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NEUTRONICS DESIGN ASPECTS OF REFERENCE ARIES–I FUSION BLANKET

by

E.T. CHENG*and the ARIES DESIGN TEAM

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*TSI Research, Solana Beach, California.

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E.T. CHENG* **and the ARIES DESIGN TEAM**

General Atomics, P.O. Box 85608, San Diego, California 92186-9784.

*Present address: TSI Research, 225 Stevens Ave., Suite 110, Solana Beach, California 92075.

ABSTRACT

A SiC composite blanket concept was recently conceived for a deuterium-tritium burning, 1000 MW(e) tokamak fusion reactor design, ARIES–I. SiC composite structural material was chosen due to its very low activation features. High blanket nuclear performance and thermal efficiency, adequate tritium breeding, and a low level of activation are important design requirements for the ARIES–I reactor. The major approaches, other than using SiC as structural material, in meeting these design requirements, are to employ beryllium, the only low activation neutron multiplying material, and isotopically tailored Li_2ZrO_3, a tritium breeding material stable at high temperature, as blanket materials.

INTRODUCTION

ARIES–I is a deuterium-tritium (D-T) burning, 1000 MW(e) tokamak fusion reactor based on advanced technology and modest extrapolation from the present physics data base.[1,2] SiC composite material was selected as the structural material for ARIES–I blanket and shield due to its very low activation features. Beryllium metal was determined to be the neutron multiplier because of the high (n, 2n) performance capability and low activation aspect. The low activation motivations for the ARIES–I design were primarily relevant to safety and environmental issues of nuclear energy. The considerations were extended to the following areas: (1) accidental release of radioactive inventory; (2) maintenance and decommissioning; and (3) waste disposal and reuse of materials.

A previous design of the ARIES–I blanket selected Li_4SiO_4 as the tritium breeding material because of its very low activation characteristics.[3] However, due to the concern that a phase change from Li_4SiO_4 to Li_2SiO_3 during neutron irradiation may impose potential difficulties in operating the blanket at desired temperatures, the reference breeding material was changed to Li_2ZrO_3, which is a more stable material at high temperatures during lithium burnup transmutation.[4] Due to afterheat and radiation hazard considerations, the natural zirconium element in the breeder, Li_2ZrO_3, is tailored to consist of enriched Zr-92 isotope (0.057% Zr-90, 0.013% Zr-91, 99.91% Zr-92, 0.019% Zr-94, and 0.003% Zr-96) in its isotopic abundance.

In this paper, we discuss the neutronics design aspects of the reference ARIES–I blanket based on the new breeding material, Li_2ZrO_3. The safety aspects of this blanket due to induced radioactivity are discussed in Ref. 5.

ARIES–I BLANKET CONCEPT

High blanket nuclear performance is one of the design requirements for the ARIES–I reactor. The major approach in meeting this design requirement is to employ beryllium, the only low activation neutron multiplying material, as the blanket material. Lead is the other possible non-fissionable neutron multiplier. However, the radiological hazard potential for lead in a fusion reactor is at least four orders of magnitude higher than SiC and beryllium.

In the conceptual design of the ARIES–I blanket, we are motivated to minimize the beryllium inventory due to resource limitation concerns. The best approach to effectively utilize the beryllium neutron multiplication is to install the beryllium component immediately behind the first wall and to maximize the beryllium fraction in this zone. To enhance the nuclear energy multiplication in the ARIES–I blanket, we allow the excess neutrons to be absorbed in silicon ($Q = 8.5$ MeV) which appears in the beryllium zone as the constituent element in the structural material, SiC.

Due to the coolant routing and heat-removal design approach adopted for the ARIES–I blanket, a minimal power density design is required in the breeder zone such that the maximum operating temperature in the breeder would not exceed the design limit. To fulfill this important design requirement, we have arranged the location of the breeder material to be as close to the first wall as possible. Another neutronics consideration for having the breeding material just behind the first wall is to enhance tritium breeding by reducing parasitic absorption.

Due to the above discussed requirements, we have selected the blanket concept that employs a beryllium neutron multiplying zone immediately behind the first wall. The tritium breeder, which is a solid breeding material, is uniformly mixed with beryllium to reduce the operating power density. High lithium-6 enrichment in the solid breeding compound will be needed due to high lithium-6 burnup in the blanket. Table 1 shows the zoning and material compositions of the ARIES–I blanket and shield design.

As shown in Table 1, the blanket consists of a structural first wall made of SiC composite. The neutronic model used in the calculation assumes a thickness of 1 cm for the first structural wall with the compositions of 67% SiC and 33% helium, by volume. In front of the first structural wall, there is a sacrificial layer of 2 mm, also made of SiC, to account for the particle erosion due to plasma edge interactions. The breeding zone is located immediately behind the first wall. It consists of 25% SiC, 70% breeder and multiplier, and 5% helium, also by volume. The breeder and multiplier is comprised of 80% beryllium and 20% solid breeder material. Both beryllium and solid breeder are at 90% of their respective theoretical density. The packing fraction of the breeder and multiplier in this zone is 80% using two-size particles. The breeder and multiplier zone is 0.2 m thick and is backed by two reflector zones. Figure 1 displays the tritium breeding ratio (TBR), blanket energy multiplication (M), and ^{9}Be $(n, 2n)$ reaction rate as a function of breeder/multiplier zone thickness. The 0.2 m breeder/multiplier zone thickness was chosen based on the considerations of adequate breeding (1.2 in 1-D calculation) and minimum beryllium inventory.

The front reflector zone is 0.1 m thick consisting of 25% SiC, 70% beryllium, and 5% helium. Use of beryllium in this reflecting zone is primarily to enhance the blanket energy multiplication by about 3%. The rear reflecting zone is made of 25% SiC (structure), 70% SiC (particles), and 5% helium. The thickness of this SiC reflector zone is 0.07 m in the inboard location, otherwise it is 0.37 m. Note the non-structural material in the reflector zones, either beryllium or SiC, is 90% dense and is with 80% packing fraction using two-size particles. Figure 2 displays M and TBR as a function of packing fraction of the Li_2ZrO_3/Be particles in the ARIES–I blanket. Note that the corresponding TBR will change by about 7% when the packing fraction of these breeder/multiplier particles in ARIES–I varies by 10%, as shown in Fig. 2. The blanket energy multiplication, however, is to be affected by only about 2%.

The SiC reflector zone is then followed by a 0.3 m gas plenum with the compositions of 75% SiC and 25%

Table 1. Helium-cooled beryllium-multiplying SiC composite blanket and shield for ARIES–I power reactor

Zone	Thickness (cm)	Compositions
First Wall		
Sacrificial layer	0.2	100% SiC
Structural wall	1	67% SiC + 33% He
Breeding Zone	20	25% SiC + 70% breeder/Be + 5% He (breeder/Be – 80% Be + 20% breeder, 72% density factor, principal breeder is Li_2ZrO_3)
Reflector 1	10	25% SiC + 70% Be + 5% He (Be density factor is 72%)
Reflector 2	37 (outboard) 7 (inboard)	75% SiC + 20% void + 5% He 75% SiC + 20% void + 5% He
Plenum	30	75% SiC + 25% He
Vacuum Vessel	1	Aluminum alloy
Shield 1	40 (outboard) 40 (inboard)	66.5% SiC + 28.5% B_4C + 5% He 56% SiC + 24% B_4C + 20% He
Shield 2	40 (outboard) 30 (inboard)	66.5% SiC + 28.5% B_4C + 5% He 66.5% SiC + 28.5% B_4C + 5% He

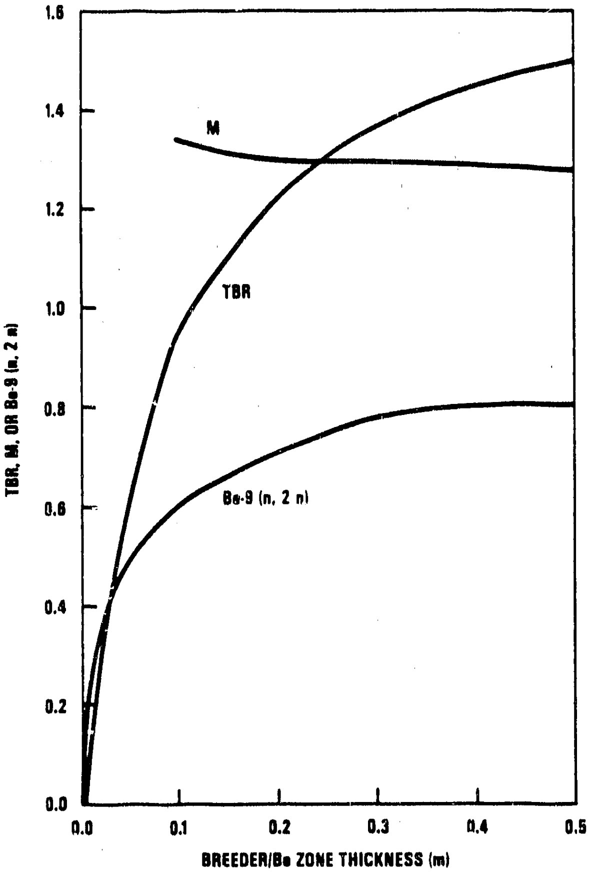

Fig. 1. Tritium breeding ratio (TBR), blanket energy multiplication (M), and Be (n, 2n) as a function of breeder (Li_2ZrO_3)/multiplier (Be) zone thickness in ARIES–I reference blanket.

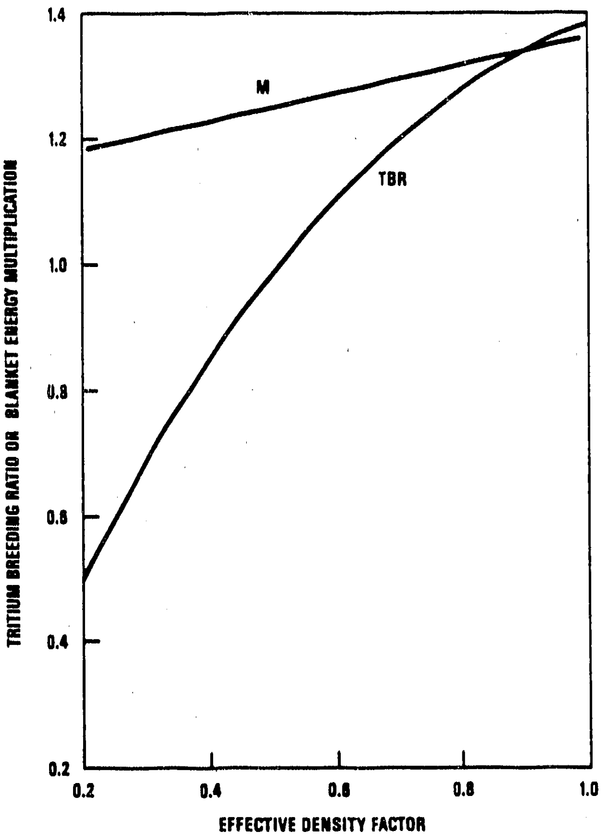

Fig. 2. Tritium breeding ratio (TBR) and blanket energy multiplication (M) as a function of effective density factor of breeder (Li_2ZrO_3)/multiplier (Be) particles in ARIES–I blanket. The effective density factor is packing fraction times theoretical density.

helium. The vacuum vessel, which is made of low-activation aluminum alloy, is located outside of the gas plenum and is 10 mm thick. In the final design the vacuum vessel is located outside the shield and a stabilizing shell was added, composed of thin aluminum sheets dispersed throughout the shield. For the neutronics analysis, a thick shell in front of the shield was retained. Note that the total blanket thickness for the inboard location is 0.7 m, while it is 1.0 m elsewhere.

The magnet shield is employed behind the blanket to protect the superconducting magnet. The most critical region of the magnet shield is located in the inboard as already well known for a tokamak reactor. For the ARIES–I reactor, the inboard shield is 0.7 m thick. The 0.3 m region nearest to the magnet employs a high density shield consisting of 95% SiC and B_4C shield and 5% helium. The SiC and B_4C shield has the compositions of 70% SiC and 30% B_4C. The 0.4 m of shield close to the vacuum vessel is, however, made of low-density shield particles. The packing fraction of these variable-size SiC and B_4C particles is 80%, allowing the particles to be extracted in order to create extra space behind the vacuum vessel when the vessel is to be disassembled. This shield zone is also cooled by low temperature helium. The shield elsewhere is designed to be 0.8 m thick and is made of high density shield materials.

The overall blanket and shield thickness is 1.4 m for the inboard location, while it is 1.8 m elsewhere. The inboard blanket and shield is capable of protecting the superconducting magnet against radiation damage through the entire life time of the ARIES–I power plant. In addition to the magnet protection, the 1.8 m blanket and shield elsewhere is also designed to reduce the activation level of reactor materials behind the blanket and shield component such that hands-on maintenance might be possible behind the shield.

ARIES–I BLANKET PERFORMANCE

Table 2 displays the neutronic performance of the ARIES–I blanket and shield. Note that the Li-6 enrichment in the solid breeder Li_2ZrO_3 is 80% in lithium when the blanket is fresh. At the end of blanket life, which is after 20 MW-y/m^2 14 MeV neutron exposure at the first wall, the lithium-6 drops to 25% of the initial enrichment, or 20%. Figure 3 shows the TBR and M as a function of ^{6}Li enrichment in the breeder. As shown in Table 2 and Fig. 3, the tritium breeding ratio for ARIES–I from a 1-D full coverage analysis is 1.21 tritons per D-T neutron when the blanket is fresh. It reduces by 5.6%, to 1.15, at the end of blanket life. The average tritium breeding ratio over the blanket life is 1.18, which is more than enough to guarantee an adequate tritium production in a realistic three-dimensional reactor geometry, including allowance for the installation of double-null divertor components, for sustaining the fusion fuel cycle in ARIES–I. This is so because in ARIES–I similar tritium breeding blankets will be installed behind the divertor components. The blanket energy multiplication is initially 1.30, and then increases slightly to 1.32 at the end of blanket life, also shown in Table 2 and Fig. 3.

Figure 4 depicts the distribution of volumetric nuclear heating rates in the ARIES–I blanket components. Note that this figure is for the demonstration of nuclear heating rate in the breeding zone only, since the breeding zone and reflector thicknesses shown here are not that for the final design. As shown in Fig. 4, the maximum volumetric nuclear heating occurs at the breeder zone in the beryllium and breeder mixture

Table 2. Neutronic performance of the ARIES–I blanket and shield

	Beginning of Life (0 MW-y/m^2) (80% Li-6)	End of Life (20 MW-y/m^2) (20% Li-6)
1. Tritium Breeding (T/D-T Neutron)		
Li-6 (n, α)T	1.1994	1.1337
Li-7 (n, n'α)T	0.0036	0.036
Be (n, T)	0.0112	0.0114
2. Neutron Multiplication (Reactions/D-T Neutron)		
Be (n, 2n)	0.7516	0.7643
3. Nuclear Heating (MeV/D-T Neutron)		
First wall	0.8375	0.8449
Breeder zone	13.35	13.06
Be reflector	1.317	1.413
SiC reflector	2.284	2.651
Plenum	0.5495	0.6345
Total blanket heating	18.34	18.60
Blanket energy multiplication, M	1.30	1.32
4. Maximum Volumetric Nuclear Heating Rates (W/cc)		
SiC first wall	6.7$^{(a)}$	
Breeder/Be mixture average	11.0$^{(a)}$	
5. Nuclear Heating and Radiation Damage at S/C Magnet		
Maximum nuclear heating (inboard)	370 W/m$^{3\ (a)}$	
Maximum fast neutron flux	2.3×10^9 n/cm^2/s$^{(a)}$	

$^{(a)}$At 1 MW/m^2.

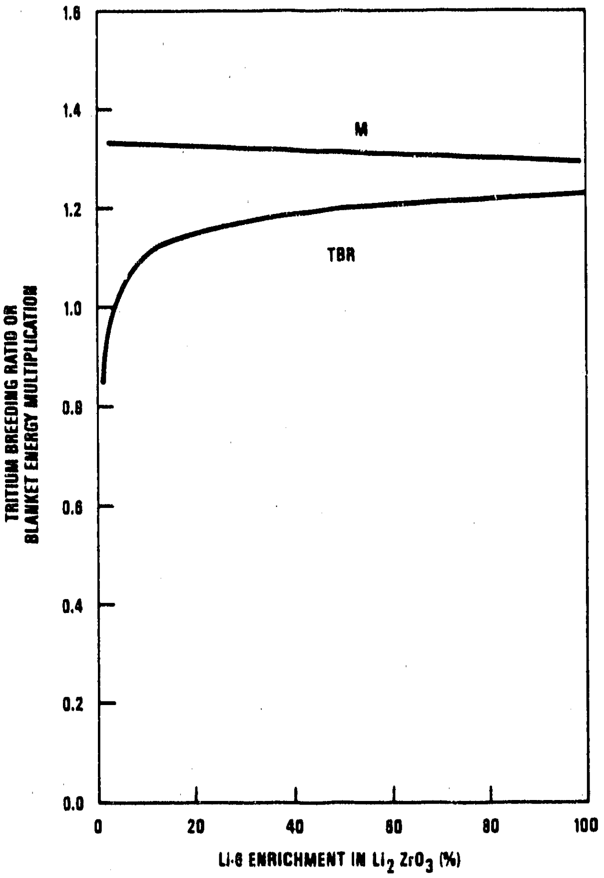

Fig. 3. Tritium breeding ratio (TBR) and blanket energy multiplication (M), as a function of ^{6}Li enrichment in Li_2ZrO_3 breeder in the ARIES–I blanket.

immediately behind the SiC first wall, and is 11 W/cc for the mixture when normalized to 1 MW/m^2 neutron wall loading. Otherwise, the volumetric nuclear heating in the breeder Li_2ZrO_3 alone will be close to 30 W/cc, as shown in Fig. 4. The volumetric nuclear heating at the SiC first wall, however, is only 6.7 W/cc at 1 MW/m^2.

The maximum nuclear heating at the superconducting magnet is located at the inboard region. It is about 370 W/m^3 at 1 MW/m^2 neutron wall loading. The fast neutron (energy above 0.1 MeV) flux at the inboard super-conducting magnet is 2.3×10^9 n/cm^2/s at 1 MW/m^2. The superconducting magnet is more than capable of operating continuously for 40 years, since the radiation damage limit is believed to be 1.0×10^{19} n/cm^2 fast neutron fluence and the neutron wall loading at the inboard region is 2.4 MW/m^2.

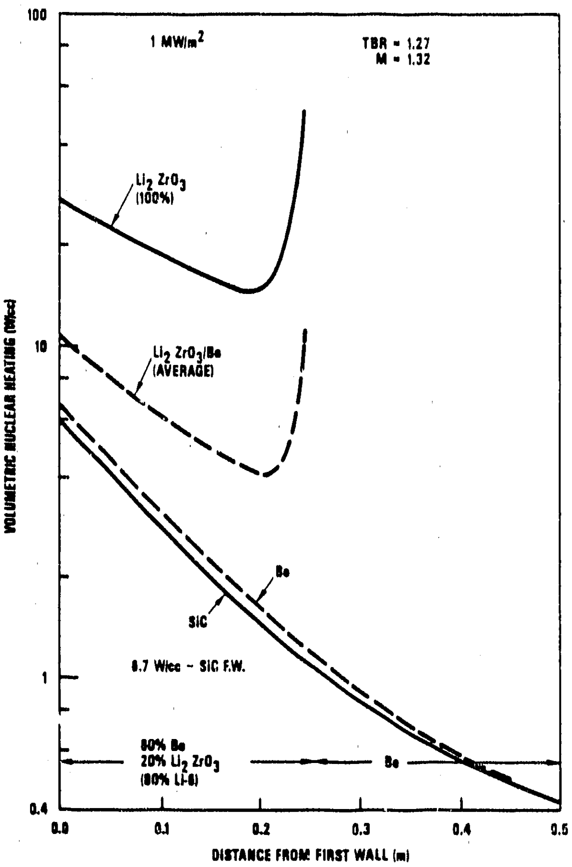

Fig. 4. Spatial distribution of volumetric nuclear heating rates in ARIES–I blanket components (normalized to 1 MW/m^2 neutron wall loading).

SUMMARY AND CONCLUSIONS

A SiC composite blanket concept was recently conceived for a D-T burning, 1000 MW(e) tokamak reactor design, ARIES–I, due to the low activation features of SiC material. High blanket nuclear performance, defined as maximum energy multiplication with adequate tritium breeding, is one of the design requirements for the ARIES reactor. Another major design requirement is to achieve a low level of activation. The major approach, other than using SiC as structural material, in meeting these design requirements is to employ beryllium, the only low activation neutron multiplying material, as a blanket material.

To maximize the blanket energy multiplication as well as to efficiently utilize the beryllium inventory, we have selected the blanket concept that employs a beryllium neutron multiplying zone immediately behind the first wall. Li_4SiO_4, LiO_2, and Li_2ZrO_3 were among the solid breeder candidate materials considered for ARIES–I. Isotopically tailored Li_2ZrO_3 was selected as the reference breeder due to the high temperature stability requirement in the ARIES–I blanket environment, although Li_4SiO_4 and Li_2O have demonstrated better low activation features. The tritium breeder, Li_2ZrO_3, is uniformly mixed with beryllium to average out the operating power density in the breeder such that the maximum operating temperature would not exceed the design limit. High lithium-6 enrichment, up to 80% in lithium, will be needed due to high burnup in the blanket. To enhance the nuclear energy multiplication in the blanket, which is 1.3 in ARIES–I, we allow the excess neutrons to be absorbed in silicon ($Q = 8.5$ MeV) which appears as either structural or reflector material, SiC.

The tritium breeding ratio for ARIES–I, from a 1–D full coverage analysis is 1.21 tritons per D–T neutron when the blanket is fresh and it drops by 5.6%, to 1.15, at the end of blanket life which is taken as 20 MW-y/m^2 first wall exposure. The average tritium breeding ratio is 1.18, which is more than enough to guarantee adequate tritium production in a realistic three-dimensional reactor geometry, including allowance for the installation of divertor components, for sustaining the fusion fuel cycle in ARIES–I.

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