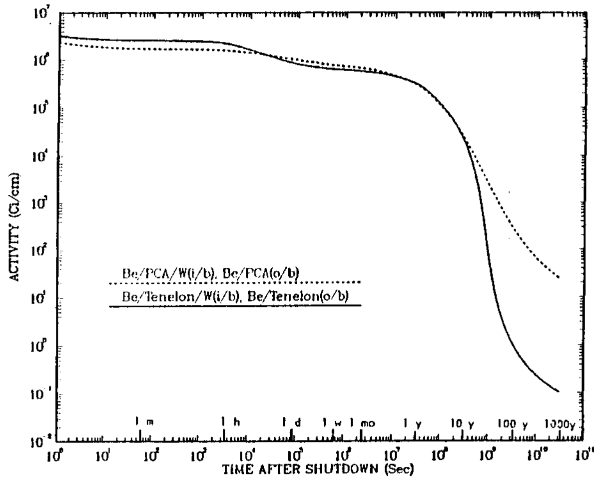


Fig. 3. Comparison between total activity production using Tenelon and PCA.

BHP with Tenelon is less than that with PCA at all times after shutdown. The total BHP at shutdown is 2.1 x 10^8 km^3 of air with Tenelon and 2.3 x 10^8 km^3 with PCA.

WASTE DISPOSAL RATING

The specific activities calculated for the different radionuclides have been used with the U.S. waste disposal concentration limits (WDL) to evaluate the radwaste of the blanket and shield of ITER. Both the 10CFR61 limits[9] (the current legal limits) and the limits calculated by Fetter[10] were used. Fetter's limits used in this analysis are the most recent values calculated by an improved model. Table 1 lists the calculated WDR values for Class C Low Level Waste (LLW). The WDR range corresponds to the range given by Fetter for the WDL of some of the radionuclides. The major contributing radionuclides and their contributions are given in parenthesis for each case. The results are given separately for the i/b and o/b regions and for both cases with PCA and Tenelon. Notice that a WDR value ≤ 1 implies that the radwaste classifies as Class C LLW and qualifies for shallow land burial. The results in Table 1 indicate that the outboard blanket and shield qualifies as Class C LLW even if PCA is used. If Tenelon is used it qualifies as class A LLW with a WDR of 0.064 using the WDL given in 10CFR61 for class A waste. In such a case, a wait period of ~ 20 years is needed before short-lived activity drops to 700 Ci/m^3. If PCA is exclusively used, then class C qualification for the inboard and outboard blanket and shield can be realized if the two are disposed of together. Further studies to examine the practicality/cost of such averaging of materials, and the contact dose/decay heat practical considerations should be done prior to waste packing and disposal.[11]

COOLANT ACTIVITY

The activity produced in the aqueous lithium salt coolant has been determined for both cases of $LiNO_3$ and LiOH salts with concentrations of 16 and 5 g/100 cm^3, respectively.

Table 1. Class C Waste Disposal Rating for ITER Blanket/Shield (No Compactness) 1 Year After Shutdown

	i/b: Be/PCA/W o/b: Be/PCA	i/b: Be/Tenelon/W o/b: Be/Tenelon
Inboard Region		
10CFR61 limits	5.96 (5.4 ^{94}Nb, 0.41 ^{63}Ni)	0.025 (0.018 ^{94}Nb, 0.004 ^{14}C)
Fetter limits	6.89 - 19.5 (5.4 ^{94}Nb, 1.4-14 ^{99}Tc)	0.0571 - 0.0593 (0.038 ^{108m}Ag, 0.018 ^{94}Nb)
Outboard Region		
10CFR61 limits	0.514 (0.446 ^{94}Nb, 0.051 ^{63}Ni)	1.54 x 10^{-3} (0.001 ^{94}Nb, 4.6x10^{-4} ^{14}C)
Fetter limits	0.585 - 1.75 (0.446 ^{94}Nb,0.129-1.29 ^{99}Tc)	4.47 x 10^{-3} - 4.69 x 10^{-3} (3.2x10^{-3} ^{108m}Ag,1x10^{-3} ^{94}Nb)
Avg. over i/b and o/b regions		
10CFR61 limits	1.179	4.4 x 10^{-3}
Fetter limits	1.35 - 3.91	0.011

The total activity produced in the coolant per cm height at the reactor midplane following 2.9 FPY operation is given in Table 2. The short term activity is dominated by $^{16}N(T_{1/2} = 7.1$ s) while the activity after 10 minutes is due to $^{14}C(T_{1/2} = 5730$ y) which is produced by the $^{14}N(n,p)$ and $^{17}O(n,\alpha)$ reactions. The total end-of-life ^{14}C activity in the coolant is 4650 Ci for $LiNO_3$ and 54 Ci for LiOH.

Since ~ 20% of the coolant in ITER will be processed per full power day for tritium recovery, ^{14}C can be removed at the same rate leading to equilibrium ^{14}C inventories of 22 and 0.26 Ci for $LiNO_3$ and LiOH, respectively. Continuous processing of the $LiNO_3$ solution for ^{14}C removal results in a small volume of high level waste that can be disposed of at a relatively low cost (< $1M).[12] Alternatively, if the ^{14}C is not extracted from the coolant during the reactor life, the ^{14}C concentration at end of life will be 11.6 and 0.14 Ci/m^3 for $LiNO_3$ and LiOH, respectively. Using the class C LLW limit of 8 Ci/m^3 from 10CFR61 implies that the volume of solid class C LLW generated by ^{14}C should be at least 581 m^3 for $LiNO_3$ and 7 m^3 for LiOH. Since the 400 m^3 coolant will be disposed of by mixing with concrete, the solid waste generated may qualify as class C LLW. Using the ^{14}C concentration limit of 600 Ci/m^3 for class C classification given by Fetter[10] implies that the total volume of the ^{14}C LLW generated with the $LiNO_3$ solution should be > 7.8 m^3.

Table 2: Coolant activity per cm height at reactor midplane (Ci/cm)

Time after Shutdown	$LiNO_3$ Solution	LiOH Solution
0	7.07×10^4	6.09×10^4
1 m	200	170
> 10 m	9.7	0.11

DECAY HEAT GENERATION

The decay heat generated in the i/b and o/b blanket and shield as a function of time following shutdown is shown in Fig. 4 for the case with Tenelon. The inboard shield produces more decay heat than does the outboard blanket and shield up to 5 days following shutdown. The inboard decay heat dominates again after ~ 7 years following shutdown. The total decay heat produced with Tenelon is compared to that with PCA in Fig. 5. Using Tenelon results in larger decay heat generation in the ~ 8 hours following shutdown. On the other hand, using PCA results in much larger decay heat generation after ~ 3 years.

The integrated decay heat values in one day after shutdown in the outboard region are 68 and 97 GJ for PCA and Tenelon, respectively. The corresponding values for the inboard shield are 86 and 141 GJ. In one week after shutdown, the integrated decay heat values in the outboard region are 345 and 309 GJ for PCA and Tenelon, respectively, with the values in the inboard region being 342 and 324 GJ, respectively. While about 50% more decay heat is generated during the first day after shutdown with Tenelon compared to PCA, slightly lower decay heat is generated with Tenelon over one week.

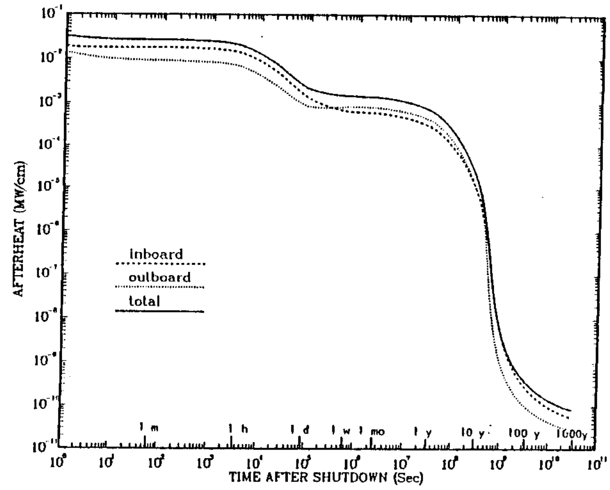


Fig. 4. Decay heat generation per cm height at reactor midplane using Tenelon.

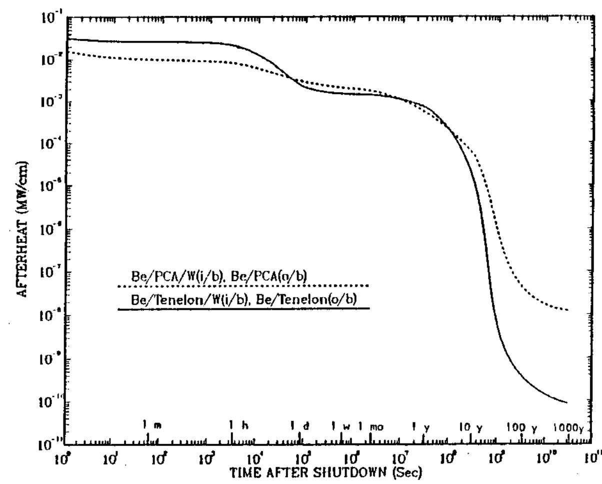


Fig. 5. Comparison between decay heat generation with Tenelon and PCA.

We compared the integrated decay heat generated in the optimized ITER inboard shield design (Be/SS/W)[4] to that obtained if one utilizes a W based shield such as that used in TIBER-II[2] and to a steel based shield without Be or W. Figure 6 shows the effect of using the different shield designs on the integrated decay heat in the inboard shield. It is clear that

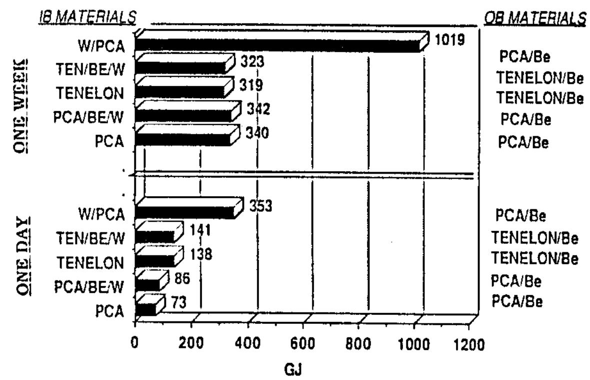


Fig. 6. Integrated decay heat in the inboard shield for different shield designs.

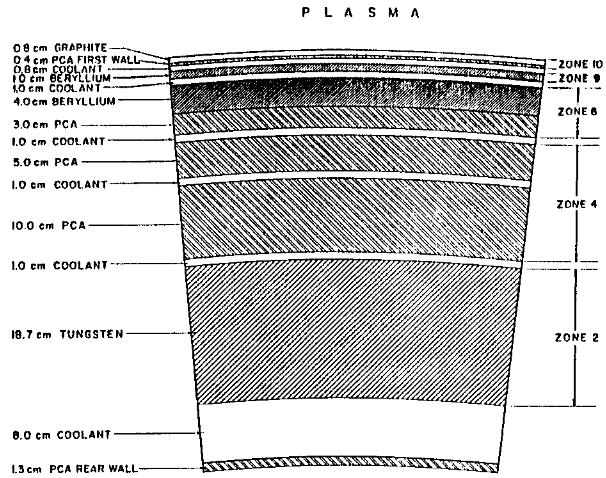


Fig. 7. Inboard shield configuration.

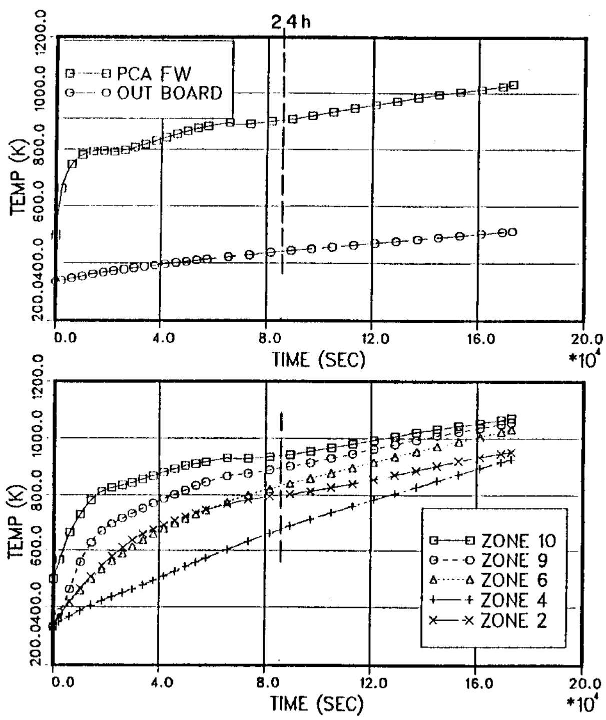


Fig. 8. Temperature histories for o/b (top) and i/b (bottom) regions following LOCA for PCA.

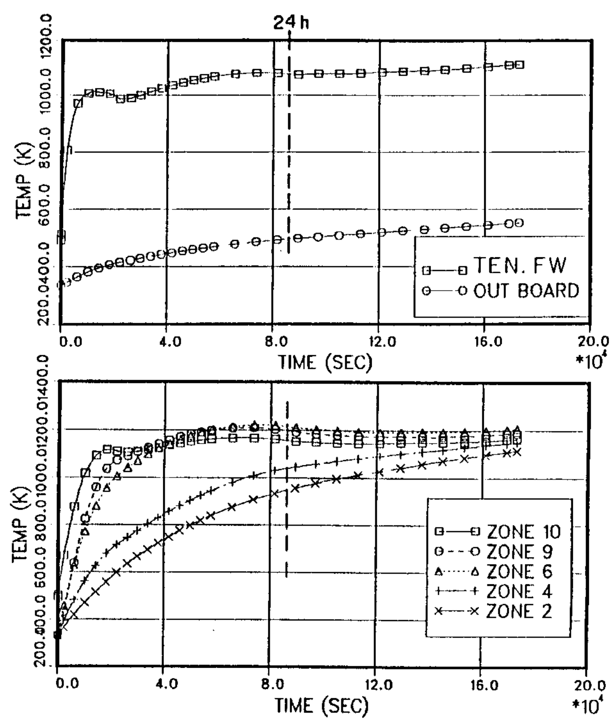


Fig. 9. Temperature histories for o/b (top) and i/b (bottom) regions following LOCA for Tenelon.

the optimized Be/SS/W shield results in decay heat very close to that in an all steel shield and much less than that in an all W shield.

LOFA/LOCA ANALYSIS

The outboard blanket and inboard shield were analyzed with respect to loss of flow (LOFA) and loss of coolant (LOCA) accidents. In the case of LOFA, there will be adequate natural circulation of coolant to provide indefinite protection. The analysis has focused on LOCA as the more critical case.

In the LOCA analysis we assume that the plasma stays on for 10 seconds after the instantaneous loss of all the coolant. The inboard and outboard sides are solved interactively assuming that the plasma volume as well as all the coolant channels are filled with air at one atmosphere. The code ATHENA,[13] a one-dimensional thermal hydraulics code developed at EG&G, Idaho was used in the analysis. In the version used there is no provision for radiation, but the effect is not expected to be major. The inner legs of the superconducting TF coils are used as a heat sink but the outboard blanket was assumed to be insulated at its outer perimeter. The outboard blanket is modelled as a first wall physically separated from the blanket, and a homogenized heat conducting zone of the Be and steel. The inboard shield is modelled as five heat conducting slabs separated by six cooling ducts as shown in Fig. 7. The analysis was performed for both PCA and low activation Tenelon as the structural materials. Figs. 8 and 9 give the temperature histories for the outboard blanket (top) and inboard shield (bottom) for PCA and Tenelon, respectively. The FW temperature in the outboard blanket reaches 625°C and 800°C in 24 hours for the PCA and Tenelon, respectively. This temperature will be substantially lowered if conduction along connecting plates is factored in. The maximum temperatures reached in the inboard shield in 24 hours are 660°C for PCA and 950°C for Tenelon. At 48 hours the PCA reaches 820°C and is still rising while the Tenelon levels off at ~ 930°C. Since the integrated decay heat for both steels is essentially the same at one week after shutdown, we would expect the temperatures at that time to be comparable.

SUMMARY

Activation analysis has been performed for the aqueous Li salt blanket and shield proposed for ITER. The o/b blanket and shield qualifies as class C waste when PCA is used and as class A waste when Tenelon is used. The i/b shield is class C only if Tenelon is used. Class C classification can be realized with PCA if both i/b and o/b blanket and shield are disposed of together. The ^{14}C production in the $LiNO_3$ solution is 4650 Ci at the end of life with about two orders of magnitude lower ^{14}C activity in the LiOH solution. The decay heat generation has been reduced considerably by using the optimized Be/SS/W shield compared to the W based shield used in TIBER-II. Tenelon results in ~ 50% more decay heat generation in the first day after shutdown compared to PCA but both alloys produce comparable integrated decay heat in one week after shutdown. Under adiabatic heat-up conditions, the structure can withstand a LOCA and after one day the temperatures do not exceed 660°C for PCA and 950°C for Tenelon.

ACKNOWLEDGEMENT

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