Need for Online Adjustment of Tritium Bred in Blanket and Implications for ARIES Power Plants

L.A. El-Guebaly, S. Malang, and the ARIES Team

July 2009

UWFDM-1372

Proceedings of 3rd IAEA Technical Meeting on First Generation of Fusion Power Plants: Design and Technology, July 13-15, 2009, Vienna, Austria. To be published by IAEA..

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

Need for Online Adjustment of Tritium Bred in Blanket and Implications for ARIES Power Plants

L.A. El-Guebaly, S. Malang, and the ARIES Team

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

http://fti.neep.wisc.edu

July 2009

UWFDM-1372

Proceedings of 3rd IAEA Technical Meeting on First Generation of Fusion Power Plants: Design and Technology, July 13-15, 2009, Vienna, Austria. To be published by IAEA..

Need for Online Adjustment of Tritium Bred in Blanket and Implications for ARIES Power Plants

L.A. El-Guebaly[1] and S. Malang[2]
and the ARIES Team

[1]*Fusion Technology Institute, University of Wisconsin, Madison, WI,* elguebaly@engr.wisc.edu
[2]Consultant, Fliederweg 3, D 76351 Linkenheim-Hochstetten, Germany, *smalang@web.de*

Abstract

For many researchers involved in fusion power plant development, the issue of tritium self-sufficiency is of particular concern because of the danger of placing the plant fuelling at risk. The tritium (T) bred in the blanket should be estimated fairly accurately as an uncertainty as small as 1% translates into 1-2 kg of T per FPY for 2-3 GW fusion power. This has a significant impact that is important not only for a shortage of T, but also for a surplus of T. The real question is not whether any blanket design could eliminate the danger of a T shortage or surplus – it should – but whether it offers a practical solution for breeding adjustment (up or down) during plant operation in order to precisely control the narrow T operating window. To mitigate concerns about T fuelling, it is less risky to produce more T during operation with the understanding that an online adjustment of the breeding level is necessary. This adjustment is feasible for power plants employing liquid breeders through fine-tuning of the ^{6}Li enrichment while difficult to envision for solid breeder blankets.

1. Introduction

The annual T consumption of any fusion power plant operating at the GW fusion power level is very high (55.6 kg per full power year (FPY) per GW). This means all fusion power plants must breed their own T needed for plasma operation as external sources of T are insufficient, impractical, and/or inaccessible. The calculated tritium breeding ratio (TBR - ratio of T produced in blanket to T consumed in plasma) should be accurately estimated as an uncertainty as small as 1% translates into 1-2 kg of T per FPY for 2-3 GW fusion power. Fusion designs developed to date displayed a wide variety of calculated TBR, ranging from 1.05 to 1.8 [1]. Each power plant should develop its own set of breeding requirements. Such requirements are design and breeder dependent and evolve with time, as will be explained later.

Due to several uncertainties in the design elements, the Net TBR during operation could be as low as 1.01 for advanced fusion designs – much lower than the calculated TBR (≈ 1.1 for ARIES designs). Early generations of fusion plants may require a Net TBR > 1.01 for shorter doubling time and faster penetration of the energy market, while a mature fusion system may call for 1.002 < Net TBR < 1.01. Moreover, fusion plants may not operate in a uniform manner, generating more/less T during operation according to the evolution of the T inventory with time, the need for variable doubling time, the need for higher/lower breeding over a certain time period (with the same integral amount of T over blanket lifetime), and/or the availability of T recovered from the detritiation system. More importantly, for licensing considerations, fusion designs cannot generate more T than needed for plasma fuelling. All these issues strongly support the argument that an online adjustment of breeding is highly desirable for all fusion power plants [1].

2. Breeding Margin

The breeding margin (calculated TBR – 1) can be divided into four distinct categories as illustrated in Fig. 1 and listed below in descending order. In a simplified model, these contributions can be added to provide a total uncertainty:

- Margin that accounts for known deficiencies in nuclear data (6-10%)
- Margin that accounts for known deficiencies in modeling (3-7%)
- Margin that accounts for unknown uncertainties in design elements (0-3%)
- Margin that accounts for T bred in excess of T consumed in plasma (1-2%).

The values between parentheses indicate the expected contribution of each category to the breeding margin of the LiPb system in particular. The reason for the wide range is that some data are incomplete and/or some values depend on the sophistication of the modeling tools. Building upon what has been accomplished over the past few decades and based on our extensive experience in blanket designs, educated guesses have been made whenever data are scarce or missing. The lower end of the range represents the adopted values for the ARIES LiPb design system utilizing the newly developed CAD/MCNPX approach [2] to calculate the overall TBR and including in the 3-D model all the engineering details that affect the breeding significantly.

Various scenarios and detailed numerical models to evaluate the breeding margin have been developed by UCLA and UW over the past two decades [3]. The 1990s numerical uncertainties/sensitivity analyses predicted 2-6% change to the calculated TBR due to uncertainties in nuclear data. More recently, reports of some experimental results for solid breeders (SB) have declared even larger uncertainties (10-20%). Reference 3 emphasized the dependence of the required Net TBR on the physics and technology parameters of fusion designs. We confirmed this statement and developed a simple but accurate approach for advanced ARIES designs, describing and quantifying the essential elements comprising the ARIES Net TBR (~1.01). The most essential requirements include [1]:

- T burnup fraction in plasma exceeding 10%
- High reliability and short repair time (< 1 day) for T processing system
- Three or more T processing systems
- T and α particles recycled at high rates
- Low T inventory in all subsystems
- Extremely low T losses to environment (< 4 g/y).

An extensive research and development (R&D) program is needed to reduce the gap between the required calculated TBR (~1.1) and Net TBR (~1.01). Both analytical and lab-based studies are necessary to validate the analytical predictions of T production rates and to demonstrate T generation, recovery, storage, and fuel cycle that eventually lead to T self-sufficiency. Active breeding-related R&D programs have been ongoing for decades in US, Europe and Japan.

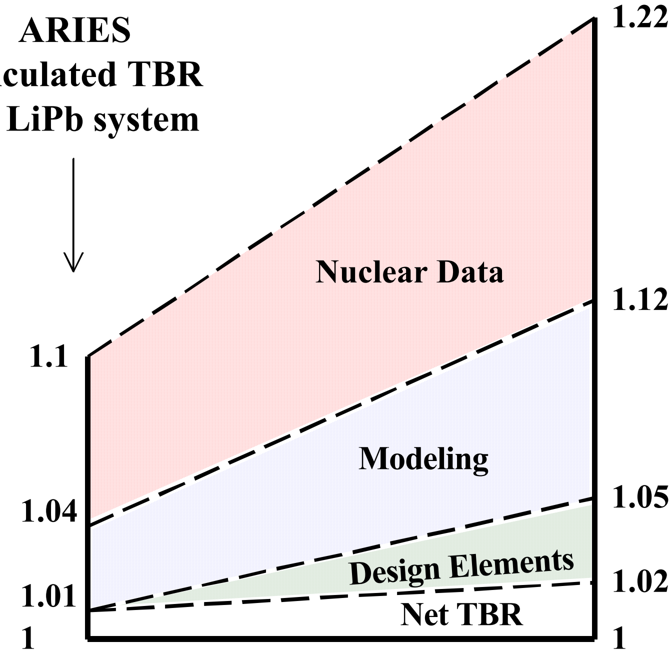

Figure 1. Calculated TBR for a range of breeding margins.

In reality, the Net TBR will not be verified until after the operation of a Demo plant with fully integrated blanket and T extraction and processing systems. We will certainly know what to design for before building the first generation of fusion power plants and any existing blanket design will be redesigned accordingly. Therefore, all blanket designs should be flexible and be able to accept a few necessary changes in order to deliver a Net TBR of 1.01. For liquid breeders, the most practical solution is to adjust the ^{6}Li enrichment online, as will be explained shortly for an over-breeding blanket (Net TBR > 1.01). For solid (or ceramic) breeders, a practical solution is to adjust the ^{6}Li enrichment after the first blanket change-out or replace a few breeding modules by shielding components. In case of an under-breeding blanket (Net TBR < 1.01), major design changes are anticipated in order to raise the TBR, unless the reference blanket parameters are determined for ^{6}Li enrichment < 90%. These major changes include thickening the blanket, replacing the W stabilizing shells of ARIES-AT by Al or Cu shells, lowering the structural content within the blanket, adding a beryllium multiplier to the blanket, increasing the plasma aspect ratio, or operating tokamaks in a single-null mode. Some of these changes may not be feasible during operation. It is therefore less risky to design an over-breeding blanket (with Net TBR of 1.01 - 1.02) and in the meantime develop a feasible scheme to adjust the breeding shortly after plant operation. Supporting calculations should be performed prior to plant operation in order to assess the impact of the preferred change(s) on breeding as well as on related design parameters (thermal, shielding, configuration, costing, etc.).

3. Online Adjustment of TBR via ^{6}Li Enrichment

3.1 Why do we need online adjustment of TBR with high accuracy?

In most discussions on the required TBR, emphasis is placed on maximizing the breeding rate of the blanket to assure T self-sufficiency. Very rarely discussed is the issue of too much breeding that could cause problems such as the storage of the excess T generated during the blanket lifetime and could become a safety issue, particularly in the absence of means to adjust the TBR during plant operation. In principle, such adjustment is feasible with liquid breeder blankets since the ^{6}Li concentration can be varied online over a wide range of interest. This is impossible for ceramic breeder blankets where an adjustment of the breeding rate would involve replacing some breeding by shielding modules or require some type of "trim rods" as used in fission reactors. To our knowledge, such a method has never been considered until now.

In order to illustrate if over-breeding can become a serious problem, the annual amount of T burned in a power plant has to be considered. The following T balance can be made for both ARIES-CS [4] and -AT [5] power plants:

	ARIES-CS	**ARIES-AT**
T burnup rate (kg/FPY)	135	97.8
Startup inventory (kg)	4	2
T decay (kg/y)	0.33	0.16
Excess T breeding (kg/FPY):		
with Net TBR = 1.01	1.35	0.98
with Net TBR = 1.02	2.7	1.96
with Net TBR = 1.05	6.75	4.89

The surplus of T generated over a blanket lifetime of 5 years (after subtracting the desired start-up inventory for a new plant (with a doubling time of 5 years) and the amount of T decayed) would be significant, depending on the Net TBR (see Fig. 2). For comparison, the total amount of T accumulated from all CANDU reactors [6] at their peak, anticipated for 2025, amounts to ~30 kg. This example shows clearly that the net T breeding averaged over the lifetime of the blanket has to be controlled with accuracy better than 1% to ensure T self-sufficiency without a storage problem for the surplus of T.

3.2 Possible methods for online adjustment of TBR of Pb-17Li blanket

In the past, most blanket and power plant studies utilized 90% enriched ^{6}Li in the eutectic lead lithium alloy to maximize the breeding. Only recently, in the ARIES-CS study [7], the design point has been moved to 70% enrichment in order to provide some extra margin to increase the TBR online, if needed. In ARIES-AT, the reference design point is 90% enriched ^{6}Li with a calculated TBR of 1.1 [8]. The sensitivity of the calculated TBR to the ^{6}Li enrichment is shown in Fig. 3 for the ARIES-AT LiPb/SiC blanket. To illustrate the online TBR adjustment scheme, we examined an extreme case of over-breeding where the 1.1 calculated TBR should actually be equal to the 1.01 Net TBR. In other words, the blanket delivers much more breeding during operation than actually needed for plasma fueling. To fix this over-breeding problem, the ^{6}Li enrichment of LiPb can be reduced to ~50% in order for ARIES-AT to provide a TBR of 1.01 (refer to Fig. 3). How can this be accomplished in practice? This is explained in the following simple example.

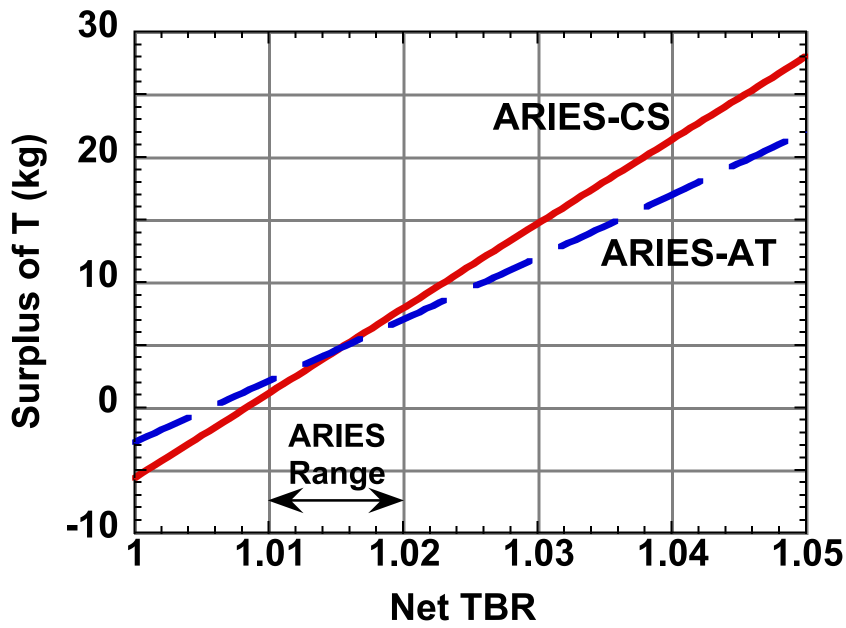

Figure 2. Impact of Net TBR on T surplus.

Assuming a total LiPb breeder volume in the entire plant of ~500 m^3, we have:

Total Pb-17Li mass ~5000 tons

Li content in $Li_{17}Pb_{83}$ with 90% enrichment (0.6 wt%) ~30 tons

Starting 90% ^{6}Li enrichment ⇒ ^{6}Li content in 90% enriched LiPb ~26.6 tons

Required 50% ^{6}Li enrichment ⇒ ^{6}Li content in 50% enriched LiPb ~14.7 tons

Required Li adjustment: 11.9 tons of ^{6}Li need to be replaced by ^{7}Li.

Two practical methods are feasible for TBR adjustment through combining two Pb-17Li eutectics with different enrichments:

a) Replace 2226 tons of the 90% ^{6}Li enriched Pb-17Li by 2226 tons of Pb-17Li with 100% ^{7}Li. For practical reasons, the amount of replaced Pb-17Li would be higher if ^{7}Li enrichment is < 100%.
b) Remove 13.5 tons of Li with 90% ^{6}Li enrichment from the eutectic alloy and replace it with 13.5 tons of ^{7}Li.

Which method is more suitable for the online adjustment of the ^{6}Li enrichment?

- Method-a is straightforward but requires an additional storage volume for the eutectic alloy (~200 m^3 in this example).
- Method-b does not require such large storage, but needs a practical method to remove about half of the Li with 90% ^{6}Li enrichment from the eutectic and feed the Li back with 100% ^{7}Li. The first step of separating the Li from the eutectic alloy is feasible by oxidizing the Li content in the alloy. The second step has already been investigated for the online replenishment of the ^{6}Li burnup by adding small amounts of Li-rich Pb-Li alloy (LiPb, Li_3Pb, or Li_7Pb_2) to the eutectic alloy [9,10].

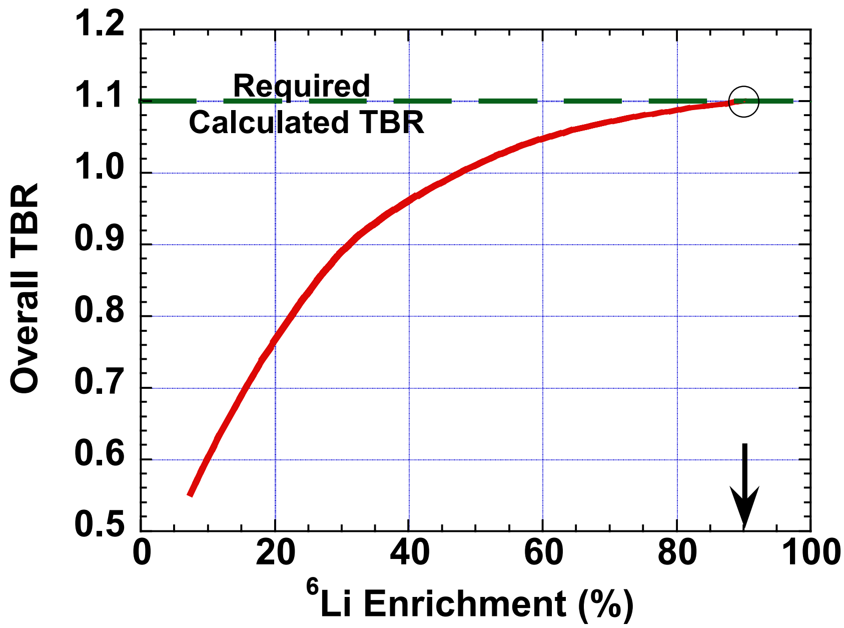

Figure 3. Sensitivity of TBR to ^{6}Li enrichment for ARIES-AT LiPb/SiC blanket [8].

This example pertains to an extreme case where the reduction of the Net TBR is assumed to be from 1.1 to 1.01. By the time a Demo blanket is manufactured and built and with the support of a dedicated breeding-related R&D program, the margin between the calculated and Net TBRs will be < 9% (probably in the order of 2-3%). This would reduce the amount of Li to be exchanged in the above example by 3-4 fold.

4. Conclusions

To avoid the T shortage problem, the calculated TBR must exceed unity by a margin. This margin evolves with time and is design and breeder-dependent. A dedicated R&D effort should reduce the difference between the calculated TBR and Net TBR. To achieve a Net TBR of 1.01 (or lower) with sufficient precision, despite the rather large uncertainties in design elements, an online control of tritium breeding is mandatory for all fusion designs. The potential problem of handling the surplus of T in case of over-breeding has been overlooked in the past studies. To avoid the potential risk of T shortage/surplus, this work underlines the need for an online adjustment of TBR and describes this possibility for liquid breeder blankets by adjusting the ^{6}Li enrichment during plant operation. Such an online adjustment is not feasible for solid breeder blankets. Since Demo is the last step before commercialization of fusion energy, the online adjustment of T bred in the blanket should be demonstrated on Demos employing liquid breeders to gain high confidence in this approach and to assure the first fleet of commercial fusion power plants meets the strict breeding requirement.

References

[1] L. El-Guebaly and S. Malang, Toward the ultimate goal of tritium self-sufficiency: technical issues and requirements imposed on ARIES advanced fusion power plants, Fusion Engineering and Design 84 (2009) 2072-2083.

[2] DAG-MCNPX User Manual. Available at: http://cnerg.engr.wisc.edu/cgi-bin/index.cgi/wiki?p=UsingDagmc

[3] M.E. Sawan and M.A. Abdou, Physics and technology conditions for attaining tritium self-sufficiency for the DT fuel cycle, Fusion Engineering and Design 81 (2006) 1131-1144.

[4] F. Najmabadi, A.R. Raffray, S. Abdel-Khalik, L. Bromberg. L. Crosatti, L. El-Guebaly et al., The ARIES-CS compact stellarator fusion power plant, Fusion Science and Technology 54, No. 3 (2008) 655-672.

[5] F. Najmabadi, A. Abdou, L. Bromberg, T. Brown, V.C. Chan, M.C. Chu, F. Dahlgren, L. El-Guebaly et al., The ARIES-AT advanced tokamak, advanced technology fusion power plant, Fusion Engineering and Design 80 (2006) 3-23.

[6] CANDU reactors: http://www.candu.org/candu_reactors.html.

[7] L. El-Guebaly, P. Wilson, D. Henderson, M. Sawan, G. Sviatoslavsky, T. Tautges et al., Designing ARIES-CS compact radial build and nuclear system: neutronics, shielding, and activation, Fusion Science and Technology 54, No. 3 (2008) 747-770.

[8] L.A. El-Guebaly, Nuclear performance assessment of ARIES-AT, Fusion Engineering and Design 80 (2006) 99-110.

[9] H. Feuerstein, D.A. Wirjantoro, L. Hoerner, S. Horn, Eutectic mixture Pb-17Li - in-situ production and Li-adjustment, Fusion Technology 2 (1994) 1257-1260.

[10] P. Hubberstey, M.J. Capaldi, F. Barbier, Replenishment of lithium lost from Pb-17Li, Fusion Technology 2 (1996) 1475-1478.