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ACTIVATION AND SAFETY ANALYSES FOR THE D-^{3}He FUELED TOKAMAK REACTOR APOLLO

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Abstract

Activation analysis was performed for the D-^{3}He fueled reactor Apollo. Three different steel alloys (PCA, 316 SS and the manganese steel Tenelon) were considered for use in the first wall, shield and vacuum vessel. The activity, decay heat and biological hazard potential (BHP) following shutdown were compared for the three alloys. PCA and 316 SS yield similar results. The total integrated decay heat generated over a period of one day after shutdown from the Tenelon is about a factor of two larger than that generated from PCA and 316 SS. This is still more than an order of magnitude lower than that obtained in a D-T fueled reactor. The results showed that after the full reactor lifetime, both PCA and type 316 SS do not qualify as class C low level waste (LLW), while Tenelon can be disposed of as class C LLW. The thermal response of the shield following a loss of coolant accident (LOCA) was determined using the different structural materials. Using the magnet as a heat sink it has been shown that the maximum first wall temperature two weeks after LOCA levels off close to 200°C even with Tenelon used as the structural material. The biological dose rate after shutdown at the back of the shield is excessive implying that all remote maintenance is needed. However, the dose rate at the back of the magnet allows for limited access for magnet maintenance.

Introduction

Apollo is a D-^{3}He fueled tokamak reactor which has a major radius of 7.43 m and an aspect ratio of 4[1]. The reactor is operated for 30 full power years and produces a net electric power of 1200 MW_e; the peak neutron wall loadings on the inboard and outboard sides of the midplane are 0.1 and 0.14 MW/m^2, respectively. The inboard shield thickness is 56.5 cm and the outboard shield thickness is 76.5 cm. The shield is made of steel and cooled with water.

Since the level of induced radioactivity in any fusion reactor depends on the type of alloy used as a structural material, three different steel alloys were chosen to study the impact of material selection on the level of induced radioactivity in Apollo. The first steel alloy used is 316 SS which is the primary candidate structural material for the International Thermonuclear Experimental Reactor (ITER). The two other steel alloys considered in this paper are PCA and the low activation austenitic steel Tenelon. Both are commonly used as structural materials in previous conceptual fusion reactor designs.

In this paper we present a comparison of radioactivity and its related quantities, i.e. the decay heat and the biological hazard potential (BHP), after shutdown for the three steel alloys in Apollo. Results from the activation calculations were used to evaluate the waste disposal ratings (WDR) for the different structural materials considered. Calculations to determine the biological dose rate after shutdown at the back of the shield and at the back of the magnet were performed. In addition, the decay heat results were used to determine the thermal response of the shield following a loss of coolant accident (LOCA).

Calculational Procedure

Calculations for a one-dimensional toroidal cylindrical geometry model were conducted using the DKR-ICF computer code [2] with activation cross sections taken from the ACTL [3] library, and for 30 full power years (FPY) of reactor operation. The neutron transmutation data is given in 46 group structure format. The decay and

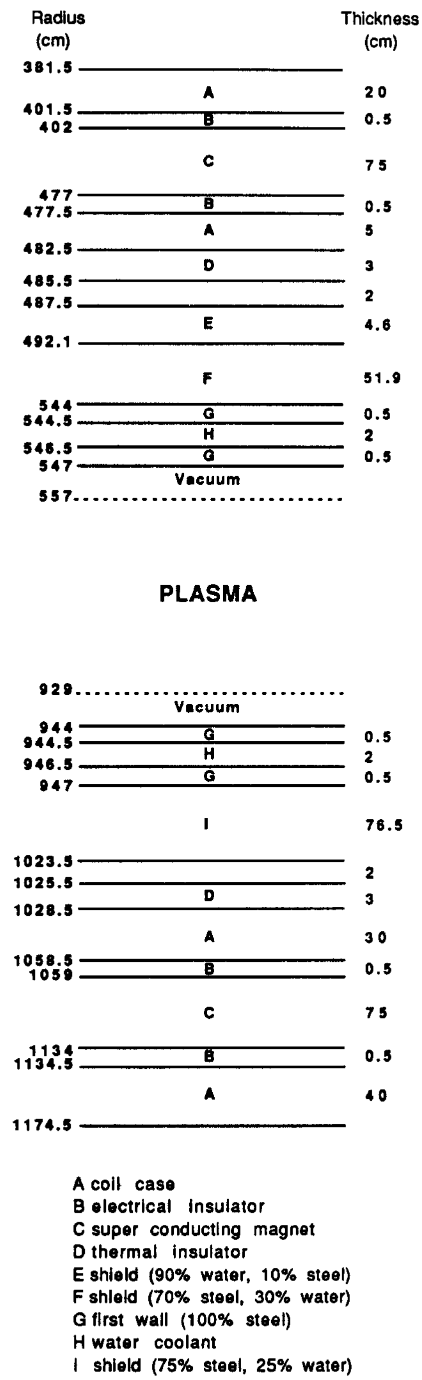

Figure 1. Radial build used in neutronics and activation calculations.

gamma source data is taken from the table of isotopes with the gamma source data being in 21 group structure format. The neutron flux used for activation calculations was generated by the one-dimensional discrete ordinates neutron transport code ONEDANT [4] using the ENDF/B-V cross section data. The radial build used in both of the neutronics and activation calculations is shown in Fig. 1. The activation results were utilized in the radwaste classification performed using the WDR [5] computer code. The gamma decay source file generated by the DKR-ICF code was used to calculate the biological dose rate using the DOSE [2] code. In addition, the computer code ATHENA [6] was used to determine the thermal response of the shield following a loss of coolant accident (LOCA) by utilizing the decay heat results. PCA, 316 SS and Tenelon were considered as structural materials. The composition of these materials is that presented in the Blanket Comparison and Selection Study (BCSS) report [7].

Results and Discussion

Activity, Decay Heat and Biological Hazard Potential (BHP)

The total activity in Apollo for the different steel alloys at shutdown is 438 MCi with PCA, 408 MCi with 316 SS and 939 MCi with Tenelon. In all three cases, the short-term activity after shutdown

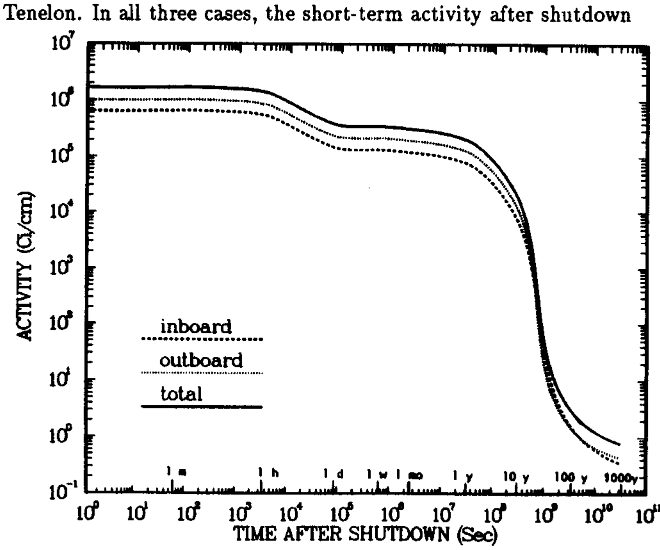

Figure 2. Activity per cm height at Apollo's midplane using Tenelon.

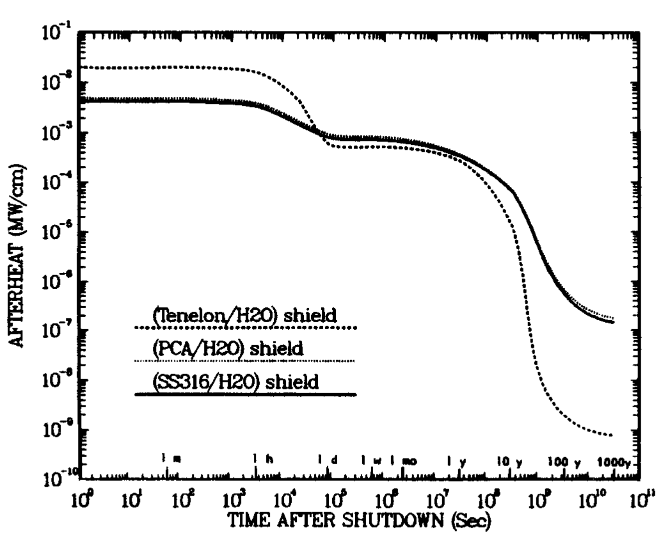

Figure 3. Comparison between decay heat generation for the different steel alloys used in Apollo.

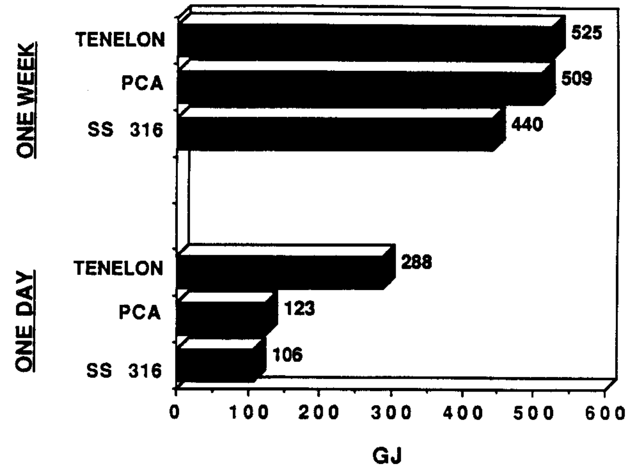

Figure 4. Integrated decay heat in Apollo.

is dominated by ^{55}Fe($T_{1/2}$ = 2.7 yr), ^{56}Mn($T_{1/2}$ = 2.6 hr), ^{51}Cr($T_{1/2}$ = 27.7 day) and ^{54}Mn($T_{1/2}$ = 313 day) with ^{56}Mn and ^{54}Mn being the most dominant isotopes in the case of Tenelon. In the period between 1 year and 10 years after shutdown, ^{55}Fe and ^{54}Mn in addition to ^{63}Ni($T_{1/2}$ = 100 yr) and ^{60}Co($T_{1/2}$ = 5.27 yr) represent the major contributors in all cases. Finally, the long-term activity comes from ^{59}Ni($T_{1/2}$ = 80,000 yr), ^{93m}Nb($T_{1/2}$ = 13.6 yr), ^{93}Mo($T_{1/2}$ = 3500 yr), ^{14}C($T_{1/2}$ = 5730 yr) and ^{63}Ni, where ^{14}C is the major contributor by far if Tenelon is used as a structural material. The total activity per cm height as a function of time following shutdown is shown in Fig. 2 for the case of Tenelon. The results for the two other alloys show a similar trend. The outboard activity is higher than the inboard activity at all times following reactor shutdown.

The decay heat generated in Apollo is almost dominated by the same isotopes that dominate the level of activity in the reactor after shutdown. If Tenelon is used as a structural material, as much as 96% of the afterheat generated at shutdown can be attributed to ^{56}Mn. A comparison between the total decay heat associated with different steel alloys is shown in Fig. 3. While both PCA and 316 SS produce a comparable amount of decay heat, Tenelon results in a larger decay heat in the first 8 hours following shutdown due to its high manganese content. Decay heat generated in Tenelon starts to drop as ^{56}Mn starts to decay. Both PCA and 316 SS generate significantly larger amounts of afterheat than Tenelon after about 3 years of reactor shutdown. If Tenelon is used, the integrated decay heat generated during the first day after shutdown in Apollo is more than twice the level generated if PCA or 316 SS is used. Nevertheless, Tenelon generates a comparable amount of decay heat within a week. Figure 4 shows the effect of using the different steel alloys on the total integrated decay heat in Apollo.

The biological hazard potential (BHP) associated with Tenelon structure is less than that with either PCA or 316 SS at all times following shutdown. In general, the results obtained for the BHP show similar variation with time after shutdown as the activity and decay heat. The total BHP at shutdown is 9.24 x 10^7 km^3 air with PCA and 9.21 x 10^7 km^3 with Tenelon or type 316 SS.

Radwaste Classification

The radwaste of Apollo's structure has been evaluated according to both 10CFR61 [8] and Fetter [9] waste disposal concentration limits (WDL). The different radionuclide specific activities calculated by the DKR-ICF code were used to calculate the waste disposal ratings after being normalized to the average inboard and outboard wall loadings of 0.065 and 0.095 MW/m^2, respectively. The waste disposal ratings for class C low level waste (LLW) are given in Table 1 for the three different structural materials. The waste disposal rating (WDR) is

Table 1. Class C Waste Disposal Rating for Apollo (No Compactness) 1 Year After Shutdown.

WDR	Tenelon/H_2O Shield		PCA/H_2O Shield		316 SS/H_2O Shield	
	NRC	Fetter	NRC	Fetter	NRC	Fetter
IB FW and Shield (no magnet)	0.034 (0.021 ^{94}Nb, 0.0118 ^{14}C)	0.0765–0.0797 (0.052 ^{108m}Ag, 0.021 ^{94}Nb)	9.577 (7.29 ^{94}Nb, 1.72 ^{63}Ni)	9.018–22.57 (7.29 ^{94}Nb, 1.5–15.04 ^{99}Tc)	3.231 (1.43 ^{63}Ni, 1.14 ^{94}Nb)	3.308–19.97 (1.14 ^{94}Nb, 1.85–18.52 ^{99}Tc)
OB FW and Shield (no magnet)	0.023 (0.015 ^{94}Nb, 0.0075 ^{14}C)	0.052–0.054 (0.035 ^{108m}Ag, 0.015 ^{94}Nb)	6.46 (5.04 ^{94}Nb, 1.06 ^{63}Ni)	6.28–16.2 (5.04 ^{94}Nb, 1.09–10.93 ^{99}Tc)	2.1 (0.887 ^{63}Ni, 0.79 ^{94}Nb)	2.35–14.54 (0.79 ^{94}Nb, 1.36–13.57 ^{99}Tc)
IB and OB First Wall and Shield	0.026 (0.017 ^{94}Nb, 0.009 ^{14}C)	0.059–0.061 (0.04 ^{108m}Ag, 0.017 ^{94}Nb)	7.346 (5.68 ^{94}Nb, 1.26 ^{63}Ni)	7.05–18 (5.68 ^{94}Nb, 1.22–12.16 ^{99}Tc)	2.42 (1.04 ^{63}Ni, 0.89 ^{94}Nb)	2.63–16.05 (0.89 ^{94}Nb, 1.49–14.89 ^{99}Tc)
IB + OB (FW, shield and magnet)	0.0815 (0.078 ^{94}Nb, 0.003 ^{14}C)	0.093–0.094 (0.078 ^{94}Nb, 0.014 ^{108m}Ag)	2.57 (2.01 ^{94}Nb, 0.42 ^{63}Ni)	2.47–6.18 (2.01 ^{94}Nb, 0.4–4.11 ^{99}Tc)	0.9 0.384 ^{94}Nb, 0.35 ^{63}Ni)	0.973–5.54 (0.38 ^{94}Nb, 0.51–5.07 ^{99}Tc)

defined [10] as the sum of the ratio of the concentration of a particular isotope to the maximum allowed concentration of that isotope taken over all isotopes. A WDR $\leq$ 1 implies that the radwaste qualifies for shallow land burial.

The results in the first three rows of the table are given separately for averaging the activities over the first wall and shield of the inboard, outboard and both inboard and outboard regions, respectively. In the fourth and last row, results are given for the waste disposal ratings for the case of disposing both the inboard and outboard regions together. The WDR range given corresponds to that provided by Fetter for the WDL of some of the radionuclides. Only Tenelon easily meets class C limits. With the exception of disposing the outboard region or the inboard and outboard regions of type 316 SS structure together, neither PCA nor 316 SS would qualify as class C waste. The major contributing radionuclides and their contributions are given in parenthesis for each case. In almost all cases, ^{94}Nb($T_{1/2}$ = 20,000 yr), which is produced from ^{93}Nb or ^{94}Mo, is the major contributor regardless of which WDL are used. In the case of PCA and 316 SS the other major contributor is ^{63}Ni($T_{1/2}$ = 100 yr) produced from ^{63}Cu if 10CFR61 limits are used, and ^{108m}Ag($T_{1/2}$ = 130 yr) produced from ^{107}Ag if Fetter limits are used. The secondary major contributors in the case of Tenelon are ^{14}C($T_{1/2}$ = 5730 yr) produced from ^{14}N and ^{17}O, and ^{99}Tc($T_{1/2}$ = 2.1 x 10^5 yr) produced from ^{98}Mo if the 10CFR61 and Fetter limits are used, respectively.

Biological Dose Rate

The biological dose rate has been calculated as a function of time following shutdown at the back of both the outboard shield and magnet for the three steel alloys. The results showed that the dose rate at the back of the shield is too high to allow hands-on maintenance. In all cases, the dose is dominated by ^{56}Mn($T_{1/2}$ = 2.6 hr) and ^{58}Co($T_{1/2}$ = 70.8 day) in the first day. ^{54}Mn($T_{1/2}$ = 313 day) and ^{60}Co($T_{1/2}$ = 5.27 yr) dominate the biological dose in the first few years following shutdown. Figure 5 shows a comparison between the different dose rates at the back of the outboard shield. Just as in the case of the decay heat (Fig. 3), the initial shape of the curve exhibits the same behavior. The dose rate at shutdown associated with

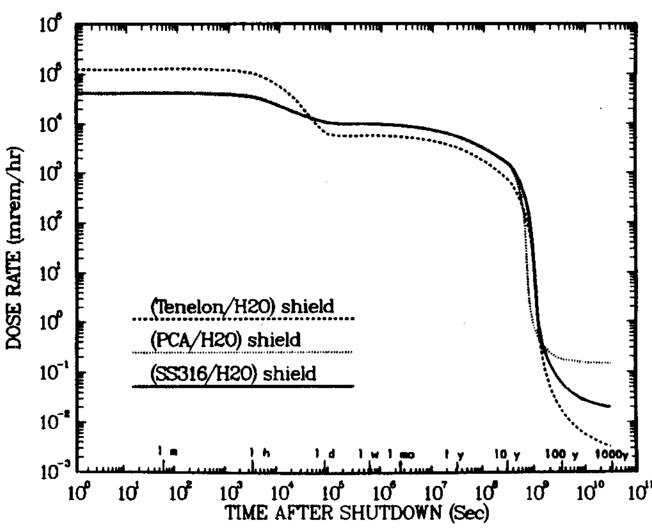

Figure 5. Comparison between dose rates at the back of the outboard shield.

the Tenelon structure is 3 times higher than that associated with either the PCA or 316 SS structures. The crossover point occurs after about 8 hours following shutdown, with both the PCA and 316 SS dose exceeding the Tenelon dose level thereafter. The large drop in the Tenelon dose rate at about 8 hours following shutdown is the result of the decay of ^{56}Mn. The calculated dose rates at the back of the magnet at shutdown are 6.51, 6.77 and 5.35 μrem/hr for PCA, 316 SS and Tenelon structures, respectively.

LOCA Analysis

The temperature history during a loss of coolant accident (LOCA) in Apollo was analyzed using a one-dimensional thermal hydraulics computer code ATHENA [6]. In the analysis, Apollo was modeled as six heat conducting slabs (first wall, shield and magnet in each region) separated by five cooling ducts. The inboard and outboard regions are solved interactively assuming that all of the coolant channels and plasma volume are filled with air at atmospheric pressure. During the LOCA analysis, the coolant is assumed to be lost instantly and the plasma is assumed to stay on for 10 seconds. The initial operating temperature ranges from a high of 500°C at the first wall to about 400°C at the back of the shield. The inner legs of the superconducting TF coils are assumed to have an initial temperature of 4.2 K allowing the coils to act as a heat sink. Figure 6 shows the temperature histories for the first wall and shield in both of the inboard and outboard sides of the reactor for the case of Tenelon. In the first few hours following LOCA, one can notice that even though no sizable increase in the first wall temperature in both the inboard and outboard regions of Apollo have taken place, both the inboard and outboard shield temperatures start to rise slowly and the inboard shield temperature reaches a maximum increase of about 80°C within the first 8 hours following LOCA. This short-term increase in the shield temperature is due to the large amount of decay heat generated by ^{56}Mn which has a half life of 2.6 hours. After one week, the average temperature ranges from a high of 200°C at the first wall of the inboard region to 150°C at the outboard shield. A comparison between the first wall temperature as a function of time for the cases of PCA and Tenelon is shown in Fig. 7. In the case of Tenelon, the first wall will exhibit a higher temperature than the PCA first wall up to five days after the plasma is turned off. The results show that two weeks after LOCA, the maximum inboard first wall temperatures are 468, 445 and 423 K for PCA, 316 SS and Tenelon structures, respectively.

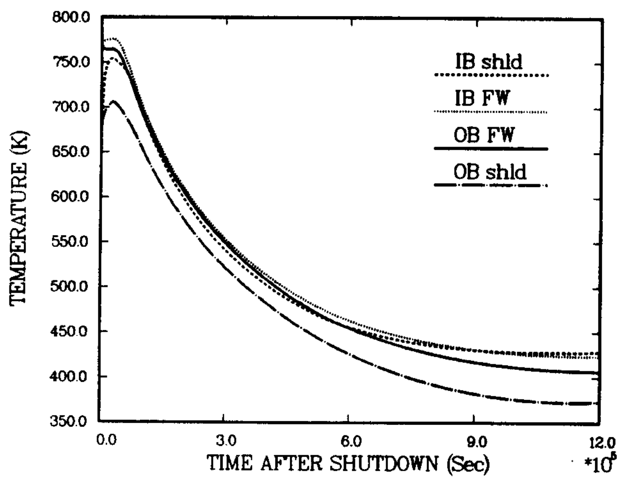

Figure 6. Temperature histories for the case of Tenelon.

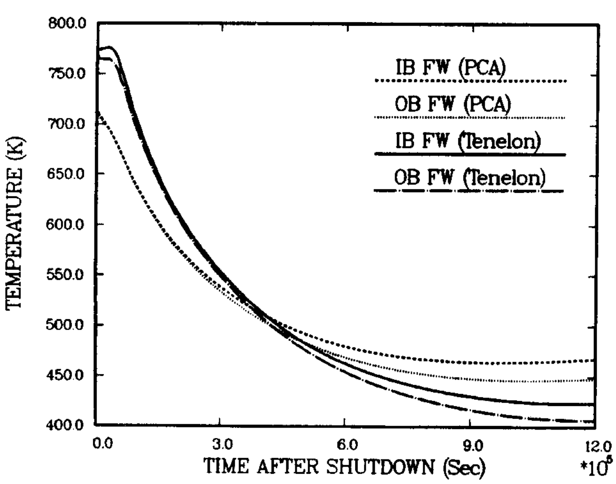

Figure 7. Comparison between the first wall temperature histories for the cases of PCA and Tenelon.

Conclusions

The short-term levels of radioactivity, decay heat and biological hazard potential (BHP) associated with the use of Tenelon as a structural material in Apollo are comparatively higher than those found if PCA or type 316 SS is used instead. However, an Apollo structure made of Tenelon would easily qualify as class C low level waste (LLW) and hence would meet the U.S. requirements for shallow land burial. The high level of the biological dose rate following shutdown at the back of the outboard shield will only allow for remote maintenance. Assuming heat dissipation to the TF magnets only, all of the three steel alloys considered can withstand a loss of coolant accident (LOCA), with the maximum first wall temperature leveling off at about 200°C in the two weeks following LOCA.

Acknowledgments

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