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NEUTRONICS ANALYSIS FOR AQUEOUS SELF-COOLED FUSION REACTOR BLANKETS

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ABSTRACT

The tritium breeding performance of several Aqueous Self-Cooled Blanket (ASCB) configurations for fusion reactors has been evaluated. The ASCB concept employs small amounts of lithium compound dissolved in light or heavy water to serve as both coolant and breeding medium. The inherent simplicity of this concept allows the development of blankets with minimal technological risk. The tritium breeding performance of the ASCB concept is a critical issue for this family of blankets. Contrary to conventional blanket designs there will be a significant contribution to the tritium breeding ratio (TBR) in the water coolant/breeder of duct shields, and the 3-D TBR will therefore be similar to the 1-D TBR.

The tritium breeding performance of an ASCB for a MARS-like-tandem mirror reactor and an ASCB based breeding-shield for the Next European Torus (NET) are assessed. Two design options for the MARS-like blanket are discussed. One design employs a vanadium first wall, and zircaloy for the structural material. The trade-offs between light water and heavy water cooling options for this zircaloy blanket are discussed. The second design option for MARS relies on the use of a vanadium alloy as the structural material, and heavy water as the coolant. It is demonstrated that both design options lead to low-activation blankets that allow class C burial. The breeder-shield for NET consists of a water-cooled stainless steel shield.

INTRODUCTION

The Aqueous Self-Cooled Blanket (ASCB) concept employs small amounts of lithium compounds dissolved in light or heavy water to serve as both the coolant and the tritium breeding medium. Several lithium compounds with sufficiently high solubility have been identified for this blanket concept.[1,2] Lithium hydroxide enriched in ^{6}Li was used as the lithium compound in the calculations presented in this paper, but a buffered salt solution may eventually be required for chemical compatibility.

In this paper, the neutronics characteristics for three ASCB blanket options[2] are assessed. It should be mentioned at this point that no additional neutron multiplier is employed in any of the applications. If a beryllium neutron multiplier was utilized the design window for the ASCB approach would be enhanced. The three ASCB options assessed in this paper are the following:

1. The application of a zircaloy based ASCB blanket to a MARS-like Tandem Mirror design with a vanadium alloy first wall, and light and/or heavy water as the coolant.
2. The application of a vanadium based (V-15Cr-5Ti) ASCB to a MARS-like Tandem Mirror design with heavy water as the coolant.
3. The application of the ASCB concept to the Next European Torus (NET), with stainless steel (SS-316) as the first-wall and structural material, and heavy or light water as the coolant.

A ZIRCALOY-BASED BLANKET FOR MARS

The relative simplicity of blanket design for tandem mirror reactors prompted an initial application of the ASCB concept to a MARS-like tandem mirror reactor. This design[2] employs spiralling tubes of zircaloy housed in a structural container of vanadium alloy (V-15Cr-5Ti) (Fig. 1). The breeder-coolant consists of water with 9.2 g of dissolved ^{6}LiOH per 100 cc of H_2O. The impact of varying the content of ^{6}Li has been addressed previously, and the final choice will be a compromise between chemical compatibility and TBR. The 1-D tritium breeding ratio for the blanket (containing 35 volume percent zircaloy, 44 percent water, and 21 percent void), is shown as a function of the light water/ heavy water content in Fig. 2. The choice of the fraction of structural content in the blanket is based on a structural analysis of the coolant tubes.[4] A S-8, P-3 ONEDANT* analysis was used to calculate the 1-D tritium breeding ratio. From Fig. 2, it can be concluded that the 1-D tritium breeding ratio shows an optimum for a mixture of 40 percent light water and 60 percent heavy water. This optimum results from the trade-off between reduced TBR due to a higher resonance absorption in zircaloy on the one hand, and enhanced TBR due to the contribution of the deuterium (n,T) reaction to the TBR on the other hand.

The tritium breeding ratios for the pure light water and pure heavy water options for a homogenized blanket, obtained from a multigroup ONEDANT calculation and a continuous energy calculation using MCNP[5], are compared in Table I. The difference in TBR between these cases can be understood when the resonance absorption in zircaloy is considered in more detail. Because light water is a more effective neutron scatterer than heavy water it is to be expected that less resonance absorption in the zircaloy will occur for the light water case. Due to the coarse group structure used in ONEDANT (30 neutron groups), the calculation overestimates the resonance absorption in zircaloy for the heavy water case by about 4 percent. Figure 3 clearly illustrates this point. This figure shows the resonance absorption behaviour in zircaloy for the MARS like blanket design. Figure 3.a illustrates the (n,g) absorption cross section in the resonance region. Figure 3.b shows the absorption in the resonance region for the light (solid) and heavy (dashed) water cooling options, based on MCNP, and Fig. 3.c illustrates the difference in the absorption as calculated by the two codes (MCNP and ONEDANT) for either H_2O cooling (dashed) or D_2O cooling (solid). From this figure, it can be concluded that:

1. The resonance absorption in zircaloy is higher for the heavy water based blanket option than for the light water based option.
2. The coarse group discrete energy treatment in ONEDANT overestimates the resonance absorption in zircaloy by about 4 percent for the heavy water case.

The TBR for the D_2O case is enhanced by the deuterium (n,T) contribution, but diminishes on the other hand due to an enhanced resonance absorption in the zircaloy. The choice between the heavy and the light water option will be determined by cost, activation and shielding properties, and tritium recovery. An isotopic separation process for tritium recovery will be required for the ASCB concept. While conventional techniques for tritium recovery can be utilized for this concept, promising result have been obtained for a novel in-situ radiolytic tritium recovery technique in development at the Chalk River Nuclear Laboratories. This radiolytic separation technique tends to favor the heavy water coolant option.[6]

A VANADIUM ALLOY BASED BLANKET FOR MARS

As an alternate blanket option for the MARS-like tandem mirror design, a vanadium alloy (V-15Cr-5Ti) based ASCB was developed. In this blanket design the vanadium alloy is used for the first wall and the blanket structural material. The vanadium alloy has the advantage of superior thermomechanical strength relative to zircaloy. However, the thermal absorption cross section is higher for the vanadium alloy and its neutron multiplication is lower than that of zircaloy. An additional concern regarding the utilization of vanadium alloy as the structural material for the ASCB is the possibility of hydrogen diffusivity. However, recent experiments[7] have indicated that the vanadium alloy, in contact with water, forms a protective oxide layer that reduces this diffusivity.

Preliminary mechanical considerations have resulted in a blanket structure similar to that of the zircaloy based ASCB, but with thinner tubes because of the higher yield stress of the vanadium alloy. This blanket contains 16 percent (by volume) vanadium alloy, 64 percent of the breeder-coolant medium and 20 percent void. Again, 9.2 grams of ^{6}LiOH per 100 cc of water were utilized for the tritium breeding compound. This blanket yields a TBR of 1.03 when cooled with heavy water and a TBR below unity when cooled with light water. The vanadium alloy's constituent metals do not have a broad resonance absorption region, as does zircaloy, and therefore the light water cooling option does not offer any advantages. For the same reason, a very small increase (roughly 1 percent) in the TBR was found, when a continuous energy MCNP analysis was used. It should be noted that the estimated TBR can be enhanced by 3 to 4 percent when the breeding compound concentration is increased to 15 g of ^{6}LiOH per 100 cc of water.

ACTIVATION CHARACTERISTICS FOR THE ZIRCALOY AND VANADIUM BLANKET

The use of low activation materials is vital for an environmentally acceptable blanket design. The activation qualities of two ASCB concepts have been calculated using the REAC[8] activation code, in an effort to establish their classification as class C waste. Waste of this class is permitted shallow land burial. The NRC has placed limits on certain radionuclides, above which class C burial is not permitted. However, these limits, listed in 10CFR61, were obtained with low level fission wastes in mind, and do not include many harmful isotopes which will be produced in the structural materials of fusion devices. Kennedy & Mann[9] have estimated limits for additional isotopes using a simple ratio technique based on the limit arrived at by NRC for ^{59}Ni. Fetter[10] has reproduced the NRC limit analysis using a more detailed model, and in the process has uncovered several significant errors in the data and the calculations of the NRC limits. A listing of the various limits is compiled in Table II.

Materials are measured for their activation characteristics using the Waste Disposal Rating (WDR). The WDR for each radionuclide is the activity calculated for that isotope, divided by the limit designated for said isotope. A total WDR is obtained by summing the fractions of all contributing isotopes. If the total is less than unity, the material meets class C requirements. In this analysis, WDRs are calculated using two sets of limits. One consists of a combination of the existing NRC limits and the estimated limits of Kennedy and Mann (the NRC limits are used where available). The other set of limits is that derived by Fetter. Irradiation time steps of 0.2 years were used in the REAC analysis. Neutron fluxes required for the REAC input flux library were calculated using ONEDANT. The following results are based on a two year operating period at a wall loading of 5 MW/m^2.

Using the NRC-based limits, a maximum WDR of 2.04 is found for the innermost portion of the zircaloy blanket which is composed of Zircaloy-4 (Zr 98.193%, Sn 1.5%, Cr 0.2%, Fe 0.1%, Ni 0.007%). However, the activation drops off sharply with increasing blanket radius. A waste processing scenario where the entire volume of blanket material is melted into a homogeneous mixture yields a total WDR of 0.236 for this mixture. The Fetter limits result in a maximum WDR of 0.711 so that the blanket qualifies for class C burial "as is". In this case, mixing the blanket volume lowers the total WDR to 0.047. In either case the major contributor to the total WDR is ^{94}Nb, which stems from the initial activation of ^{94}Zr and ^{96}Zr.

The vanadium alloy is an excellent low activation material. In fact, no radionuclides with class C limits are created from the three basic elements of this alloy. However, commercial V-15Cr-5Ti contains many undesirable impurities including 300 ppm of molybdenum, which is the major contributor to the total WDR of this material via the production of ^{94}Nb. The maximum WDR of this alloy using the NRC-based limits is 2.21, while the maximum WDR using the Fetter limits is 0.707. These WDRs can be reduced significantly through the use of higher quality V-15Cr-5Ti, with smaller amounts of molybdenum. Volume mixing can further reduce the total WDR of this blanket concept.

AN ASCB BREEDER SHIELD FOR NET

The ASCB concept has been applied to develop a breeder-shield[3] for the Next European Torus (NET).[11,12] The evolving design results in a 1.7 cm thick stainless steel (SS-316) first wall and coolant region, a 30 cm thick breeder shield region encased in a 1.5 cm thick SS-316 container, and a 30 cm thick shield region. The breeder shield region uses heavy or light water as the coolant with 5 percent ^{6}LiOH or 5 percent natural ^{NAT}LiOH dissolved in it. The shield region contains 80 volume precent SS-316 and 20 volume percent light water. The content of structural material is varied in the breeder shield region and the corresponding TBR for fully enriched LiOH (solid line) and natural LiOH (dashed line) is shown in Fig. 4. The required TBR for NET is thought to be between 0.4 and 0.8. From Fig. 4, it can be concluded that the breeding requirements for NET can be met with an ASCB based breeder-shield, resulting in a low technology system, without the additional design complexities associated with a separate tritium breeding blanket. Further neutronics calculations revealed that the tritium breeding ratio can be enhanced by about 3 percent if HT-9 is used. A heavy water option for the breeder shield yields a TBR which, depending on the amount of LiOH in the coolant, is about 10 percent higher than the light water option.

CONCLUSIONS

The ASCB concept leads to elegant blanket designs for near-term and long-term fusion applications. The first application examined was that of an ASCB applied to a MARS-like tandem mirror reactor. When zircaloy was used as the blanket structural material, tritium breeding ratios of 1.15 were obtained with a mixture of light and heavy water. Tritium breeding ratios close to 1.1 were calculated when either pure heavy or pure light water was utilized. The basic assumption that light water may be favored because of the structure of the resonance absorption region in zircaloy was confirmed when a continuous energy MCNP analysis was used to estimate the TBR. The MCNP analysis gave results slightly higher (of the order of 4 percent) than the multigroup approach used in ONEDANT. The issue of whether light or heavy water should be utilized in a final design remains open. It is probable that the choice between the two will be based more on cost, corrosion and activation issues rather than on neutronics performance. A second design option for the MARS-like blanket is based on the use of the V-15Cr-5Ti alloy for the blanket structural material. In this case a TBR of 1.08 was estimated when heavy water cooling is utilized. Light water cooling is no longer an option because it yields a TBR below unity. For both design options (i.e. zircaloy or vanadium alloy as the blanket structural material) an activation analysis showed that the class C requirements for shallow land burial are met.

The second application of the ASCB was to a breeder-shield for NET. Stainless steel (PCASS) was used as the basic structural material and the use of either light or heavy water cooling yielded results for the tritium breeding ratio in compliance with those required by the NET design. This results in a low technology blanket-shield that can be applied with minimal R&D effort. The ASCB as a design option generally has the advantage that the use of materials and processes for which extensive data are available greatly facilitates the R&D effort required to validate it.

ACKNOWLEDGEMENT

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TABLE I

COMPARISON BETWEEN TBR BASED ON ONEDANT AND MCNP FOR A HOMOGENIZED ZIRCALOY-BASED BLANKET FOR MARS FOR THE D_2O AND H_2O COOLANT OPTIONS ($5\%\ ^6Li$)

	MCNP	ONEDANT
D_2O	1.11	1.07
H_2O	1.12	1.13

TABLE II

CONCENTRATION LIMITS FOR CLASS C WASTE DISPOSAL

ISOTOPE	HALF LIFE (YEARS)	10CFR61 (Ci/m^3)	KENNEDY & MANN (Ci/m^3)	FETTER (Ci/m^3)
^{10}Be	$1.6x10^6$	N/A	7000	0.0
^{14}C	$5.7x10^3$	80	N/A	$2.2x10^4$
^{26}Al	$7.2x10^5$	N/A	20	0.18
^{59}Ni	$7.6x10^4$	220	200	$2.8x10^4$
^{63}Ni	100	7000	300	$3.9x10^7$
^{90}Sr	29	7000	N/A	N/A
^{93}Zr	$1.5x10^6$	N/A	200	$4.9x10^5$
^{91}Nb	700	N/A	N/A	1100
^{92}Nb	$3.5x10^7$	N/A	300	0.36
^{94}Nb	$2.0x10^4$	0.2	N/A	0.35
^{93}Mo	$3.5x10^3$	N/A	30	790
^{98}Tc	$4.2x10^6$	N/A	N/A	0.28
^{99}Tc	$2.1x10^5$	3	N/A	7.4
^{108m}Ag	127	N/A	N/A	5.2
^{205}Pb	$1.5X10^7$	N/A	5	$6.4X10^3$
^{210m}Bi	$3.0X10^6$	N/A	N/A	2.3

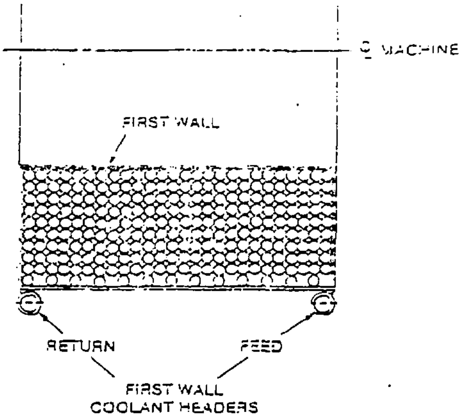

FIGURE 1. Schematic of the ASCB blanket applied to a MARS-like tandem mirror.

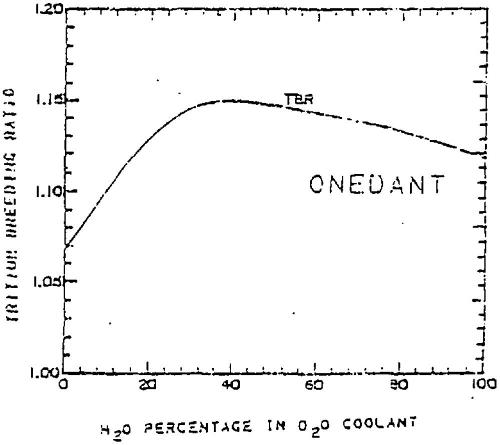

FIGURE 2. 1-D TBR as function of the H_2O fraction in the heavy water coolant for the zircaloy-based MARS-like blanket.

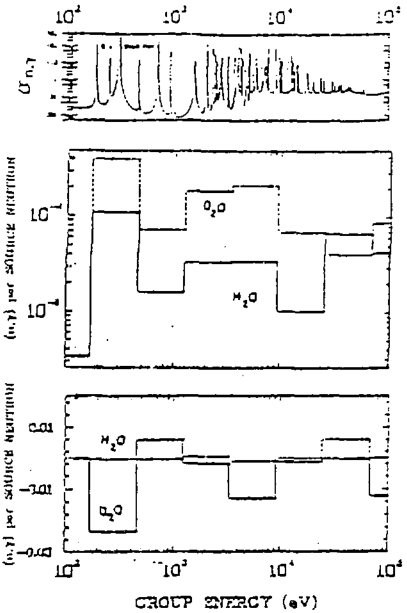

FIGURE 3. Resonance absorption behavior in zircaloy for the MARS like blanket design.

Fig. 3.a. (n,g) Absorption cross section in the resonance region.

Fig. 3.b. Absorption in the resonance region for the light (solid) and heavy (dashed) water cooling options, based on MCNP.

Fig. 3.c. Difference in absorption as calculation by the two codes (MCNP and ONEDANT) for either H_2O (dashed) or D_2O (solid) coding.

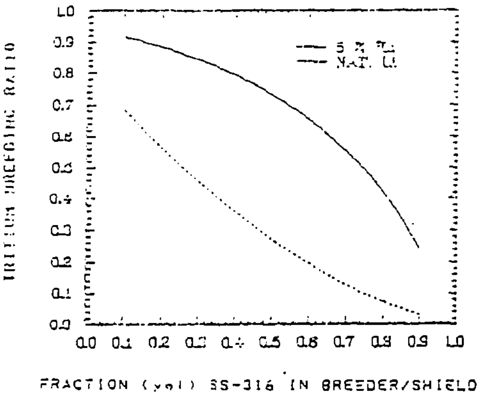

FIGURE 4. TBR versus volume percent SS-316 in the breeder shield for an ASCB based shield design for NET.