Safety and Environmental Aspects of the Apollo-L2 D-^{3}He Reactor

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September 1991

UWFDM-860

Presented at the 14th IEEE/NPSS Symposium on Fusion Engineering, 30 September – 3 October 1991, San Diego CA; published in IEEE 91CH3035-3 (1992) 704.

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Abstract

Apollo-L2 is a D-^{3}He fueled tokamak reactor design that utilizes direct conversion. The reactor shield is made of steel and cooled with water. Three different austenitic steel alloys (PCA, 316 SS and Tenelon) were chosen to study the impact of material selection on the environmental and safety attractiveness of the reactor. The thermal response of the different shields following a loss of coolant accident (LOCA) was determined up to two weeks after an unscheduled shutdown of the reactor. The Tenelon structure encountered the highest temperature increase following the accident. The maximum temperature a Tenelon first wall reaches is 500°C. The nickel-stabilized steel structures (PCA and 316 SS) result in the highest off-site dose due to its high radioactive cobalt content. ^{58}Co and ^{60}Co are the major contributors to the calculated dose. The low temperature of the structure during a LOCA results in the release of a very small fraction of the radioactive inventory at the onset of an accident. Hence, the Apollo-L2 design achieves the inherent safety criteria with respect to activation products. The radwaste of the reactor structure was evaluated according to both 10CFR61 and Fetter waste disposal concentration limits (WDL) for each of the three steel alloys selected. At the end of the reactor lifetime only the PCA structure would not qualify as a low level waste (LLW). Tenelon can be disposed of as Class A low level waste if the 10CFR61 waste disposal limits are used.

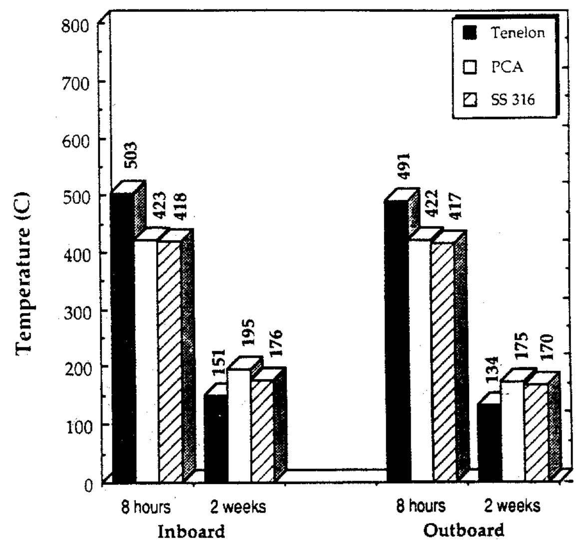

Figure 1. The first wall temperature of Apollo-L2 following a LOCA.

Introduction

Safety analysis has been performed for Apollo-L2 to identify the possible safety and environmental advantages of using the D-^{3}He fuel cycle. Apollo-L2 is a tokamak reactor design that utilizes direct conversion. It produces 1200 MWe of net electric power leading to peak neutron wall loadings of 0.1 and 0.14 MW/m^2 on the inboard and outboard sides of the reactor midplane, respectively. The reactor has an austenitic steel water cooled shield. The first wall thickness is 1 cm and is made of steel. The inboard shield consists of 2 layers. The first layer is 51.9 cm thick and consists of 70% steel and 30% water. The second layer is 4.6 cm thick and consists of 10% steel and 90% water. The outboard shield is made of only one layer of steel which is 76.5 cm thick consisting of 75% steel and 25% water.

The options of using the two nickel-stabilized (PCA and 316 SS), and the manganese-stabilized (Tenelon) austenitic steels have been assessed. The lower nickel content in Tenelon reduces the inventory of the cobalt isotopes, improves waste management and reduces the accidental off-site dose. Meanwhile, the higher manganese content results in a higher decay heat and hence higher temperature increase in case of a loss of coolant accident (LOCA). The decay heat generated was utilized to calculate the temperature rise in the first wall and shield during the first 2 weeks following the LOCA. The off-site doses have been calculated for the total radioactive inventory generated in the reactor and as a function of its structure temperature following the loss of coolant. The radioactive inventories generated by the three different steel alloys were used to calculate the waste disposal ratings (WDR) at the end of the reactor lifetime.

Calculational Procedure

A one-dimensional toroidal cylindrical geometry model that includes both the inboard and outboard first wall, shield and magnets has been used in the neutronics and activation calculations. The one-dimensional discrete ordinates neutron-transport code ONEDANT [1] along with the ENDF/B-V cross section data files were used to generate the neutron flux in the different reactor zones. The neutron flux was then used in several activation calculations performed using the DKR-ICF [2] code with activation cross sections taken from the ACTL [3] library. The reactor was assumed to operate for 30 full power years (FPY) which corresponds to 40 years of operation at 75% availability. The decay heat results were used to determine the thermal response of the shield following a loss of coolant accident using the ATHENA [4] code.The activation results were utilized in the radwaste classification and the off-site dose calculations performed according to the worst case weather conditions used in the FUSCRAC3 code [5]. The elemental composition of PCA, 316 SS and Tenelon alloys used in this paper are those reported in the BCSS [6] study.

Thermal Response to a LOCA

The first wall and shield of the inboard and outboard regions have been analyzed with respect to loss of coolant accidents. The plasma was assumed to stay on for 10 seconds following the loss of cooling in the reactor shield. The code ATHENA (a version of RELAP5) was used in the analysis. The inboard and outboard sides are solved interactively assuming that all of the coolant channels are filled with air at atmospheric pressure. 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. The analysis was performed for the three steel alloys (PCA, 316 SS and Tenelon).

Figures 1 and 2 give the temperature histories in the inboard and outboard sides of the reactor for the first wall and shield, respectively. As shown in the figures, a structure made of Tenelon will have the highest thermal response following a LOCA within the first 8 hours. That initial increase in the temperature is caused by the large amount of decay heat generated by ^{56}Mn which has a half-life of 2.578 hours. After two weeks, a PCA structure results in the highest temperature and a Tenelon structure

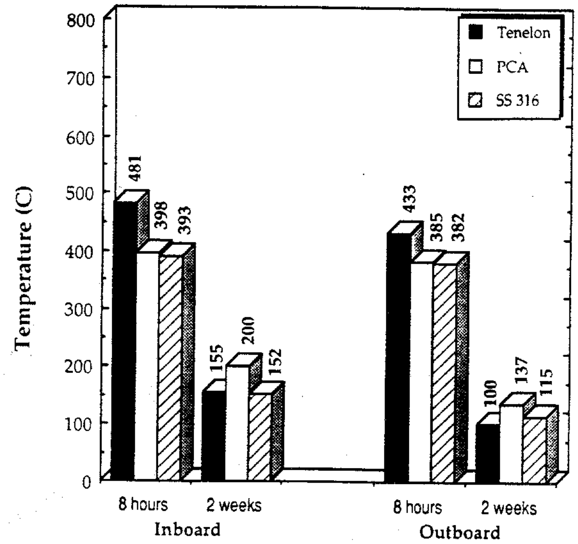

Figure 2. The shield temperature of Apollo-L2 following a LOCA.

results in the lowest temperature. This analysis showed that the highest temperature an Apollo-L2 structure made of austenitic steel would reach as a result of a LOCA is about 500°C.

Activation Product Mobilization

The maximum temperature reached by the activation products generated in the reactor structure is determined by the amount of energy available at the onset of an accident. The highest temperature the structure would reach determines the release fraction of these radioactive products. Since the Apollo-L2 water cooled steel structure concept has no important chemical reaction concerns, the decay heat generated in the structure during a loss of coolant accident has been identified as the major source of energy available to mobilize the radioactive inventory. The low temperature of the shield following a LOCA indicates that only a small fraction of the inventory can be released following such an accident.

The release characteristics used in calculating the off-site doses following the accidental release of the activation products represent the worst case conditions. Based on these assumptions it is possible to calculate the potential off-site doses produced by the release of 100% of the radioactive inventory for each of the 3 steel alloys. As shown in Table 1, both the nickel-stabilized austenitic steel alloys, PCA and 316 SS, have higher potential for off-site doses if their radioactive inventories were released than the manganese-stabilized austenitic steel alloy Tenelon. The key element for PCA and 316 SS is cobalt. ^{58}Co and ^{60}Co produced from nickel and cobalt in the steel contribute about 60% of the potential off-site dose. The PCA and 316 SS compositions used here contain 16% and 13.2% of nickel, respectively. The rest of the dose is dominated by the manganese isotopes. The key element for Tenelon is manganese. ^{54}Mn and ^{56}Mn produced from iron and manganese in Tenelon produce about 85% of the potential dose. The Tenelon composition used in this analysis contains 15% manganese.

Since mobilizing all of the radioactive products is quite unlikely, off-site dose calculations were done based on the experimental volatility rates [7] of the different radioactive nuclides in the structure as a function of the shield temperature during a LOCA. A summary of the results is shown in Table 2. Even though the highest temperature the structure would reach is less than 500°C the volatility rates used in this paper were those given at 600°C and 800°C for the nickel-stabilized and manganese-stabilized austenitic steel alloys in dry air, respectively. To estimate the release fractions for each radioisotope, we assumed a 10 hour LOCA in which the 1 hour release rates are used for the full 10 hours to account for any possible loss of oxide protection. Another conservative assumption made in the calculations was to assume an average sheet thickness of 5

Table 1. Potential Off-Site Doses from 100% Release.

	PCA	316 SS	Tenelon
Prompt Dose at 1 km (Rem)			
WB	5.25e4	4.49e4	4.96e4
BM	6.08e4	5.21e4	5.54e4
Lung	1.61e5	1.37e5	1.05e5
LLI	4.46e4	3.83e4	3.82e4
WB Early Dose (Rem)			
At 1 km	6.54e4	5.67e4	5.38e4
At 10 km	3.52e4	3.06e4	2.45e4
WB Chronic Dose At 1 km (Rem)			
Inh + Grd	1.49e6	1.38e6	6.90e5
Ingestion	1.32e6	1.19e6	9.48e5
Total	2.81e6	2.57e6	1.64e6
WB Chronic Dose At 10 km (Rem)			
Inh + Grd	8.30e5	7.66e5	3.75e5
Ingestion	7.38e5	6.64e5	5.26e5
Total	1.57e6	1.43e6	9.01e5
Cancers			
Sum Organs	2.65e5	1.42e5	8.72e4
WB	1.59e5	1.32e5	9.36e4
Population Dose (Man-Rem)			
WB	1.00e9	8.36e8	5.92e8

mm which is the thickness of the reactor first wall. Also, since no cobalt was detected in the PCA volatility test, cobalt volatility was included in the dose calculations by using its volatility rate detected from a ferritic steel HT-9 test in dry air. As shown in the table a structure made of PCA would result in the highest off-site dose. However none of the steel alloys used produce a whole body early dose greater than 14 rem which is far below the 200 rem prompt dose limit adopted by the ESECOM [8] committee as a threshold for avoidance of early fatalities in case of accidental release of the radioactive inventory. The elimination of the nickel element in Tenelon resulted in the elimination of the accident hazard of the cobalt isotopes. Both PCA and 316 SS off-site doses are dominated by ^{58}Co and ^{60}Co. If the cobalt volatility is not included in the analysis, both PCA and 316 SS would only produce an off-site dose which is in the same order of that produced by Tenelon ($\sim$30 mrem). In such case, the off-site dose in each of the 3 alloys is dominated by ^{54}Mn and ^{56}Mn.

To account for any other accident scenario we have not considered in this paper, another set of off-site dose calculations has been performed and presented in Table 3. In producing the table we used the same assumptions used in producing Table 2 except for the volatility data. The maximum reported data at 1300°C and 1200°C for the nickel-stabilized and manganese-stabilized austenitic steels were used, respectively. PCA and 316 SS still result in higher off-site doses than Tenelon. However, even at such high temperatures none of the steel alloys resulted in a whole body early dose in excess of 66 rem. The two manganese isotopes ^{54}Mn and ^{56}Mn produce about two thirds the dose in either PCA or 316 SS and almost 100% of the dose in Tenelon.

Tritium Inventory

A small amount of tritium is produced in D-^{3}He reactors due to the D-D reaction. In Apollo-L2 only 50% of the tritium produced is assumed to be burned in the plasma. The amount of tritium exhausted from the plasma chamber is 20.7 grams per full power day of operation. The tritium is removed from the exhaust fuel system through the vacuum pumps and resides for only a few hours in the reactor tritium processing system at any

Table 2. Off-Site Doses Using Experimental Volatility Data at 600°C.

	PCA	316 SS	Tenelon
Prompt Dose at 1 km (Rem)			
WB	10.1	8.79	2.77e-2
BM	11.8	10.2	3.11e-2
Lung	33.7	30	5.90e-2
LLI	8.42	7.35	2.36e-2
WB Early Dose (Rem)			
At 1 km	13.2	11.6	2.91e-2
At 10 km	0.91	0.81	1.67e-3
WB Chronic Dose At 1 km (Rem)			
Inh + Grd	373	348	2.68e-1
Ingestion	193	181	5.08e-1
Total	566	529	7.76e-1
WB Chronic Dose At 10 km (Rem)			
Inh + Grd	25.9	24.2	1.81e-2
Ingestion	13.4	12.6	3.52e-2
Total	39.3	36.8	5.33e-2
Cancers			
Sum Organs	26.4	24.5	4.445e-2
WB	20.1	18.9	4.556e-2
Population Dose (Man-Rem)			
WB	1.28e5	1.2e5	288.2

Table 3. Off-Site Doses Using Experimental Volatility Data at 1300°C.

	PCA	316 SS	Tenelon
Prompt Dose at 1 km (Rem)			
WB	58.2	60.1	16
BM	68.3	70.4	17.8
Lung	138	139	32
LLI	65.3	66.5	12.2
WB Early Dose (Rem)			
At 1 km	63.7	65.6	16.9
At 10 km	4.02	4.14	0.95
WB Chronic Dose At 1 km (Rem)			
Inh + Grd	913	939	191
Ingestion	855	896	253
Total	1768	1835	444
WB Chronic Dose At 10 km (Rem)			
Inh + Grd	62.8	64.6	12.9
Ingestion	59.3	62.2	17.6
Total	122.1	126.8	30.5
Cancers			
Sum Organs	106.2	108.6	21.1
WB	71.9	74.2	22
Population Dose (Man-Rem)			
WB	4.55e5	4.7e5	1.39e5

time during operation. The tritium can be stored in uranium getter beds where it decays to ^{3}He. In this case the steady state inventory of the stored tritium is estimated to be 134 kg.

To avoid the safety implications of tritium handling one might consider the option of burning 100% of the tritium produced in the plasma chamber. Burning all the tritium in the plasma results in doubling the number of 14.1 MeV neutrons and hence allowing more high energy threshold reactions which consequently produce more radioactive nuclides. Since intermediate and long term activities in the Apollo-L2 shield are dominated by radionuclides produced by (n,2n) and (n,p) reactions, such activities will approximately double as a result of burning all the tritium in the plasma. However, this increase in activity should not change the conclusions reached regarding the waste disposal rating of the reactor shield as most of the radionuclides that dominate the WDR are produced by (n,γ) reactions. Similarly the thermal response of the shield following a LOCA is not expected to change significantly as the decay heat generated in the first few hours following the accident is dominated by short-lived nuclides such as ^{56}Mn.

Safety Assurance Level

According to the ESECOM definition of level of safety assurance (LSA), an Apollo-L2 austenitic steel structure could qualify for LSA = 1. This LSA is achieved on the basis of inventory due to the fact that the highest temperature the structure would reach following a LOCA ranges only between 400°C and 500°C. The analysis shown in the previous section showed that the highest off-site early dose ranges from 14 to 66 rem for a nickel-stabilized austenitic steel structure at 600°C and 1300°C, respectively. This dose value is far below the 200 rem value recommended by the ESECOM committee as a threshold for avoidance of early fatalities. The dose produced by a Tenelon structure would be only 30 mrem (at 800°C) which is far below the 5 rem level where evacuation plans need to be considered. Since austenitic steel in general is fairly resistant to oxidation below 600°C, it is fair to assume that the highest possible mobilization rates of the activation products are the ones used in this analysis.

Waste Disposal Rating (WDR)

The specific activities calculated for the different radioactive nuclides have been used with waste disposal concentration limits (WDL) to evaluate the radwaste of the shield and magnet of Apollo-L2. Both the 10CFR61 limits [9] published in the U.S. Code of Federal Regulations and the limits calculated by Fetter [10] were used in the calculations. Since radiation damage effects will greatly be reduced in a D-^{3}He environment, the calculations were made considering that the first wall, shield and magnet will last for the full life of the reactor (30 FPY). The use of only one first wall and shield assembly for the full life of the reactor has the advantage of reducing the total amount of radioactive waste to be disposed.

The waste disposal ratings for Class A and Class C low level waste (LLW) are shown in Table 4. Two sets of results are presented in the table. The first set gives the waste disposal ratings for Class A and Class C waste for each of the three steel alloys and with the activities being averaged over the total volume of the first wall and shield of both the inboard and outboard regions of the reactor. The second set gives the waste disposal ratings with the activities being averaged over the total volume of the inboard and outboard regions which include the first wall, shield and magnet. The 10CFR61 Class A WDR values are given after waiting periods of 15 and 10 years if only the first wall and shield or the first wall, shield and magnet are disposed together, respectively. These waiting periods are required to allow for the specific activity of the short-lived nuclides ($T_{1/2} \leq 5$ years) to drop below 7000 Ci/m^3. On the other hand, the Class C values were calculated after only one year cooling period for both the 10CFR61 and Fetter limits.

Only a Tenelon structure would qualify as Class A LLW. If Class C limits are considered then 316 SS would qualify for shallow land burial only if the first wall, shield and magnet are disposed of together. ^{63}Ni($T_{1/2} = 100$ yr) produced from ^{63}Cu and ^{94}Nb($T_{1/2} = 20,000$ yr) produced from ^{93}Nb and ^{94}Mo are the major contributors to the waste disposal ratings of PCA or 316 SS alloy if the 10CFR61 limits are used. However, if the Fetter limits are used, ^{99}Tc($T_{1/2} = 2.1\text{x}10^5$ yr) produced from ^{98}Mo, in addition to ^{94}Nb are the dominant contributors to the WDR. In the case of a Tenelon structure, WDR is dominated by ^{94}Nb, ^{14}C($T_{1/2} =$

Table 4. Waste Disposal Rating (WDR) for Apollo-L2 Structure.

WDR	PCA	316SS	Tenelon
Shield			
Class A (10CFR61 limits)	295 (232 ^{63}Ni, 58 ^{94}Nb)	206 (192 ^{63}Ni, 9 ^{94}Nb)	0.4 (0.17 ^{94}Nb, 0.09^{14}C)
Class C (10CFR61 limits)	7.5 (5.8 ^{94}Nb, 1.3 ^{63}Ni)	2.47 (1.06 ^{63}Ni, 0.91 ^{94}Nb)	0.027 (0.017 ^{94}Nb, 0.01 ^{14}C)
Class C (Fetter)	7.2 (5.8 ^{94}Nb, 1.24 ^{99}Tc)	2.68 (1.53 ^{99}Tc, 0.91 ^{94}Nb)	0.06 (0.04 ^{108m}Ag, 0.017 ^{94}Nb)
Shield and Magnet			
Class A (10CFR61 limits)	102 (80.5 ^{63}Ni, 20.2 ^{94}Nb)	72.5 (66.8 ^{63}Ni, 3.83^{94}Nb)	0.85 (0.76 ^{94}Nb, 0.04 ^{63}Ni)
Class C (10CFR61 limits)	2.59 (2.02 ^{94}Nb, 0.43 ^{63}Ni)	0.91 (0.38 ^{94}Nb, 0.36 ^{63}Ni)	0.079 (0.076 ^{94}Nb, 0.003 ^{14}C)
Class C (Fetter)	2.49 (2.02 ^{94}Nb, 0.42 ^{99}Tc)	0.979 (0.51 ^{99}Tc, 0.38 ^{94}Nb)	0.09 (0.076 ^{94}Nb, 0.014 ^{108m}Ag)

5730 yr) produced from ^{14}N and ^{17}O, and ^{108m}Ag($T_{1/2}$ = 130 yr) produced from ^{107}Ag.

Summary

An Apollo-L2 Tenelon structure would qualify for Class A low level waste (LLW) and hence meet the U.S. requirements for shallow land burial. Assuming heat conduction to the magnets, the highest temperature an austenitic steel structure would reach following a loss of coolant accident is less than 500°C. However, conservative estimates for the early off-site dose were calculated based on experimental data for the volatilization of austenitic steel in dry air at temperatures ranging from 600°C and 1300°C. At 600°C, PCA and 316 SS would result in a whole-body early off-site dose less than 14 rem. The dose released from the Tenelon structure is about 30 mrem requiring no public evacuation plans. The Apollo-L2 steel structure could qualify for a level of safety assurance (LSA) of one.

Acknowledgement

Support provided by Bechtel National Inc., Grainger Electric Corp., Grumman Corp., Kernforschungsanlage Jülich, and the Wisconsin Electric Utilities Research Foundation.

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