TIBER Activation Analysis

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TIBER ACTIVATION ANALYSIS

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Summary

TIBER-II is an engineering test reactor designed to establish the technical feasibility for fusion, and is a U.S. option for the prospective International Thermonuclear Test Reactor (ITER). The TIBER-II baseline design has 3 m major radius, 3.6 aspect ratio, and 1.1 MW/m^2 average neutron wall loading. The inboard shield is about .5 m thick and structurally consists of tungsten alloy and PCA alloy. The outboard is 1.52 m thick and utilizes PCA as structure and beryllium as a neutron multiplier. An aqueous solution of 160 g $LiNO_3$/liter is used throughout as a coolant and breeder. A one-dimensional cylindrical model for TIBER is used to calculate the neutron flux and the radioactivities. Activities are calculated during and after 2.5 full power years (FPY) of operation. TIBER total activity is ~ 2 MCi/cm at the end of operation and is dominated by the inboard activity. The high volumetric fraction of the PCA/W alloys in the inboard shield, used to provide magnet protection at the limited inboard space, makes the inboard specific activity two orders of magnitude higher than that of the outboard and dominant all the time. The decay heat due to β and γ decay produces about .05 W/cc in the inboard at shutdown and for a few weeks. Under adiabatic conditions, this heat would raise the inboard shield temperature up to 1150 °C. A considerable part of this heat is generated by the γ decay which might help, through the γ transport, to smooth the heat concentration. Waste disposal ratings of the TIBER structures have been calculated, and it is found that both the inboard and the outboard shield are classified as Class C radwaste.

Introduction

Activation calculations have been performed in the TIBER study to identify important safety, environmental, and radwaste issues of the TIBER design. This paper summarizes the radioactivity and its related quantities, e.g. the afterheat and the biological hazard potential (BHP) of the coolant, structure, and air in TIBER. A comparison of the different lithium salts considered for tritium breeding is made; the waste disposal ratings (WDR) of TIBER's structures are presented. These calculations have been carried out using the radioactivity code RACC along with its associated activation data libraries RACCXLIB and RACCDLIB [1].

Lithium Salts Activation

Different lithium salts have been considered for use in the water coolant for tritium breeding. A comparison of these salts' activation levels has been made using a one dimensional cylindrical geometry. In this model, a 20 cm thick Be zone (3% PCA, 73.6% Be, and 20.8% aqueous solution) starts at 96.5 cm radius and is followed by a 100 cm thick steel zone (80% PCA, 20% aqueous solution). Lithium nitrate ($LiNO_3$), lithium hydroxide (LiOH), lithium carbonate (Li_2CO_3) and lithium bicarbonate ($LiHCO_3$) salts have been used in the water with concentrations slightly below their solubility limits in the cold water. The coolant is assumed to spend 1/10 of the time in the reactor. Figure 1 shows the specific activities for the different aqueous solutions after 3.2 FPY of operation. The short term activities in all salts are dominated by ^{16}N ($T\frac{1}{2}$=7.1 s), while the long term activities, except of LiOH, are due to ^{14}C ($T\frac{1}{2}$=5370 y).

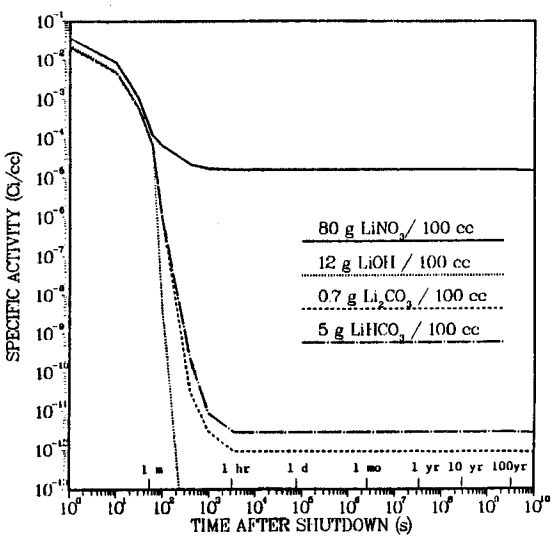

Fig. 1. Specific activities of Li salts.

As it appears in this figure, the least activity is due to LiOH (vanishes in a few minutes) followed by Li_2CO_3 and $LiHCO_3$ respectively. The highest activity is produced by $LiNO_3$; however, based on other considerations such as the salt compatibility with structure, and its radiolysis, $LiNO_3$ has been chosen for the TIBER base case. The $LiNO_3$ activity, although the highest among the lithium salts considered, represents only a small fraction of the total system activity. The $LiNO_3$ activity is 4% of the structure activity at shutdown, and 4.3 orders of magnitude less in the period of 1 minute to 10 years after shutdown. After 100 years, the $LiNO_3$ activity is about 17% of the Be and PCA activity.

TIBER Base Case

A one-dimensional toroidal cylindrical geometry model, that incorporates all the available details of the inboard and the outboard shields, has been used for the activation calculations. In this model, the neutron source magnitude and location have been adjusted to yield the average neutron wall loadings on the inboard and the outboard shields, which are .88 MW/m^2 and 1.52 MW/m^2 respectively. Figure 2 shows a schematic of this model, the material fractions in each zone, and the identification of each zone that will be used hereafter. The concentration of $LiNO_3$ in water is 160 g/liter. The elemental

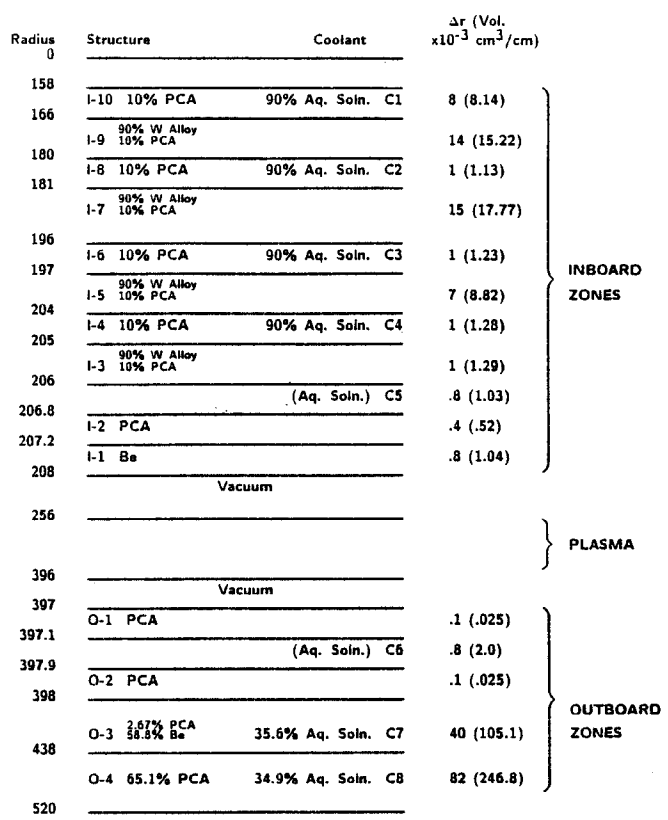

Fig. 2. TIBER's radial build at midplane.

composition of PCA used is that reported in the BCSS study [2]. The W alloy detailed composition is not known, and only major constituent elements (W, Fe, Ni) are included in the calculations. Most of the results presented are given per cm; to obtain the total of any quantity in this case, one has to multiply by the TIBER average height which is ≃ 400 cm. The reactor is assumed to be in continuous operation for 2.5 FPYs. The coolant is assumed to spend half of the operation time in the reactor.

Coolant Activity

Table 1 summarizes the radioactivity and the decay heat of the coolant at various times after shutdown. As mentioned before, the short term activity is due to ^{16}N, and the long term activity is due to ^{14}C. This is also true with respect to the decay heat. Decay heat in this table is the result of both β and γ decay. The γ decays of the ^{16}N excited states produce 71% of the short term afterheat. A considerable part of this γ heat will likely be transported to the surrounding structure.

Structure Activity

The TIBER activity at shutdown and apart from the coolant is about 1.7 MCi/cm. Although the outboard volume is ~ 6.24 times the inboard volume, and the neutron wall loading on the outboard is about twice the neutron wall loading on the inboard, the inboard activity dominates the total activity of TIBER for about 3 years after shutdown, as is shown in Fig. 3. The radioactivity (Ci/cm) of TIBER is also given in Table 2 for various times, where the

Table 1. Activity and Afterheat of the Coolant

Time	0	1 m	1 hr
Activity Ci/cm	5.8×10^{4}	199	23
^{16}N ($T\frac{1}{2}$ = 7.1 s)	5.7×10^{4}	176	0
^{6}He ($T\frac{1}{2}$ = 0.8 s)	1.4×10^{3}	0	0
^{8}Li ($T\frac{1}{2}$ = .84 s)	1.3×10^{2}	0	0
^{14}C ($T\frac{1}{2}$ = 5730 y)	23	23	23
Decay Heat (W/cm)	3.12×10^{3}	9.63	6.5×10^{-3}
^{16}N	3.11×10^{3}	9.62	0
^{6}He	12.9	~ 0	0
^{8}Li	4.76	~ 0	0
^{14}C	6.5×10^{-3}	6.5×10^{-3}	6.5×10^{-3}

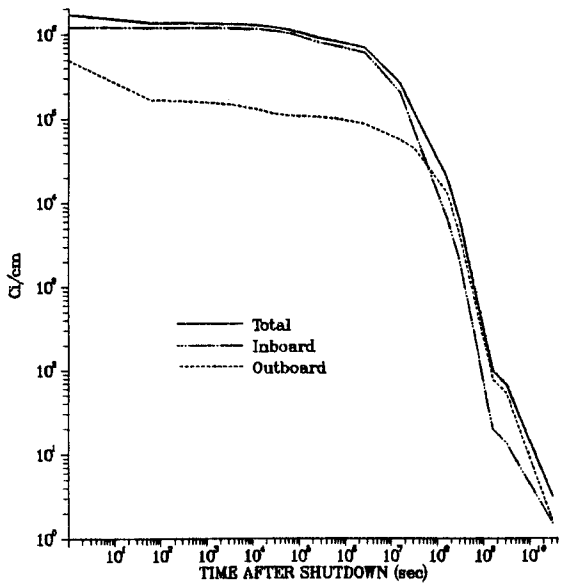

Fig. 3. TIBER's total activity.

contributions of the different zones, as well as the inventory of the radioactive isotopes involved, are given in percentage of the activity at any time. At shutdown, about 20% of the activity is attributed to ^{6}He which is generated in the Be zones of the outboard shield. This decays in a few seconds, and for about 3 years the tungsten isotopes (^{181}W, ^{185}W, ^{187}W) dominate. Long term activity is due to ^{55}Fe, ^{63}Ni, and ^{93}Mo.

The specific activity is concentrated in the inboard zones all the time. In the outboard shield, the total activity is dominated by the beryllium zones (O-3, O-4), and the specific activities of the double first walls (O-1, O-2) are about 2-3 orders of magnitude higher than those of the Be zones. With respect to the inboard shield the highest activation level is associated with the W-PCA zone I-3 for about 3 years,

Table 2. Total Radioactivity in TIBER (Ci/cm)

TIME	1) 0.0 s	2) 1.0 m	3) 1.0 d	4) 1.0 w	5) 1.0 mo	6) 6.0 mo	7) 1.0 y	8) 5.0 y	9) 10.0 y	10) 100.0 y
SYSTEM (TOTAL)	1.706e+06	1.365e+06	1.071e+06	8.239e+05	6.861e+05	2.585e+05	1.158e+05	2.004e+04	5.578e+03	6.561e+01
ISOTOPE/ZONE	%	%	%	%	%	%	%	%	%	%
HE--6*(BETA-)	19.82	0.00								
C--14*(BETA-)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
V--52*(BETA-)	0.46	0.47	0.00							
CR-51*(BETA+)	1.60	2.00	2.49	2.78	1.86	0.11	0.00			
MN-54*(BETA+)	0.87	1.09	1.38	1.77	2.01	3.76	5.51	1.09	0.06	0.00
MN-56*(BETA-)	3.74	4.66	0.01							
FE-55*(BETA+)	4.10	5.13	6.54	8.45	9.98	23.71	46.30	92.10	87.22	0.00
CO-57*(BETA+)	0.46	0.58	0.74	0.94	1.07	1.91	2.67	0.36	0.01	0.00
CO-58*(BETA+)	1.78	2.23	2.81	3.44	3.29	1.98	0.74	0.00		
CO-60*(BETA-)	0.13	0.16	0.21	0.27	0.32	0.80	1.66	5.66	10.50	0.01
NI-63*(BETA-)	0.01	0.01	0.01	0.02	0.02	0.05	0.11	0.61	2.12	91.54
NB-93M(IT)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	3.78
MO-93*(BETA+)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.06	4.41
TA182*(BETA-)	0.28	0.36	0.45	0.57	0.59	0.63	0.47	0.00		
W-181*(BETA+)	11.24	14.05	17.83	22.48	24.04	30.04	27.15	0.11	0.00	
W-185*(BETA-)	30.22	37.78	47.71	58.65	56.72	36.91	15.25	0.00		
W-187*(BETA-)	24.27	30.33	19.28	0.39	0.00					
TOTAL (BETA-)	79.41	74.28	67.94	60.02	57.70	38.41	17.50	6.28	12.63	91.65
TOTAL (BETA+)	20.21	25.27	31.91	39.93	42.30	61.59	82.50	93.72	87.35	4.57
TOTAL (IT)	0.38	0.45	0.16	0.05	0.00	0.00	0.00	0.00	0.02	3.78
Z O N E I-10	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.10
Z O N E I-9	1.82	2.28	2.17	1.82	1.76	1.23	0.60	0.06	0.06	0.13
Z O N E I-8	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.06
Z O N E I-7	14.36	17.95	18.13	16.90	16.55	12.79	7.66	1.35	1.34	1.28
Z O N E I-6	0.05	0.07	0.05	0.06	0.06	0.10	0.18	0.31	0.31	0.35
Z O N E I-5	32.18	40.21	43.23	44.62	44.46	38.88	27.73	6.61	6.55	2.66
Z O N E I-4	0.29	0.36	0.31	0.38	0.40	0.71	1.25	2.18	2.17	0.96
Z O N E I-3	19.07	23.82	23.29	20.66	20.56	18.20	13.17	3.22	3.20	1.50
Z O N E I-2	2.58	3.19	2.77	3.37	3.54	6.28	11.14	19.58	19.49	13.63
Z O N E I-1	0.78	0.00								
Z O N E O-1	2.49	3.08	2.76	3.39	3.57	6.42	11.43	20.11	19.96	9.14
Z O N E O-2	2.08	2.57	2.27	2.77	2.92	5.19	9.21	16.17	16.08	9.59
Z O N E O-3	23.15	5.06	4.07	4.92	5.08	8.52	14.84	25.74	25.99	42.79
Z O N E O-4	1.13	1.40	0.94	1.11	1.11	1.67	2.78	4.64	4.83	17.81

Table 3. Total Decay Heat in TIBER (W/cm)

TIME	1) 0.0 s	2) 1.0 m	3) 1.0 d	4) 1.0 w	5) 1.0 mo	6) 6.0 mo	7) 1.0 y	8) 5.0 y	9)10.0 y	10) 100.0 y
SYSTEM (TOTAL)	6.714e-03	3.529e-03	1.629e-03	7.496e-04	6.058e-04	2.092e-04	9.006e-05	1.943e-05	9.284e-06	8.496e-09
ISOTOPE/ZONE	%	%	%	%	%	%	%	%	%	%
HE--6*(BETA-)	46.92	0.00								
AL-28*(BETA-)	0.43	0.61	0.00							
V--52*(BETA-)	1.71	2.70	0.00							
CR-51*(BETA+)	0.09	0.17	0.36	0.67	0.46	0.03	0.00			
MN-54*(BETA+)	1.10	2.09	4.52	9.70	11.36	23.17	35.31	5.62	0.17	0.00
MN-56*(BETA-)	13.43	25.45	0.09	0.00						
FE-55*(BETA+)	0.04	0.08	0.16	0.35	0.43	1.12	2.27	3.62	2.00	0.00
CO-57*(BETA+)	0.09	0.17	0.37	0.79	0.92	1.81	2.63	0.29	0.01	
CO-58*(BETA+)	2.71	5.17	11.08	22.71	22.35	14.65	5.72	0.00		
CO-60*(BETA-)	0.51	0.96	2.09	4.53	5.56	15.23	33.10	90.38	97.66	0.72
NI-63*(BETA-)	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.08	0.15	83.80
NB-93M(IT)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.26
MO-93*(BETA+)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	7.62
TA182*(BETA-)	0.56	1.06	2.29	4.79	5.15	5.96	4.61	0.00		
W-185*(BETA-)	6.37	12.12	26.01	53.50	53.31	37.86	16.27	0.00		
W-187*(BETA-)	24.97	47.49	51.30	1.71	0.00					
TOTAL (BETA-)	95.59	91.62	82.95	65.66	64.47	59.22	54.06	90.46	97.81	85.69
TOTAL (BETA+)	4.38	8.31	17.04	34.33	35.53	40.78	45.94	9.54	2.19	9.05
TOTAL (IT)	0.04	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	5.26
Z O N E I-10	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.09
Z O N E I-9	1.12	2.12	2.64	1.63	1.56	1.12	0.52	0.06	0.07	0.20
Z O N E I-8	0.01	0.02	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.07
Z O N E I-7	7.64	14.52	18.52	13.76	13.29	9.87	5.08	1.57	1.59	1.99
Z O N E I-6	0.09	0.18	0.07	0.12	0.13	0.17	0.24	0.30	0.30	0.43
Z O N E I-5	14.08	26.73	34.95	32.16	31.38	24.70	15.03	7.72	7.83	3.67
Z O N E I-4	0.42	0.77	0.42	0.83	0.88	1.21	1.72	2.19	2.19	1.10
Z O N E I-3	11.06	21.02	25.79	16.76	16.25	13.63	8.81	3.73	3.78	1.62
Z O N E I-2	3.65	6.77	3.59	7.08	7.48	10.41	14.88	19.15	19.18	13.70
Z O N E I-1	1.84	0.00								
Z O N E O-1	3.31	6.12	3.52	6.96	7.37	10.43	15.11	19.78	19.84	9.27
Z O N E O-2	2.85	5.28	2.95	5.84	6.17	8.62	12.36	15.93	15.95	9.57
Z O N E O-3	51.67	12.26	5.89	11.61	12.15	15.85	21.41	25.03	24.86	41.18
Z O N E O-4	2.25	4.20	1.66	3.23	3.34	3.97	4.82	4.53	4.40	17.11

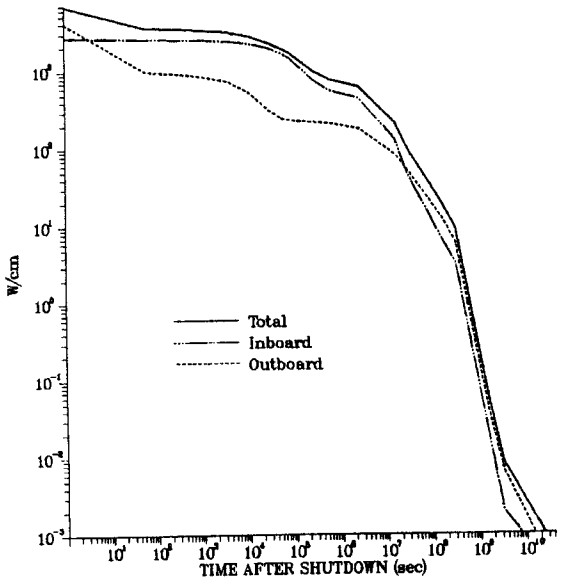

Fig. 4. TIBER's total afterheat.

after which the PCA first wall has the largest level of activation.

Decay Heat Generation

At shutdown and after 2.5 FPY of operation, there is about 2.7 MW of heat generated by the radioactive isotopes in both the inboard and the outboard shields. Table 3 summarizes the total decay heat at several times, and the percentage contributions of the different isotopes and shield zones to the total heat. Figure 4 shows the total decay heat per 1 cm length of TIBER as a function of time. As seen in this figure, the outboard shield, which has a large amount of beryllium, generates heat slightly more than that produced by the inboard shield. Once the ^{6}He ($T\frac{1}{2}$=.8 s, $^{9}Be(n,\alpha)^{6}He$), which generates ~ half of the total heat at shutdown, decays, the inboard shield starts to produce more heat than the outboard for about 1 year. In this period, the major contributing isotopes to the inboard shield and to the reactor, are the tungsten isotopes ^{187}W ($T\frac{1}{2}$=34 h), and ^{185}W ($T\frac{1}{2}$=75 d). Other isotopes that have significant contributions are ^{56}Mn, ^{58}Co, ^{60}Co, and ^{63}Ni. Because of the high volume fraction of the W alloy and PCA in the inboard shield, which is required for adequate protection of the inboard part of the magnet, the specific decay heat is higher in the inboard than in the outboard.

The decay heat mentioned so far and used in the LOFA/LOCA analysis [3] is generated by both β and γ decay. More than 50% of the total afterheat, most of the time, is associated with the γ decay. If the transport of the γ is considered, it is possible that the heat source could be smoothed, alleviating the problems encountered in the LOFA/LOCA analysis of the inboard shield.

BHP and Air Activation

The BHP is defined as the amount of air/water required to dilute the isotopes concentration in air/water to their maximum permissible concentration (MPC) defined by the NRC regulations in 10CFR20. Again, the inboard shield dominates the BHP-air for 1 year after shutdown. The isotope ^{185}W produces 40-66% of the BHP-air in this period. After 1 year, the isotopes ^{54}Mn, ^{60}Co, ^{55}Fe, and ^{63}Ni are the major contributing isotopes to the BHP.

Air activation is calculated in a 10 m thick air zone, at standard temperature and pressure, that follows the outboard shield. The air is assumed to be stagnant for the 2.5 FPY operation time. At shutdown, the activation level of the air in the first 1 m zone is 7.89×10^{-11} Ci/cc and is primarily due to ^{16}N. The ^{14}C activity at this time is 1.53×10^{-12} Ci/cc which is higher than its MPC in air (10^{-13} Ci/cc). Thus the air should be routinely exchanged.

Radwaste Classification

The radwastes of TIBER's structure have been evaluated according to 10CFR61. These regulations need to be updated to include the long lived isotopes produced by the hard neutron spectrum of the fusion reactors. Fetter[4], using 10CFR61 methodology, has calculated new waste disposal concentration limits (WDL) for many isotopes. There are large discrepancies in the limits of the common isotopes in both sets. For those isotopes, Fetter's limits, in general, are much higher. It is required that the NRC review the limits and include more isotopes. Both sets of limits have been used to calculate the WDR for the inboard and the outboard shields. Fortunately both sets classify both shields as Class C-LLW. The major contributing isotopes to the WDR are ^{63}Ni and ^{94}Nb, when 10CFR61 limits are used, and ^{94}Nb, ^{93}Mo, and ^{99}Tc, when Fetter's limits are used.

Conclusions

TIBER's radioactivity, afterheat, and BHP are dominated by the inboard shield as a result of the use of the W/PCA alloys in this shield. The afterheat in the inboard is large, and requires special design for safety considerations. A large fraction of this heat, however, is produced by the γ decay, which might help through the γ transport to alleviate the heat concentration. The activity of the $LiNO_3$, although the highest among Li salts considered, is negligible compared to the structure activity. The inboard/outboard shields radwastes are classified as Class C.

Acknowledgement

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