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NEUTRONICS ASPECTS OF ARIES-II AND ARIES-IV FUSION POWER REACTORS

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ABSTRACT

The ARIES study investigates the potential of tokamaks as fusion power reactors and focuses on improving the economic and safety features of fusion by integrating the environmental constraints into the design from the beginning. The ARIES-II and ARIES-IV designs incorporate advanced physics and technologies that would be available over the next 5-20 years. The two designs have the same plasma physics but different fusion-power-core designs.[1] ARIES-II uses liquid Li as a coolant/breeder with V alloy structure while ARIES-IV employs solid breeder with He coolant and SiC/SiC composite structure. Low activation materials were utilized in the design to reduce the radioactive inventory. A variety of blanket/shield options was examined for both designs and the relative merits of the various materials as a function of blanket/shield thickness were demonstrated. The lifetime of the structural components was determined based on the radiation-induced damage in V and SiC. In this paper, a comparison between the two designs based on detailed neutronics analysis is presented.

I. INTRODUCTION

The ARIES study aims at determining the potential economic, safety and environmental features of tokamak reactors and identifies the physics and technology areas with high leverage for achieving the best power reactor design. The study has developed four visions for tokamaks, each with a different degree of extrapolation in physics and technology. All four ARIES designs are 1000 MW electric power reactors. ARIES-I assumes a minimum extrapolation in physics and incorporates advanced technologies. ARIES-III focuses on the potential of D-^{3}He fueled reactors as they offer greater environmental and safety advantages than DT reactors. It utilizes the present-day technology and requires a large extrapolation in plasma physics. ARIES-II and ARIES-IV assume potential advances in physics and technology. The two designs have the same plasma physics but different fusion-power-core designs. Proper material choice is important for the safety goals of ARIES. To eliminate the need for deep geological burial of the radioactive waste, it is necessary to select materials that do not become strongly radioactive when bombarded by neutrons. Chemically modified metallic alloys, such as vanadium, Tenelon, Fe1422, and modified HT-9, are readily available and recent developments in manufacturing of ceramics have indicated the feasibility of producing a SiC/SiC composite that can be used in fusion reactors. In this paper, we will concentrate on the shielding aspects as opposed to the radiological issues of these materials.

The ARIES-II and IV parameters are constantly being revised as the design evolves. General features of the "most up-to-date" ARIES-II and -IV designs include the operation in the second stability regime with 3.4% β, plasma current of $\sim$5 MA, magnetic field at coil of 16 T, aspect ratio of 4, major and minor radii in the range of 5.2-5.8 m and 1.3-1.5 m, respectively, average neutron wall loading of 3.5 MW/m^2, and 40 years of operation at $\sim$75% availability. A tritium breeding blanket is required to supply both ARIES-II and -IV with tritium. The coolant, breeder, and structural material are different in both designs. ARIES-II uses liquid Li as the coolant and breeder with the low activation V5Cr5Ti alloy as the structural material. ARIES-IV employs Li_2O breeder and He coolant with the low activation SiC/SiC composite as the structural material. No beryllium multiplier is used in either design and as a goal the blanket should achieve an overall tritium breeding ratio $\geq$1.05. The blanket is followed by the shield which is primarily used to protect the superconducting toroidal field (TF) magnets against radiation. Since the thickness of the shield directly affects the size and cost of the machine, an extensive analysis was performed to optimize the shield composition and to design an efficient shield. A variety of shield options was examined and the ability of various materials to protect the magnet was assessed. The radiation damage to the V and SiC structural materials was analyzed and the lifetime of the different components was estimated.

II. BLANKET DESIGN

A series of calculations using the one-dimensional (1-D) code ONEDANT[2] and the poloidal geometry model was first performed for the V/Li blanket to evaluate the impact of the blanket parameters on both the tritium breeding ratio (TBR) and neutron energy multiplication (M). The Li enrichment was varied between 7.42% (natural) and 50% ^{6}Li and the blanket thickness was gradually increased from 10 to 80 cm. The V structural content was kept fixed at 10% by volume and a meter thick re-

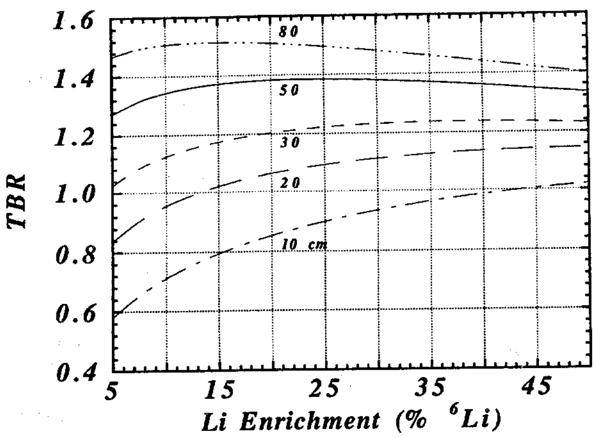

Fig. 1. Effect of Li enrichment on TBR for different blanket thickness.

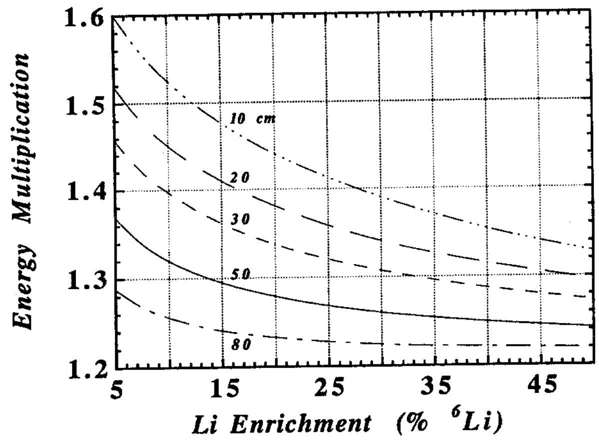

Fig. 2. Effect of Li enrichment on M for different blanket thickness.

flector/shield was placed behind the blanket. The results are illustrated in Figs. 1 and 2. As Fig. 1 indicates, the TBR increases with Li enrichment and peaks at higher enrichment for thinner blankets. As expected, M decreases as the enrichment increases, for all blanket thicknesses. It should be mentioned that M includes the energy from both blanket and reflector/shield. Since the inboard side is constrained in space, it was decided to consider a 20 cm thick blanket for the inboard (i/b) side and adjust the outboard (o/b) blanket thickness to satisfy the breeding requirements. The 1-D results of a toroidal model, where the i/b and o/b blankets are represented simultaneously, indicates that 20 cm i/b and 50 cm o/b blankets utilizing natural Li should result in a decent TBR. Coupling the results of the 1-D toroidal model with the fractions of source neutrons incident on the i/b and o/b sides, the overall TBR and M amount to 1.09 and 1.36, respectively. Provision was made for the current drive antenna which occupies $\sim$1 m^2 of the o/b surface area. As noted, the i/b and o/b blankets provide sufficient tritium for ARIES-II and no breeding blanket needs to be installed in the divertor region.

Similar neutronics analyses were performed for the ARIES-IV Li_2O/SiC helium cooled blanket.[3] The results indicate that the i/b and o/b blankets need to be 35 and 60 cm thick, respectively. Furthermore, a 45 cm thick blanket should be installed in the divertor region in order to achieve an overall TBR of 1.05. The blanket contains $\sim$15 v/o SiC structure, 5 v/o He coolant and 80 v/o natural Li_2O with 90% density fraction and 80% packing fraction. The energy multiplication amounts to 1.06.

III. SHIELD DESIGN

The intent of this work is to design an efficient low activation shield to protect the TF magnets against radiation. This involves the assessment of the shielding capability of the various candidate materials, optimization of the composition of the shield, and determination of the thickness of the shield required to keep the radiation damage at the magnet below a certain level. The analysis was mainly carried out for the i/b shield as it strongly affects the overall size of the machine.

The analysis was performed using the 1-D code ONEDANT with a P_3-S_8 approximation. The 46 neutron and 21 gamma group cross section used is derived from the ENDF/B-V evaluation. In the calculational model, the geometric configuration of ARIES-II and IV was maintained. The different components of the blanket and shield were modeled in toroidal cylindrical geometry around the machine axis, permitting the representation of the inboard and outboard sides simultaneously. The plasma shift toward the outboard is taken into account in modeling the neutron source. The poloidal distribution of the wall loading shows that the wall loading peaks at the midplane of the inboard and outboard at values of 3.4 and 5.75 MW/m^2, respectively.

The shield design is generally governed by the radiation tolerance of the magnet. In order to insure the proper performance of the TF coils, the radiation effects must be below certain limits. For instance, at the end of 30 full power years (FPY) of operation the fast neutron fluence ($E_n > 0.1$ MeV) should not exceed 10^{19} n/cm^2 to avoid degradation of the critical properties of the Nb_3Sn superconductor material. It is undesirable to subject the magnet to a nuclear heating above 50 kW to avoid excessively high cryogenic load to the cryoplant. A limit of 2 mW/cm^3 is imposed on the peak nuclear heating in the winding pack. The end-of-life (EOL) dose to the glass-fiber-filled (GFF) polyimide is limited to 10^{11} rads to ascertain the mechanical and electrical integrity of the insulator. It should be mentioned that the fluence and dose limits are at least a factor of 2-3 lower than the experimental values at which degradation of properties was observed. Our neutronics calculations indicate that the predominant magnet radiation limits are the EOL fast neutron fluence and the nuclear heat load to the magnets. Hence, the shield is optimized to primarily minimize these effects.

Table I

Radiation Effects at TF Magnets for Various Shield Design Options for ARIES-II and -IV.

	ARIES-II	ARIES-IV				
Shield Type	$V/SS/B_4C/Pb$	$SiC/B_4C/Pb$	$V/B_4C/Pb$	$SS/B_4C/Pb$	Heterogeneous Multilayers	Homogeneous
Composition	53 cm SS shield 22 cm B_4C 2 cm Pb shield	48 cm SiC shield 23 cm B_4C shield 5 cm Pb shield	36 cm V shield 29 cm B_4C shield 3 cm Pb shield	34 cm SS shield 26 cm B_4C shield 1 cm Pb shield	14 layers of SiC & B_4C 1 cm Pb shield	SiC & B_4C (50% each)
Inboard shield thickness (cm)	77	76	68	61	74	73
Total inboard FW/B/R/M/S* thickness (cm)	113	145	137	130	143	142
T Production in shield (g @ 40 y)	2	3	3	3	30	40
Radiation Effects at Magnet:						
Peak fast neutron fluence to Nb_3Sn (10^{19} n/cm^2 @ 30 FPY)	1	1	1	1	1	1
Peak nuclear heating in W.P. (mW/cm^3)	1.7	2.0	1.5	1.8	1.4	1.9
Peak dose to insulator (10^{10} rads @ 30 FPY)	2.3	2.8	2.2	2.4	2.0	2.6
Peak dpa in Cu stabilizer (10^{-3} dpa @ 30 FPY)	5.3	5.3	5.6	5.5	5.6	6.2

*First wall/blanket/reflector/manifold/shield.

A. ARIES-II Shielding Analysis

The analysis has focused on optimizing the major factors that influence the shield performance. These factors are the composition of the shield, material arrangement, and coolant content within the shield. The i/b zone was configured into 3 regions: blanket, reflector, and shield. V is used as the primary structural material in all components. Low activation steel filler material is employed in the reflector and shield as it offers better shielding performance than V. Our analysis shows that the Tenelon filler has a higher shielding capability compared to modified HT-9 and Fe1422. Therefore, the 20 cm thick i/b blanket is followed by a 15 cm thick reflector composed of 15 v/o V, 10 v/o Li, and 75 v/o Tenelon filler. The thickness of the reflector is determined such that the V structure of the shield has an acceptable neutron-induced damage at EOL. The composition of the shields was then optimized to reduce the radiation damage at the magnet. First, the Tenelon filler in the shield was traded for Li coolant and the results reveal that both fast neutron fluence and nuclear heating minimize at no coolant in the shield. However, 5 v/o Li was considered to meet the cooling requirements. B_4C and Pb was then introduced to enhance the performance of the SS shield. The optimization analysis indicates that the optimal shield consists of 53 cm SS shield followed by 22 cm B_4C shield, and then 2 cm Pb shield. Each layer contains 5 v/o Li coolant and 15 v/o V structure and the shield satisfies all magnet radiation limits as indicated in Table I.

The results presented so far pertain to the i/b side of the reactor. In the divertor region, enough shield is provided to protect the upper/lower parts of the TF magnets. The wall loading therein amounts to $\sim$2 MW/m^2. In order to meet the magnet radiation limits, the divertor shield needs to be at least 90 cm thick with a composition of 47 cm SS shield, 38 cm B_4C shield, and 5 cm Pb shield. For the o/b side, the 50 cm thick blanket is followed by a 5 cm thick reflector, and then a fairly thick shield (102 cm) to virtually zero out the nuclear heating in the outer legs of the TF magnets. Here, the shield is made out of a pure SS shield instead of a thinner, but more expensive, SS/B_4C shield. Based on this shield design, the integrated nuclear heating in the TF coils totals to $\sim$15 kW. Using a cryoplant efficiency of 310 W per W (Ref. 4), the cryogenic load amounts to $\sim$5 MW. This is an acceptable load as it represents only 0.5% of the reactor power.

B. ARIES-IV Shielding Analysis

The ARIES-IV blanket is backed by a 20 cm thick SiC reflector, 13 cm He manifold, and then the shield. The blanket, reflector, and shield have a minimum He coolant content of 5% by volume. The He manifold is composed to 50% SiC and 50% He. Although the He gas has no shielding characteristics, the possibility of achieving a high thermal efficiency of 49% (vs.

Table II

Key Shielding Parameters and Cost Items for AIRES-II AND -IV DESIGNS

	ARIES-II	ARIES-IV	
		SiC-Based Shield	SS-Based Shield
Thickness (cm):			
FW	1	1	1
Blanket	20/50/0*	35/60/45	35/60/45
Reflector	15/5/0	20	20
Manifold	–	13	13
Shield	77/102/90	76/81/59	61/64/46
Total	113/158/90	145/175/138	130/158/125
Unit Cost ($/kg)			
SiC (structure/filler)		435/55	
V	180		
B_4C	220	220	
SS filler	23	23	
Pb	16	16	
η_{th}	45%	49%	
M	1.36	1.06	
R (m)	5.16	5.80	5.56
a (m)	1.29	1.45	1.39
Cost (M$)			
Blanket/Reflector	25	198	182
Shield	220	286	240
LSA	3	2	2
COE (mills/kWh)	52	63	60

*For inboard/outboard/divertor regions

45% for the Li system) makes it an attractive coolant for the SiC structure. A set of calculations was performed to optimize the SiC shield. The analysis shows that in order to satisfy the magnet radiation limits, the all SiC shield will be fairly thick. Therefore, other materials should be incorporated in the shield. B_4C and Pb have proven to be very effective at improving the performance of the SiC shield in particular. A 76 cm thick shield is sufficient to protect the inner legs of the TF magnets with an optimal composition of 48 cm SiC shield, 23 cm B_4C shield, and 5 cm Pb shield. The effect of the SiC and B_4C arrangement within the shield was investigated. As an alternative to the two thick layers, the SiC/B_4C shield was configured into alternating thinner layers of SiC and B_4C, about 5 cm thick each. The other possibility of using a homogeneous mixture of SiC and B_4C was also examined. The calculations show that the multilayered and homogeneous SiC/B_4C shields save approximately 2 and 3 cm in shield thickness, respectively. There is, however, a price paid for these savings in terms of the design complexity and the in-shield T inventory, which adversely affects safety. Listed in Table I is the T production in the B_4C. As expected, the T production considerably increases as the B_4C is brought up closer to the plasma. As these two options exhibit no clear outstanding advantages, the two separate SiC and B_4C layers option was selected as the preferred option for the SiC-based shield.

An attempt was made to reduce the size of the SiC shield by including some low activation metallics in the shield. These metallics are used only as filler materials and do not carry any structural load. It was found that a considerable reduction in the shield thickness of 8 and 15 cm can be achieved by including V and modified HT-9 fillers, respectively, in the SiC shield. Table I details the composition of the different options. Each layer of the shield contains 5 v/o He coolant and 15 v/o SiC structure and the magnet radiation limits are met for all options.

IV. LIFETIME OF V AND SiC STRUCTURES

Generally, the radiation damage to the first wall and blanket is an important issue in fusion reactors. In ARIES-II and IV, there is some concern that the V and SiC structural materials will not survive the intense radiation environment and will require frequent replacement over the 40 years of operation. The lifetime of the structure is determined by the level of neutron-induced atomic displacements and transmutations attainable during operation. For V structure, the atomic displacement is limited to 200 dpa.[5] For SiC structure, the atomic displacement is not a concern as recent theoretical models predict lower atomic displacement in SiC compared to metals.[6] On this basis, the lifetime of the SiC should be determined by the transmutation product level which is considered an indicative of the SiC burn-up rate. It should be mentioned that the effects of such products (He and H) on the interfacial areas and on the mechanical and thermal properties of the SiC/SiC composites are unknown at the present time.[7]

The dpa, He and H production rates were computed for the i/b and o/b sides of the reactor. The o/b side exhibits higher damage and, therefore, should be replaced on a more frequent basis compared to the i/b. Our calculations show that the dpa rate in the o/b V FW is 70 dpa/FPY. This implies that the o/b FW/B/R (which is designed as one unit) should be replaced every 3 FPY. The corresponding EOL FW/B/R fluence is $\sim$17 MWy/m^2. On the other hand, the EOL dpa value at the first layer of the shield is below the 200 dpa limit and, therefore, the shield is considered to be a lifetime component. The He and H production rates in the o/b SiC FW are 10,073 and 3,732 appm/FPY, respectively. This translates into a burn-up rate of $\sim$2% per FPY. As stated earlier, the effect of burn-up on the SiC properties is unknown. If 3% is an acceptable burn-up limit for SiC, the o/b FW/B/R/M (which is designed as one unit) will be replaced every 1.5 FPY. This corresponds to an EOL FW/B/R/M fluence of $\sim$10 MWy/m^2. The SiC structure of the shield has a low burn-up level of $<$0.1% at EOL and this qualifies the shield to be a lifetime component.

V. COMPARISON BETWEEN ARIES-II AND -IV DESIGNS

A list of dimensions for the different components of the inboard, outboard, and divertor regions for the candidate shield options is given in Table II. The specified shield parameters enabled the system code analysts to define the cost implications of the various options and their impact on the different reactor components and, thus, on the economic characteristics of the device.[8] The relevant shield parameters that would directly impact the cost have also been listed in Table II. The energy multiplication directly determines the shield thermal power and the thermal conversion efficiency is a major factor contributing to the cost of electricity (COE). The unit cost for the various shielding materials, of relevance here, is given in the table. The thicker SiC-based shield results in the largest and most expensive machine. The steel-based shield would have some cost savings but exhibits relatively higher levels of activation. Since the steel-based shield still meets the safety criteria of the design, it was decided to select the SS-based shield as the reference shield for the ARIES-IV design. The ARIES-II design benefits from the thinner shield, less costly materials, and higher EOL FW/B/R fluence. Because of the low inventory of the radioactive materials, the ARIES-II and -IV designs were able to achieve levels of safety assurance (LSA) of 3 and 2 (or 1), respectively (an inherently safe reactor would have a level 1 safety rating and fission reactors usually have LSA=4). The significance of the LSA rating is that many of the reactor components do not have to be nuclear grade and thereby result in capital cost savings of 10-25%. The ARIES-IV design meets the criteria for passive safety and has a good chance to achieve a LSA of 1. The ARIES-II design should adopt several safety features to obviate any possible fire of the Li coolant/breeder in case of an accident. This includes the exclusion of all water from the building, a drain tank to collect the Li in case of a spill, and a steel liner on all floors to prevent Li-concrete interactions.

VI. CONCLUSIONS

The key neutronics issues for ARIES-II and -IV have been addressed. The blanket parameters were carefully optimized to achieve an overall TBR in excess of unity. The ARIES-II Li/V blanket covers $\sim$85% of the space surrounding the plasma while full coverage was found essential for the ARIES-IV Li_2O/SiC/He blanket. The shield is designed to provide adequate protection for the TF magnets. Low activation materials were employed in the blanket and shield to improve the safety features of the design. ARIES-IV has a thicker shield compared to ARIES-II. This has led to a larger and more costly machine with more attractive safety features, however. Implementing the recommendations of the economic assessments which stress the importance of designing a high-performance low-cost shield, a trade-off was made between the salient safety feature of having an all SiC shield and the cost savings of including the more efficient stainless steel material in the ARIES-IV shield. The study showed a cost reduction of $\sim$5% in COE and the design still meets the criteria for passive safety.

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