Activation Analysis of the PULSAR-II Fusion Power Reactor

H.Y. Khater and the ARIES Team

September 1995

UWFDM-990

Presented at the 16th IEEE/NPSS Symposium on Fusion Engineering, 1–5 October 1995, Champaign IL.

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

Activation Analysis of the PULSAR-II Fusion Power Reactor

H.Y. Khater and the ARIES Team

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

September 1995

UWFDM-990

Presented at the 16th IEEE/NPSS Symposium on Fusion Engineering, 1–5 October 1995, Champaign IL.

Activation Analysis of the PULSAR-II Fusion Power Reactor

Hesham Y. Khater and the ARIES Team
Fusion Technology Institute
University of Wisconsin-Madison
1500 Engineering Drive, Madison, WI 53706-1687

ABSTRACT

The PULSAR-II pulsed tokamak power plant design utilizes a blanket made of the vanadium alloy, V-5Cr-5Ti, and cooled with liquid lithium. The shield is made of a mixture of the low activation austenitic steel (Tenelon) and vanadium. The blanket is assumed to be replaced every 5.6 full power years (FPY) and the shield is assumed to stay in place for 30 FPY. The activity induced in the blanket at the end of its lifetime is higher than the activity induced in the shield after 30 FPY. At shutdown, the blanket and shield activities are 2678 MCi and 1747 MCi, respectively. One year after shutdown the shield activity drops to 18 MCi compared to 84 MCi for the blanket. The total decay heat generated in the blanket at the end of its lifetime is 34.7 MW and drops to 17.6 MW within an hour. At shutdown, 25.3 MW of decay heat are generated in the shield, dropping to only 0.1 MW within the first year. One week after shutdown, the values of the integrated decay heat are 1770 GJ for the blanket and 469 GJ for the shield. The radwaste classification of the reactor structure is evaluated according to both the NRC 10CFR61 and Fetter waste disposal concentration limits. After 5.6 years of irradiation, the blanket will only qualify for Class C low level waste. After 30 years of operation, the shield will also qualify for disposal as Class C waste. Only remote maintenance will be allowed inside the containment building.

INTRODUCTION

The PULSAR reactor study [1] examined the possibility of obtaining better fusion economics by using a pulsed, inductively-driven tokamak design instead of the commonly proposed steady-state, noninductively driven tokamak design. The operating cycle consists of a set of 2-hour burn phases separated by a 200-second dwell phase. During the burn phase, plasma confinement is partially sustained by an inductively-driven plasma current.

Detailed activation analysis was performed to identify the safety, environmental and radwaste characteristics of the PULSAR-II reactor. The structure is made of vanadium alloy and cooled with liquid lithium. Several activation-related issues were investigated. The activity, decay heat and biological hazard potential (BHP) were calculated for up to 1000 years following shutdown. The waste disposal ratings (WDR) of the reactor structure were also evaluated. In addition, biological dose rates were calculated at selected locations inside the reactor containment.

The neutron flux used in the activation calculations was generated by the one-dimensional discrete ordinates neutron transport code ONEDANT [2]. The calculations used toroidal cylindrical geometry models with the inboard and outboard sides modeled simultaneously. The peak neutron wall loadings on the inboard and the outboard sides are 2.227 and 2.927 MW/m^2, respectively. The analyses were performed for an average peak neutron wall loading of 2 MW/m^2.

The calculations were conducted using the DKR-ICF code [3] with activation cross sections taken from the ACTL [4] library. 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 blanket was assumed to survive for 5.6 years, the shield was assumed to stay in place for the duration of the reactor lifetime. The inboard and outboard regions are assumed to extend over the heights of 7 and 10 meters, respectively.

Due to the length of the burn time (2 hours) compared to the dwell time (200 seconds), the calculations were performed with the assumption of continuous operation rather than pulsed operation. Although 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]. Therefore, our results for the radioactive inventories could be overestimated by up to 33%.

The structure activation results were utilized in the radwaste classification. The DOSE code [3] was used to calculate the biological dose rates doses behind the outboard's first wall, blanket, shield and vacuum vessel. The materials used in the blanket and shield of PULSAR-II are presented in Table I. The elemental compositions of the vanadium alloy (V-5Cr-5Ti) and the low activation austenitic steel (Tenelon) are taken from the Blanket Comparison and Selection Study (BCSS) report [6].

Table I
Materials Used in the PULSAR-II Analysis

Inboard	
VV	95% Tenelon
B_4C Shield	15% V-5Cr-5Ti, 80% B_4C
Al Shell	100% Al
Shield	15% V-5Cr-5Ti, 80% Tenelon
Reflector	15% V-5Cr-5Ti, 75% Tenelon
Blanket	10% V-5Cr-5Ti
FW	28.6% V-5Cr-5Ti
Outboard	
FW	28.6% V-5Cr-5Ti
Blanket	10% V-5Cr-5Ti
Reflector	15% V-5Cr-5Ti, 75% Tenelon
Shield	15% V-5Cr-5Ti, 80% Tenelon
Al Shell	100% Al
ES Shield	15% V-5Cr-5Ti, 60% Tenelon
VV	95% Tenelon

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

The activity induced in the blanket at the end of its lifetime is higher than the activity induced in the shield after 30 full power years. At shutdown, the blanket and shield activities are 2678 MCi and 1747 MCi, respectively. Fig. 1 shows the total activity induced in the different regions of PULSAR-II as a function of time following shutdown. The amount of radioactivity generated in the inboard and outboard sides of the blanket at shutdown are almost equal. The blanket activity drops to 464 and 294 MCi within the first day and the first week following shutdown, respectively. The outboard region of the shield produces about 70% more activity at shutdown than the inboard region. One day after shutdown, the outboard region produces more than twice the inboard region. One year after shutdown the shield activity drops to 18 MCi compared to 84 MCi for the blanket.

The blanket short-term activity (following its replacement) is dominated by ^{48}Sc ($T_{1/2}$ = 43.7 hr), ^{51}Cr ($T_{1/2}$ = 27.7 day), ^{47}Sc ($T_{1/2}$ = 3.349 day), and ^{45}Ca ($T_{1/2}$ = 162.7 day). The shield short-term activity after shutdown ($\leq$1 day) is dominated by ^{51}Cr, ^{54}Mn, ^{56}Mn, and ^{187}W ($T_{1/2}$ = 23.9 hr). In the period between 1 day and 1 year after shutdown, ^{54}Mn and ^{60}Co dominate the activity induced in the shield. During the same period of time, the blanket's activity is dominated by ^{49}V ($T_{1/2}$ = 337 day), ^{45}Ca, and ^{46}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}C, ^{93m}Nb, ^{94}Nb, and ^{93}Mo ($T_{1/2} = 3.5\times10^3$ yr). For the blanket, the steel component is present in its reflector.

The temporal variation of the decay heat generated in the blanket and shield is shown in Fig. 2. The total decay heat generated in the blanket at the end of its lifetime is 34.7 MW and drops to 17.6 MW within an hour and to only 1 MW within one week. At shutdown, 25.3 MW of decay heat are generated in the shield. The decay heat drops to only 0.28 MW within a day and 0.1 MW within the first year. Fig. 3 shows the integrated decay heat generated in the different regions of the blanket and shield, respectively. One week after shutdown, the values of the integrated decay heat are 1770 GJ for the blanket and 469 GJ for the shield. These results are useful for predicting the thermal response of the blanket and shield to a LOCA and/or LOFA.

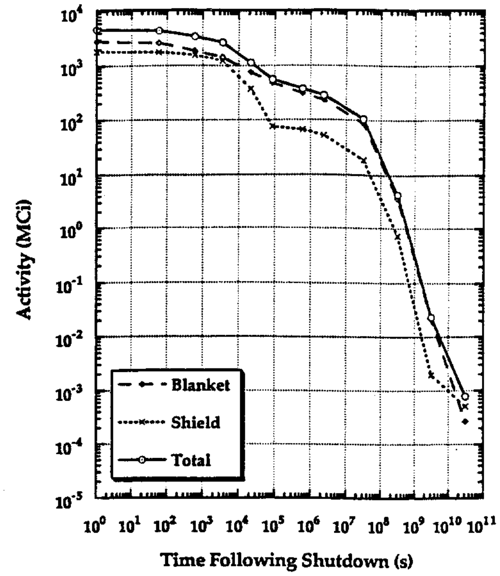

Fig. 1. Activity induced in PULSAR-II blanket.

The decay heat generated in PULSAR-II is generally dominated by the same isotopes that dominate the level of activity in the reactor. The short-term decay heat generated in the blanket is due to ^{48}Sc and ^{52}V ($T_{1/2}$ = 3.76 min). ^{46}Sc and ^{49}V are the dominant nuclides up to one year following the blanket replacement or the reactor shutdown. ^{94}Nb and ^{14}C dominate the decay heat generated in the blanket several hundred years following the end of its lifetime. In the shield case, ^{56}Mn and ^{52}V produce most of the decay heat generated within the first 8 hours. Within the first year after shutdown, ^{56}Mn and ^{60}Co are the major sources of decay heat. The long-term decay heat is governed by the decay of ^{94}Nb and ^{108m}Ag ($T_{1/2}$ = 130 yr).

Fig. 4 shows the biological hazard potential in air as a function of time following shutdown for the blanket and shield, respectively. The total BHP in the blanket at shutdown is 780×10^6 km^3, two-thirds of which is contributed by the inboard region. On the other hand, the total BHP generated in the shield at shutdown is 128×10^6 km^3 air with about two-thirds contributed by the outboard region. The short-term BHP is dominated by ^{49}V and ^{48}Sc in the case of the blanket, and ^{54}Mn, ^{56}Mn, and ^{52}V in the

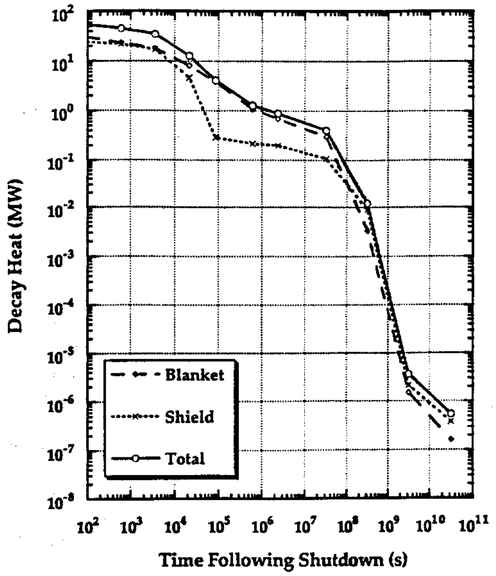

Fig. 2. Decay heat induced in PULSAR-II.

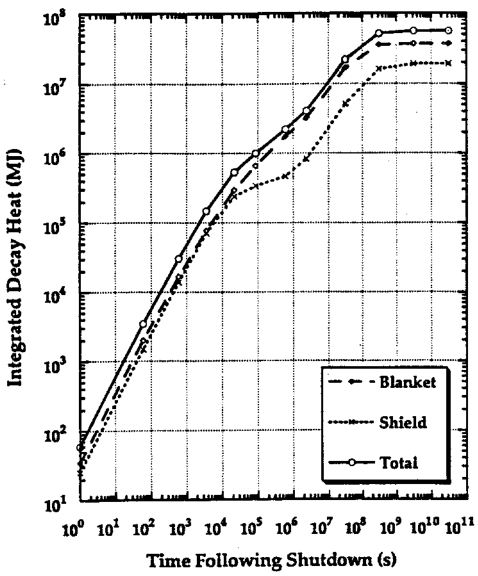

Fig. 3. Integrated decay heat in PULSAR-II.

case of the shield. While ^{49}V is responsible for most of the BHP in the blanket for times ($\leq$10 years), ^{60}Co and ^{54}Mn are the major sources of mid-term BHP generated in the shield. Finally, in addition to ^{94}Nb, the long-term BHP is produced by ^{93}Mo and ^{108m}Ag in case of the blanket and shield, respectively.

RADWASTE CLASSIFICATION

The radwaste of the blanket and shield of PULSAR-II were evaluated according to both the NRC 10CFR61 [7] and Fetter [8] waste disposal concentration limits (WDL). The waste disposal rating (WDR) is defined 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 and for the particular class. If the

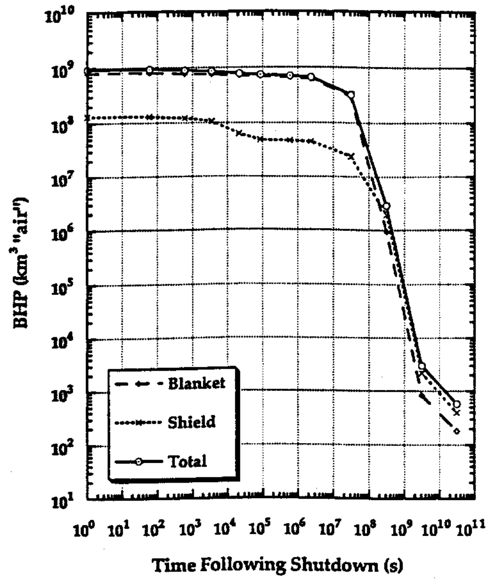

Fig. 4. Biological hazard potential in PULSAR-II.

calculated WDR ≤ 1 when Class A limits are used, the radwaste should qualify for Class A waste. If the WDR is > 1 when Class A WDL are used but ≤ 1 when Class C limits are used, the waste is termed Class C waste. Using Class C limits, a WDR > 1 implies that the radwaste does not qualify for shallow land burial.

Specific activities calculated by the DKR-ICF code were also used to calculate the waste disposal ratings for the blanket and shield of PULSAR-II. The waste disposal ratings for Class A and Class C low level waste are shown in Table II. The values in the table are given for both noncompacted and compacted (between brackets) values. Noncompacted values are based on averaging the specific activities over the total volume of a particular region assuming that internal voids will be filled with concrete before disposal. On the other hand, compacted values correspond to crushsing the waste before disposal. As shown in the table, if the 10CFR61 limits are used, ^{3}H produces about 80% of the Class A WDR of the blanket. ^{94}Nb is the second major contributor to the waste disposal rating. ^{94}Nb is also the main contributor to Class A in the case of the shield. The other major contributor is ^{60}Co produced from the cobalt, nickel and copper impurities in the steel. The Class C WDR of both the blanket and shield are dominated by ^{94}Nb. If Fetter limits are used, the blanket WDR is dominated by ^{108m}Ag ($T_{1/2} = 130$ yr) and ^{26}Al. On the other hand, the shield rating is dominated by ^{94}Nb and ^{208}Bi ($T_{1/2} = 3.68 \times 10^5$ yr).

It was concluded that after 5.6 years of irradiation, the blanket would only qualify for Class C LLW according to both NRC and Fetter limits if the waste is not compacted. A compacted blanket would only qualify for Class C rating if NRC limits were used. After 30 years of operation, the shield would also qualify for disposal as Class C waste.

Table II
PULSAR-II Waste Disposal Ratings

WDR	Blanket	Shield
Class A (10CFR61)	5.77 (25.4) ^{3}H (80%)	1.72 (1.81) ^{94}Nb (60%)
Class C (10CFR61)	0.095 (0.42) ^{94}Nb (90%)	0.104 (0.109) ^{94}Nb (90%)
Class C (Fetter)	0.33 (1.46) ^{108m}Ag (70%)	0.192 (0.202) ^{94}Nb (50%)

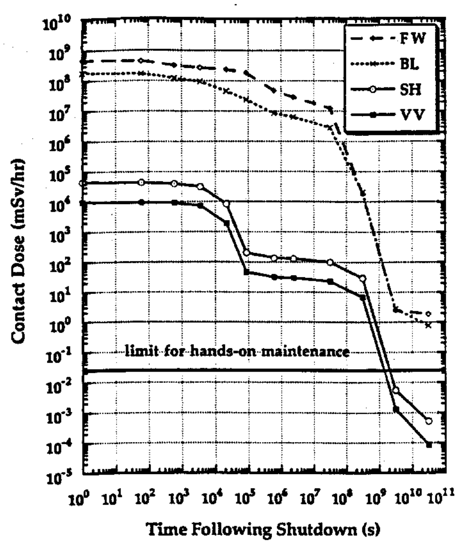

Fig. 5. Contact dose in PULSAR-II.

BIOLOGICAL DOSE RATES

Biological dose rates were calculated for maintenance evaluation. The doses were calculated using the DOSE code, which combines the decay gamma source and the adjoint dose field to determine the biological dose rates at different times following shutdown. The decay gamma source at different times following shutdown was calculated using the DKR-ICF code. The biological doses were calculated at four different locations behind the first wall, blanket, shield, and vacuum vessel of the outboard side for both reactors. A limit of 25 μSv/hr for hands-on maintenance was used in this analysis, assuming that maintenance personnel work for 40 hours a week and 50 weeks a year. Results in Fig. 5 shows that by assuming the 25 μSv/hr limit for hands-on maintenance, only remote maintenance would be allowed at any of the locations considered inside the containment building of PULSAR-II. During the first few weeks following shutdown, ^{48}Sc, ^{52}V, and ^{46}Sc are the principal contributors to the dose.

SUMMARY

PULSAR-II is the second of two tokamak conceptual designs examined in the PULSed Advanced Reactor (PULSAR) system study. The operating cycle of the reactor consists of a set of 2-hour burn phases separated by 200-second dwell periods. The reactor uses vanadium as the main structure material and liquid lithium as the breeder. Due to radiation damage, the blanket needs to be replaced every 5.6 FPY. The shield is expected to survive for the duration of the reactor lifetime (30 FPY). The activity induced in the blanket at the end of its lifetime is higher than the activity generated in the shield after 30 FPY. At shutdown, the blanket and shield activities are 2678 MCi and 1747 MCi, respectively. One year after shutdown the blanket activity drops to 84 MCi compared to 18 MCi for the shield. At the end of its lifetime, a noncompacted blanket will qualify for disposal as Class C low level waste according to both NRC and Fetter waste disposal limits. A compacted blanket will only qualify for a Class C rating if NRC limits are used. The shield will also qualify for a Class C rating. Only remote maintenance is allowed inside the PULSAR-II containment building.

ACKNOWLEDGEMENT

This work was supported by the U.S. Department of Energy.

REFERENCES

[1] "The PULSAR Tokamak Design Study," University of California San Diego report, unpublished.
[2] R. O'Dell et al., "User's Manual for ONEDANT: A Code Package for One-Dimensional, Diffusion-Accelerated, Neutral Particle Transport," Los Alamos National Laboratory report, LA-9184-M, 1982.
[3] D. L. Henderson and O. Yasar, "DKR-ICF: A Radioactivity and Dose Rate Calculation Code Package," University of Wisconsin Fusion Technology Institute report, UWFDM-714, vol. 1, April 1987.
[4] M. A. Gardner and R. J. Howerton, "ACTL: Evaluated Neutron Activation Cross Section Library — Evaluation Techniques and Reaction Index," Lawrence Livermore National Laboratory report, UCRL-50400, vol. 18, 1978.
[5] S. E. Spangler, J. E. Sisolak and D. L. Henderson, "Calculational Models for the Treatment of Pulsed/Intermittent Activation within Fusion Energy Devices," *Fusion Eng. Design*, **22**, p. 349, 1993.
[6] D. Smith et al., "Blanket Comparison and Selection Study," Argonne National Laboratory report, ANL/FPP/TM-122, 1984.
[7] "Licensing Requirements for Land Disposal of Radioactive Waste," Nuclear Regulatory Commission, 10CFR part 61, *Federal Register*, **FR 47** p. 57446, 1982.
[8] S. Fetter, E. T. Cheng and F. M. Mann, "Long Term Radioactive Waste from Fusion Reactors: Part II," *Fusion Eng. Design*, **13**, p. 239, 1990.