Breeding Potential of Candidate Breeders for the U.S. Demo Power Plant

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ABSTRACT

The U.S. Demo will utilize either liquid metal (LM) or solid breeder (SB) for tritium breeding. A prime goal for the breeder is to provide tritium self-sufficiency that ensures the self-sustaining operation of the Demo plant. Neutronics analysis have been performed for 20 breeders to examine their ability to breed tritium and multiply the neutron energy. A few promising LM (Li and $Li_{17}Pb_{83}$) and SB (Li_2O and Li_2TiO_3) were selected for further analysis to illustrate the impact on breeding of the candidate low activation structures (V, SiC, and FS) and neutron multipliers (Be, Be_2C, BeO, and Pb). Among the various breeders considered in the analysis, lithium provides the highest breeding followed by lithium lead, then Li_2O. The study has concluded that Li and $Li_{17}Pb_{83}$ have the potential for tritium self-sufficiency without a neutron multiplier. Solid breeders will most likely require a neutron multiplier to achieve net breeding in realistic designs. All structures degrade the breeding and enhance the energy multiplication, except SiC which degrades both. Vanadium has the least impact on the breeding of LM and SB, followed by FS and SiC, except for $Li_{17}Pb_{83}$. All multipliers significantly enhance the SB breeding, except BeO, and the SB energy multiplication, except Pb. Besides neutronics performance, other features of LM and SB will be key factors in selecting the Demo materials.

I. INTRODUCTION

The U.S. Demo design is at an early phase of development. The community-wide study is conducted by the University of California-San Diego and involves nationwide experts from industry, national laboratories, and universities. Design options have been identified that lead to a Demo power plant with enhanced safety, environmental, and economic features. These options must meet the Demo requirements which are based on projections of customer and utility needs. The engineering-related requirements include the use of the same technologies incorporated in commercial power plants, demonstration of a closed tritium fuel cycle, generation of no radioactive waste greater than Class C, and production of electricity at a competitive cost. The safety and environmental requirements limit the material choices and the high performance requirements provide strong incentives to operate at high coolant temperature and thermal efficiency.

Detailed engineering designs have not been established yet. Instead, several options have been examined and their potential to meet the Demo requirements were assessed. These options include material choices for breeder, structure, coolant, and neutron multiplier. The present work examines the ability of the various materials to meet the breeding and performance requirements. The candidate structural materials are the vanadium alloys, SiC/SiC composites, and low activation ferritic steels (FS). Many breeders are readily available and can provide the Demo with sufficient tritium for fueling. Besides neutronics performance, other features (such as safety, thermo-mechanical properties, tritium control, fabricability, compatibility, reliability, etc.) will be considered in selecting the Demo breeder and structure.

II. LITERATURE SURVEY

An extensive literature survey was conducted to identify the breeder options for the U.S. Demo. The study has revealed that 26 breeders have been examined in previous fusion designs of commercial, experimental, and Demo power plants. Only 11 breeders were actually considered in the 60 worldwide fusion studies performed over the past 25 years. Lithium and lithium lead ($Li_{17}Pb_{83}$) are the most widely used liquid metals while lithium oxide (Li_2O) is the most widely used solid breeder. Recently, the Europeans and Canadians expressed interest in developing lithium titanate (Li_2TiO_3) as

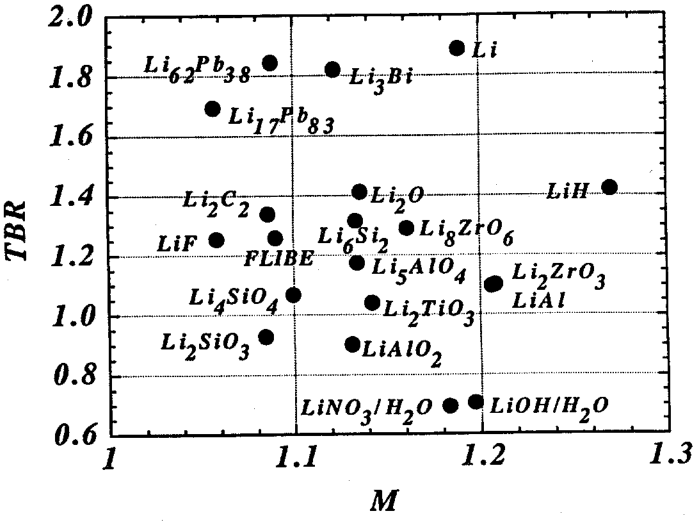

Fig. 1. T-M plot for various breeders.

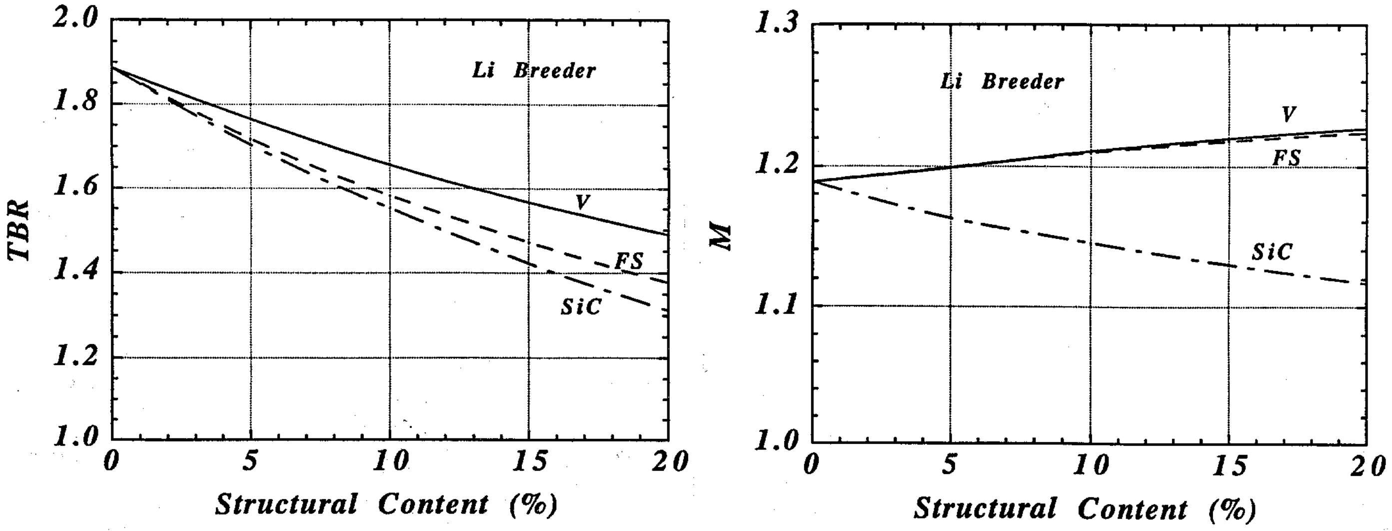

Fig. 2. Effect of V, SiC, and FS structural content on TBR and M for Li breeder.

an alternative low-activation SB material. The properties of most breeders have been extensively discussed in the literature. Some properties and safety concerns are expected to limit the use of several breeders under the operating conditions of Demo.

III. NEUTRONICS PERFORMANCE OF CANDIDATE BREEDERS

A comparative study was conducted for 20 breeders to examine their ability to breed tritium and multiply the neutron energy. The design elements that impact the neutronics performance were excluded from the analysis in order to assess the breeding potential of the various breeders on an equal basis. As such, an idealized calculational model was developed using a simple one-dimensional cylindrical geometry with a fairly thick blanket (2 m) made of 100% dense natural breeder at room temperature. Later, a few promising LM and SB were selected for further analysis to illustrate the impact of the various structures and neutron multipliers on the neutronics performance.

The results of the first set of analysis are plotted in Fig. 1. Among all breeders considered in the study, lithium provides the highest breeding, followed by lithium lead. Among the SB, Li_2O provides the highest breeding. It should be mentioned that the local TBR and energy multiplication (M) are likely to be degraded by the design elements. Previous studies [1] indicated that the local TBR could drop by up to 40% when all elements are included in the designs. The factors that degrade the breeding are the blanket coverage, configuration, heterogeneity, structural content, finite size, Li burnup, assembly gaps, side walls, and penetrations. Thus, in a realistic design, lithium and lithium lead have the potential to breed sufficient tritium while SB will most likely require a neutron multiplier to achieve net breeding.

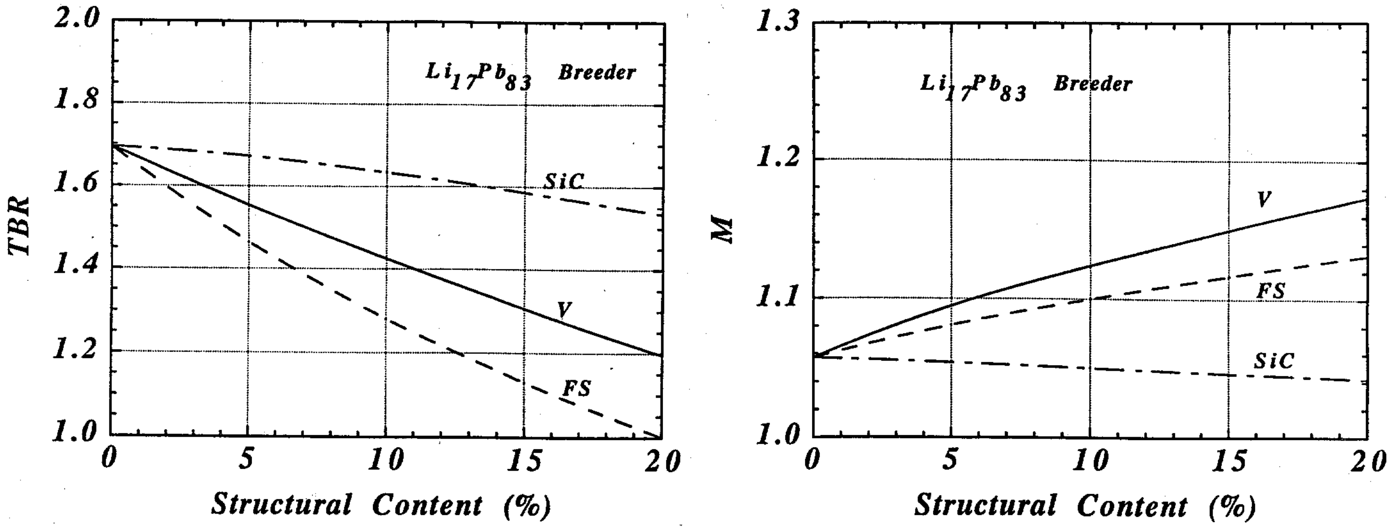

Fig. 3. Effect of V, SiC, and FS structural content on TBR and M for $Li_{17}Pb_{83}$ breeder.

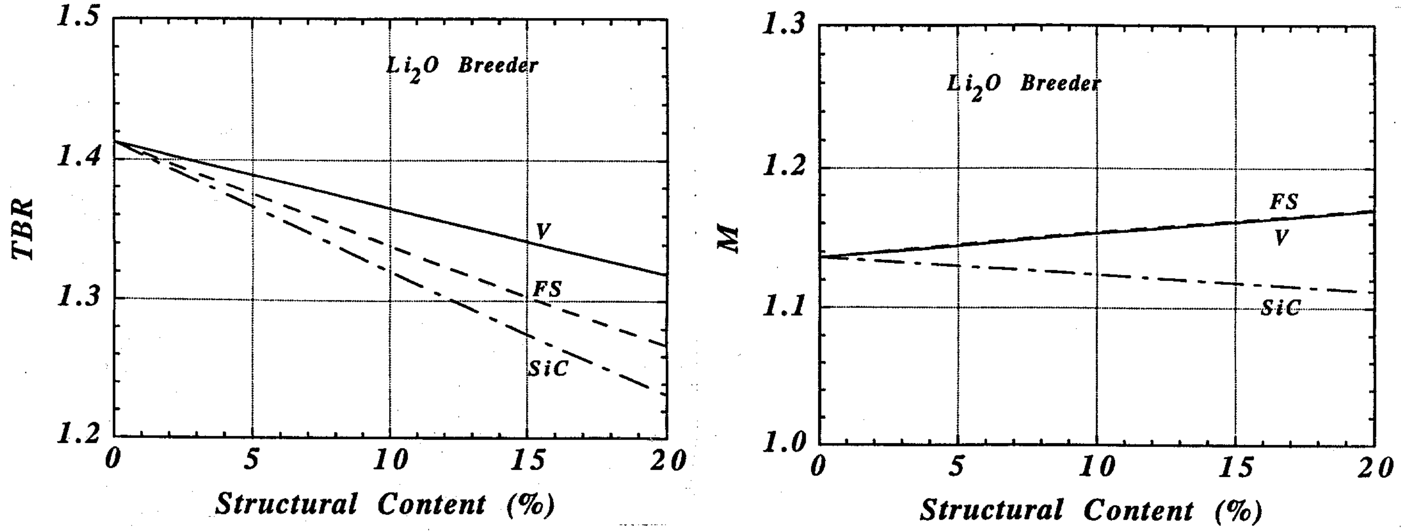

Fig. 4. Effect of V, SiC, and FS structural content on TBR and M for Li_2O breeder.

In the second set of calculations, two LM and SB were selected to illustrate the effect on TBR and M of the structures and neutron multipliers. The breeders are Li, $Li_{17}Pb_{83}$, Li_2O, and Li_2TiO_3. Figs. 2, 3, 4, and 5 illustrate the impact of the three candidate structural materials: V alloy (V5Cr5Ti), SiC/SiC composites, and FS (modified HT-9). Note that all structures degrade the breeding and enhance the energy multiplication, except SiC which degrades both. Vanadium has the least impact on the breeding of LM and SB, followed by FS and SiC, except for $Li_{17}Pb_{83}$. The effect of using a neutron multiplier with SB is displayed in Figs. 6 and 7. Here the SB blanket follows the multiplier zone. As anticipated, Be is the best neutron multiplier, followed by Pb, Be_2C and BeO. All multipliers multiply the neutron energy, except Pb. This study suggests that Be_2C is a potential multiplier that may provide sufficient breeding for a Li_2O blanket. It should be pointed out that Be_2C is chemically less reactive than beryllium metal and therefore has less safety concerns.

IV. DEMO TRITIUM BREEDING REQUIREMENT

The tritium breeding requirement was identified for the U.S. Demo. The main implication of the established requirement of a closed T fuel cycle is that the breeding blanket will supply all the tritium (T) needed for Demo operation (0.2 - 0.3 kg/d). An external T supply is only needed at the start of operation and for a short period of time until steady state T production is reached. To warrant the T self-sufficiency for Demo, the uncertainties in all design elements should be accounted for when estimating the breeding level for the various blanket options. The largest source of uncertainty (~10%) is that for the basic nuclear data and calculational models. Thus, the overall tritium breeding ratio (TBR) should exceed 1.1 to assure that the net TBR achievable after Demo operation exceeds unity. Actually, the achievable TBR could range between 1 and 1.2, for ±10% uncertainty. Therefore, provisions should be made in the

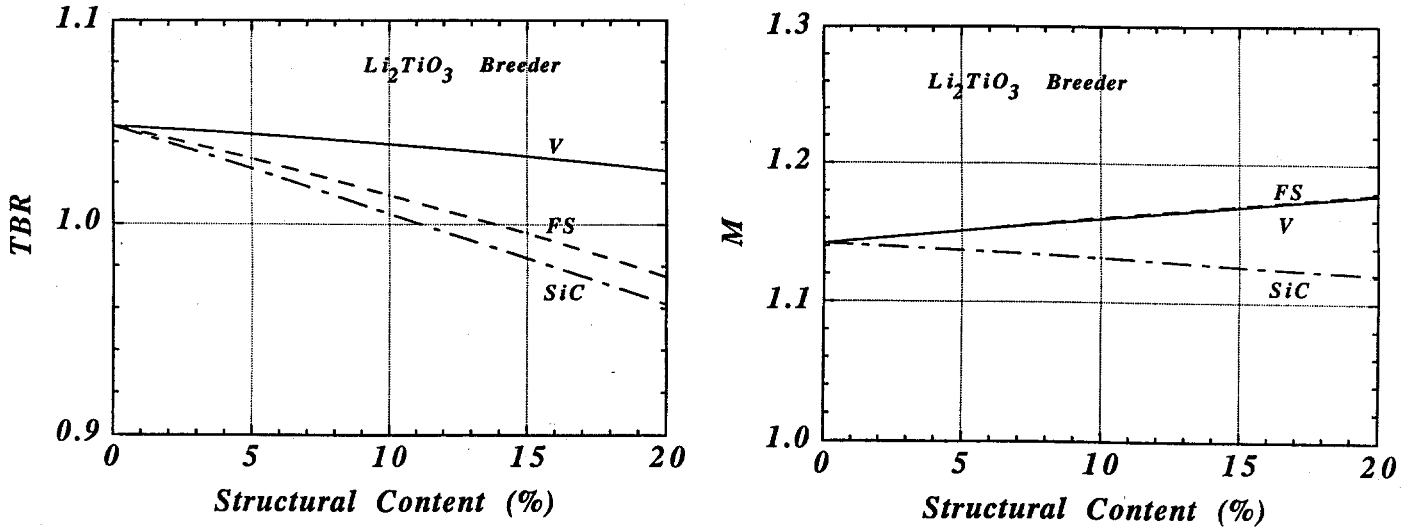

Fig. 5. Effect of V, SiC, and FS structural content on TBR and M for Li_2TiO_3 breeder.

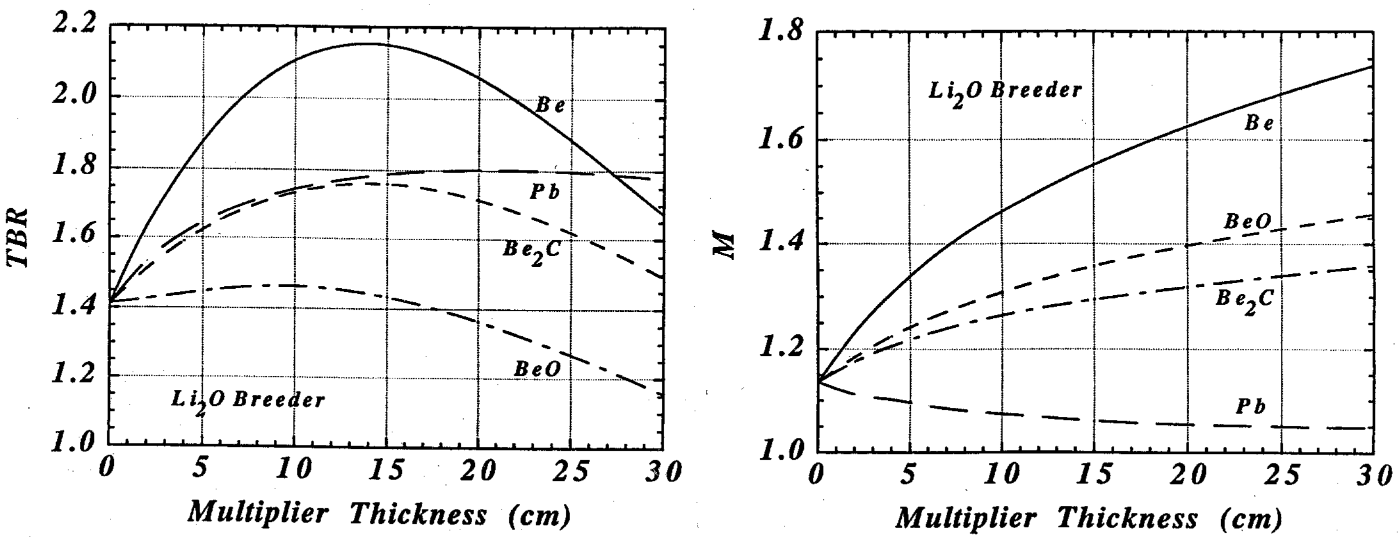

Fig. 6. Effect of Be, Pb, Be_2C, and BeO neutron multipliers on TBR and M for Li_2O breeder.

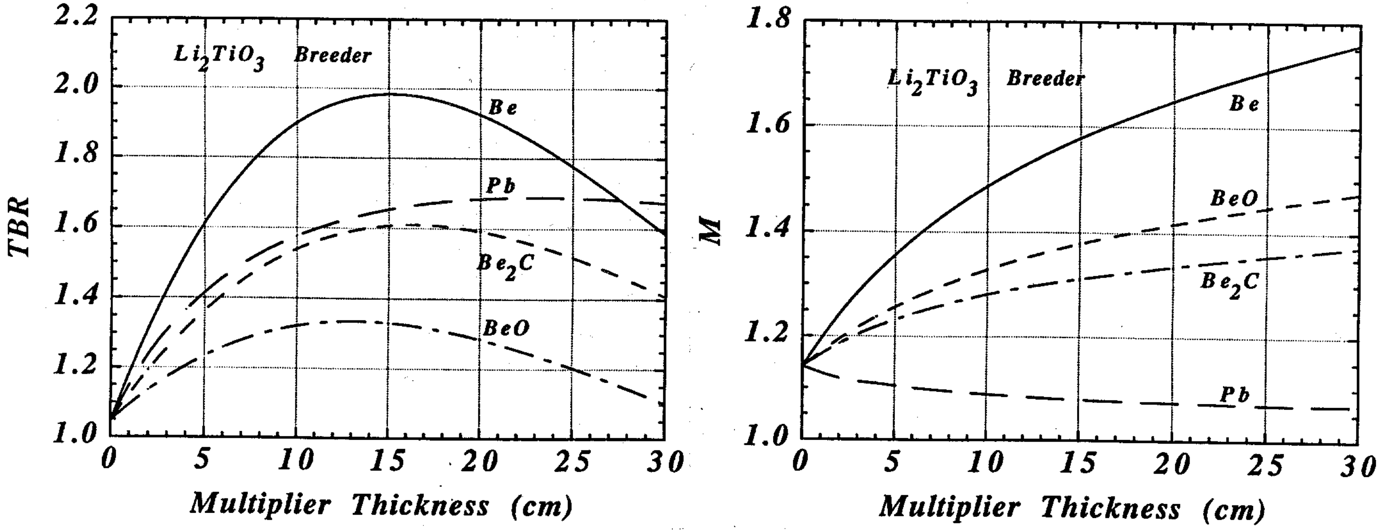

Fig. 7. Effect of Be, Pb, Be_2C, and BeO neutron multipliers on TBR and M for Li_2TiO_3 breeder.

blanket design to adjust the breeding after operation to the required level. It should be mentioned that the overall TBR should be calculated for the reference design and the effect of the elements that degrade the breeding (such as penetrations, assembly gaps, side walls, Li burnup, and configuration) should all be included in the computed TBR. To enhance the breeding, it is recommended to reduce the structure, maximize the blanket coverage, and locate penetrations off midplane as much as practically possible. Other options, particularly for blankets with marginal breeding, include the use of neutron multiplier and/or enriching the lithium.

V. SUMMARY

The neutronics analysis has concluded that Li, $Li_{17}Pb_{83}$, Li_2O and Li_2TiO_3 breeders have the potential to meet the U.S. Demo breeding requirements. LM can provide T self-sufficiency while SB will most likely require a neutron multiplier to achieve net breeding in a realistic design. Besides neutronics performance, other features will be considered in selecting the Demo breeder and structure. The safety features will be a key factor in the selection process. Design solutions will be identified in the Demo study to address the various safety concerns associated with the selected materials.

ACKNOWLEDGMENT

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REFERENCES

[1] L. A. El-Guebaly, "Neutronics Assessment for the ARIES Advanced Reactor Studies," *Fusion Engineering and Design*, vol. 28, pp. 658-664, 1995.