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# Activation and Waste Disposal of the ARIES-II Tokamak Fusion Power Reactor

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## ABSTRACT

A detailed activation analysis has been performed for the tokamak fusion power reactor ARIES-II. The reactor uses vanadium alloy as a structural material and liquid lithium as a coolant and tritium breeder. The total activity produced in the reactor at shutdown is 3848 MCi and drops to only 59 MCi during the first year following shutdown. Calculations of the decay heat showed that it is 53 MW at shutdown and it takes a relatively short time ( $< 1$  day) to decay by about a factor of 10. One week after shutdown, the values of the integrated decay heat generated in the structure are 548 and 1298 GJ for the reactor inboard and outboard regions, respectively. This heat represents less than 2% of the reactor thermal power and hence does not present a safety hazard. The biological hazard potential was calculated according to the NRC regulations specified in 10CFR20. The total BHP at shutdown is  $388 \times 10^6$  m<sup>3</sup> air. The radwaste classification of ARIES-II structure has been evaluated according to both the NRC 10CFR61 and Fetter waste disposal concentration limits. Except for the reactor outboard blanket which would qualify as Class A low level waste, the rest of the reactor structure would only qualify for Class C rating. The outboard blanket has a Class A rating value of 0.95 which is based on allowing it to cool down for about 10 years following the end of the reactor lifetime.

## I. INTRODUCTION

Activation analysis has been performed to identify the possible safety, environmental and radwaste advantages of ARIES-II. The reactor has a vanadium (V-5Cr-5Ti) blanket which utilizes lithium as both the coolant and breeder [1]. The total blanket and shield thickness are 112 and 157 cm, respectively. The blanket is 20 cm thick at the inboard and 50 cm thick at the outboard. The shield is composed of layers of low activation austenitic steel (Tenelon) and B<sub>4</sub>C supported by vanadium structure and also cooled with Li. The reactor is assumed to operate continuously for 30 full power years and produces a net electric power of 1000 MW<sub>e</sub>. Several activation-related issues for the reactor structure have been examined. The activity, decay heat and biological hazard potential (BHP) have been calculated for up to 1000 years following shutdown. Off-site doses caused by the release of 100% of radioactive inventory are also calculated. Evaluation of the structure activity and biological hazard potential are needed to calculate the potential effects of radioactive inventory release in the event of an accident. In addition, results of the

decay heat calculation are essential to examine the thermal response of the reactor shield following a loss of coolant accident (LOCA). Another issue that have been examined in this analysis is the waste disposal rating (WDR) of the reactor structure at the end of its lifetime. The waste disposal rating is needed to determine if the structure would satisfy the regulations criteria for shallow land burial as a low level waste (LLW).

## II. 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. The neutron transmutation data used is in a 46 group structure format. The decay and gamma source data is taken from the table of isotopes [4] with the gamma source data being in 21 group structure format. The reactor is assumed to operate continuously for 30 full power years (FPY) which corresponds to 40 years of operation at 75% availability. While the reactor blanket was assumed to be replaced every three full power years, the shield was assumed to stay in place for the duration of the reactor lifetime. While assuming continuous operation does not affect the calculated activities for radionuclides with half-lives much less than the shortest period of continuous operation or much greater than the reactor lifetime, the radioactive inventory of radionuclides with intermediate half-lives is overestimated by the inverse of the reactor availability [5]. Hence, our results for the radioactive inventory could be up to 33% conservative.

The neutron flux used for the activation calculations was generated by the one-dimensional discrete ordinates neutron transport code ONEDANT [6] using the ENDF/B-V cross section data. The analysis uses a P<sub>3</sub> approximation for the scattering cross sections and S<sub>8</sub> angular quadrature set. The peak neutron wall loadings used were 3.4 and 5.75 MW/m<sup>2</sup> for the inboard and the outboard regions, respectively. The structure activation results were utilized in the radwaste classification. The structure activation and decay heat results were utilized in determining the off-site doses and thermal response of the shield following a loss of coolant accident (LOCA), respectively [7]. The activation results have been also utilized in off-site dose calculations performed by the FUSCRAC3 [8] code. The off-site doses are produced by the accidental release of the total radioactive inventory from the reactor containment building assuming the worst case weather conditions.

### III. STRUCTURE ACTIVITY, DECAY HEAT AND BIOLOGICAL HAZARD POTENTIAL (BHP)

The total activities in the ARIES-II inboard and outboard regions at shutdown are 1203 MCi and 2645 MCi, respectively. Since the outboard region volume is more than three times the inboard volume and the neutron wall loading on the outboard is about 70% higher than its value in the inboard region, the outboard activity dominates the total activity in the reactor at all times following shutdown.

The shield's short-term activity after shutdown ( $\leq 1$  day) is dominated by  $^{51}\text{Cr}$  ( $T_{1/2} = 27.7$  day),  $^{54}\text{Mn}$  ( $T_{1/2} = 312.2$  day),  $^{56}\text{Mn}$  ( $T_{1/2} = 2.6$  hr) and  $^{187}\text{W}$  ( $T_{1/2} = 23.9$  hr). On the other hand, the blanket's short-term activity (at the end of its lifetime) is dominated by  $^{48}\text{Sc}$  ( $T_{1/2} = 43.7$  hr),  $^{51}\text{Cr}$ ,  $^{47}\text{Sc}$  ( $T_{1/2} = 3.349$  day) and  $^{45}\text{Ca}$  ( $T_{1/2} = 162.7$  day). In the period between 1 day and 1 year after shutdown,  $^{54}\text{Mn}$  and  $^{60}\text{Co}$  ( $T_{1/2} = 5.27$  yr) dominate the activity induced in the shield. During the same period of time, the blanket's activity is dominated by  $^{49}\text{V}$  ( $T_{1/2} = 337$  day),  $^{45}\text{Ca}$  and  $^{46}\text{Sc}$  ( $T_{1/2} = 83.81$  day). Finally, the long-term activities induced in both the shield and blanket come from the steel components and are dominated by  $^{14}\text{C}$  ( $T_{1/2} = 5730$  yr),  $^{93\text{m}}\text{Nb}$  ( $T_{1/2} = 16.1$  yr),  $^{94}\text{Nb}$  ( $T_{1/2} = 2 \times 10^4$  yr) and  $^{93}\text{Mo}$  ( $T_{1/2} = 3.5 \times 10^3$  yr). Fig. 1 shows the total activity induced in the different regions of ARIES-II as a function of time following shutdown. The total structure activity (inboard plus outboard) drops to 396 and 59 MCi in one day and one year following shutdown, respectively.

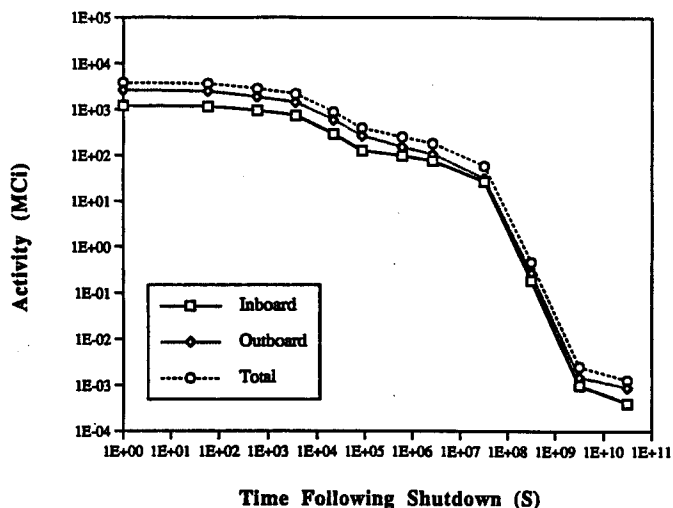


Fig. 1. Activity induced in ARIES-II structure.

The temporal variation of decay heat after shutdown is shown in Fig. 2. The decay heat generated in ARIES-II is almost dominated by the same isotopes that dominate the level of activity in the reactor after shutdown.  $^{56}\text{Mn}$  and  $^{52}\text{V}$  ( $T_{1/2} = 3.76$  min) produce most of the decay heat generated in the shield within the first 8 hours. Within the first year after shutdown,  $^{56}\text{Mn}$  and  $^{60}\text{Co}$  are the major sources of decay

heat. The long-term decay heat is governed by the decay of  $^{94}\text{Nb}$  and  $^{108\text{m}}\text{Ag}$  ( $T_{1/2} = 130$  yr). In the mean time, the short-term decay heat generated in the blanket is due to  $^{48}\text{Sc}$  and  $^{52}\text{V}$ .  $^{46}\text{Sc}$  and  $^{49}\text{V}$  are the dominant nuclides up to one year following the blanket replacement or the reactor shutdown.  $^{94}\text{Nb}$  and  $^{14}\text{C}$  dominate the decay heat generated in the blanket several hundred years following the end of its lifetime. The total decay heat generated in ARIES-II at shutdown is 53 MW and drops to 3.23 MW in one day and 0.3 MW in one year. Fig. 3 shows the total integrated decay heat in the different regions of the reactor during the first 2 months following shutdown. One week after shutdown, the values of the integrated decay heat generated are 548 and 1298 GJ for the inboard and outboard regions, respectively. These results are useful for predicting the thermal response of the structure to a LOCA.

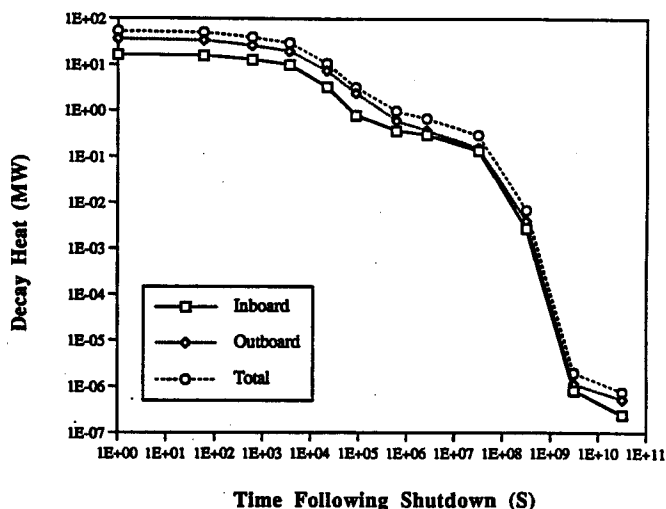


Fig. 2. Decay heat induced in ARIES-II structure.

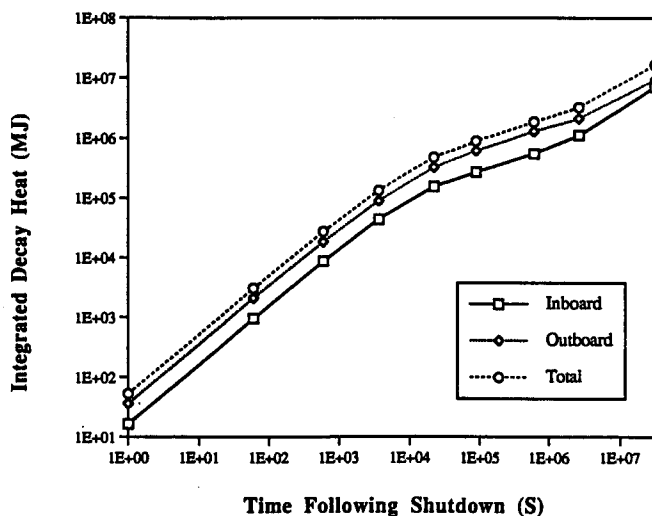


Fig. 3. Integrated decay heat in ARIES-II structure.

The biological hazard potential was calculated using the maximum permissible concentration limits in air for the different isotopes according to the NRC regulations specified in 10CFR20 [9]. The BHP as a function of time following shutdown is shown in Fig. 4 with the contributions of the inboard and outboard regions indicated. The total BHP at shutdown is  $388 \times 10^6 \text{ km}^3$  air with about two-thirds of it contributed by the outboard region. The short-term BHP is dominated by  $^{54}\text{Mn}$ ,  $^{56}\text{Mn}$  and  $^{52}\text{V}$  in the case of the shield, and  $^{49}\text{V}$  and  $^{48}\text{Sc}$  in the case of the blanket. While  $^{60}\text{Co}$  and  $^{54}\text{Mn}$  are the major sources of midterm BHP ( $\leq 10$  years) generated in the shield,  $^{49}\text{V}$  is responsible for most of the BHP in the blanket. Finally, in addition to  $^{94}\text{Nb}$ , the long-term BHP is produced by  $^{108\text{m}}\text{Ag}$  and  $^{93}\text{Mo}$  in the case of the shield and blanket, respectively.

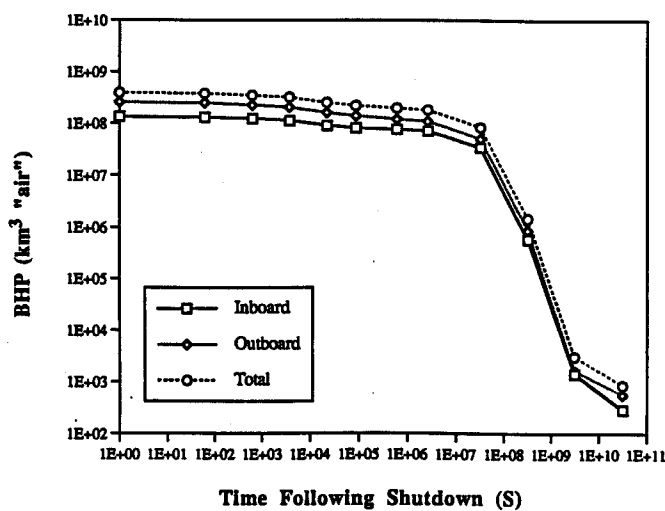


Fig. 4. Biological hazard potential in ARIES-II structure.

#### IV. RADWASTE CLASSIFICATION

The radwaste of ARIES-II structure has been evaluated according to both the NRC 10CFR61 [10] and Fetter [11] waste disposal concentration limits (WDL). The different radionuclide specific activities calculated by the DKR-ICF code were used to calculate the waste disposal ratings. The waste disposal ratings for Class A and Class C low level waste (LLW) are shown in Fig. 5 and Fig. 6 for the shield and blanket, respectively. The results in the figures are given for both Class A and Class C with the activities averaged over the total volume of the first wall and shield of both the inboard and outboard regions. The 10CFR61 Class A WDR is given after a waiting period of about 10 years to allow for the specific activity of short-lived nuclides ( $T_{1/2} \leq 5$  years) to drop below  $7000 \text{ Ci/m}^3$ . The  $7000 \text{ Ci/m}^3$  limit is 10 times larger than the limit specified by the NRC for Class A disposal of short-lived nuclides where the waste form is not specified. By comparison with other isotopes for which limits are given for different waste forms, the factor of 10 is used for isotopes contained in metal waste. Since the NRC regulations

do not specify any limit for short-lived activity for Class C LLW, the Class C WDR values were calculated after a one year cooling period for both 10CFR61 and Fetter limits.

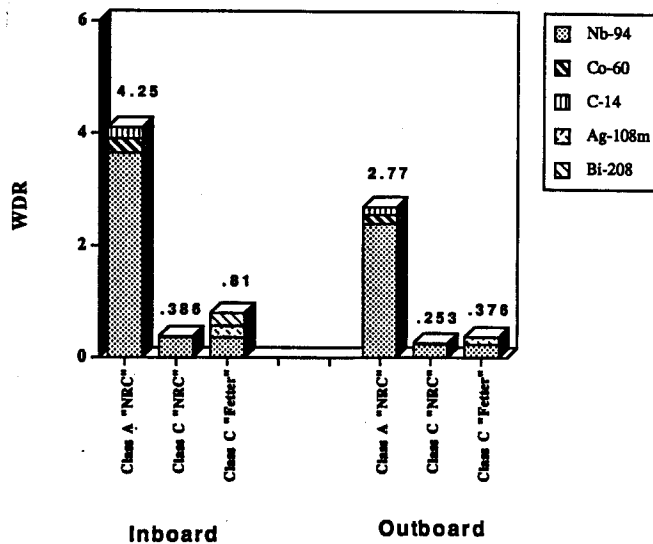


Fig. 5. Waste disposal rating for the ARIES-II shield.

The contributions from the different radionuclides to the WDR are also shown in the figure.  $^{94}\text{Nb}$  ( $T_{1/2} = 2 \times 10^4 \text{ yr}$ ), which is produced from  $^{93}\text{Nb}$  and  $^{94}\text{Mo}$ , is the major contributor to the waste disposal rating for both Class A and Class C. Another major contributor to Class A is  $^{60}\text{Co}$  produced from the cobalt, nickel and copper impurities in the steel.  $^{14}\text{C}$  ( $T_{1/2} = 5730 \text{ yr}$ ) produced from  $^{14}\text{N}$  and  $^{17}\text{O}$  is the other major contributor for the Class C rating if the 10CFR61 limits are used. If Fetter limits are used,  $^{108\text{m}}\text{Ag}$  ( $T_{1/2} = 130 \text{ yr}$ ) produced from  $^{107}\text{Ag}$  becomes a major contributor to the Class C waste disposal rating for the cases of the inboard blanket and the outboard shield.  $^{26}\text{Al}$  ( $T_{1/2} = 7.3 \times 10^5 \text{ yr}$ ) produced from  $^{27}\text{Al}$  and  $^{208}\text{Bi}$  ( $T_{1/2} = 3.68 \times 10^5 \text{ yr}$ ) produced from  $^{209}\text{Bi}$  are the other major contributors to the outboard blanket and inboard shield, respectively.

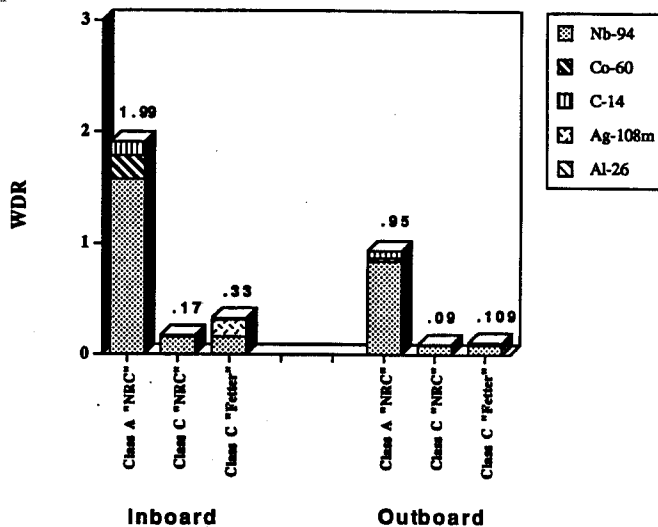


Fig. 6. Waste disposal rating for the ARIES-II blanket.

It is concluded that except for the outboard blanket which would qualify as Class A low level waste, the rest of the reactor structure would only qualify for Class C rating. The outboard blanket's Class A rating value of 0.95 is based on allowing it to cool down for about 10 years.

#### IV. OFF-SITE DOSES

Off-site doses are produced by the accidental release of the radioactive inventory present in the containment building. The off-site doses were calculated due to the release of 100% of the radioactive products contained in the ARIES-II blanket and shield. The calculations used the worst release characteristics as defined by the ESECOM [12] methodology (class F wind stability, 1 m/s wind speed, etc.). However, since the existence of radioactivity does not in itself represent a safety hazard, the second step in any safety analysis should consider a set of pessimistic but rather credible accident scenarios for mobilizing and releasing the radioactive inventory [7]. Table I shows the potential doses for ARIES-II's shield and blanket.

Table I. Off-site Doses (Sv) Produced by 100% Release of the Activation Products

	Blanket	Shield
<b>Prompt Dose at 1 km</b>		
WB	8.30E+02	1.18E+03
BM	9.24E+02	1.31E+03
Lung	1.07E+03	2.23E+03
LLI	7.86E+02	9.45E+02
<b>WB Early Dose</b>		
at 1 km	8.39E+02	1.24E+03
at 10 km	5.63E+01	7.18E+01
<b>WB Chronic Dose at 1 km</b>		
Inh + Grd	1.56E+03	1.30E+04
Ingestion	1.15E+03	1.22E+04
Total	2.71E+03	2.53E+04
<b>WB Chronic Dose at 10 km</b>		
Inh + Grd	1.05E+02	8.86E+02
Ingestion	7.93E+01	8.48E+02
Total	1.84E+02	1.73E+03

#### VI. CONCLUSIONS

The major advantage of ARIES-II vanadium structure is that it generates low levels of intermediate and long-lived radioactivity compared to other metallic structural materials. Thus, safety concerns for the formation of highly radioactive isotopes in the blanket and shield are greatly eased. The radioactivity generated in the reactor is slightly higher than an all vanadium system because of the steel filler (Tenelon) used in the shield. The detailed activation analysis reveals that the

entire blanket and shield easily qualify for near surface shallow land burial as Class A or Class C low level waste. The analysis also indicates that the activity level approaches 1.5 MCi/MW<sub>th</sub> after 3 full power years of operation and it takes a relatively short time (< 1 day) to decay by an order of magnitude. Calculations of the decay heat show that it is 53 MW at shutdown and decays in roughly the same manner as the activity. This heat represents 2% of the thermal power. It is spread out over the large mass of the blanket and shield (about 6500 tonnes) and does not seem to present a safety problem even in the event of a loss of a coolant accident.

#### ACKNOWLEDGMENT

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