Tritium Breeding Strategy for Advanced Fusion Power Plants

L.A. El-Guebaly

University of Wisconsin-Madison

laila.elguebaly@wisc.edu

Executive summary of proposed strategic element:

The transition from ITER to fusion DEMO and power plant requires the development of a tritium breeding blanket to generate tritium (T) in unprecedented large quantities to sustain the plasma operation. There is a definitive need to breed all T required to fuel the plasma and sustains its operation: 55.6 kg of T per GW of fusion power, per full power year (FPY) of operation. This white paper provides our current understanding of the breeding-related challenges for the prominent US dual-coolant lead lithium (DCLL) blanket [1,2], pinpoints the uncertainties in the tritium breeding prediction, and suggests a strategy to assure T self-sufficiency and mitigate the risk of a shortage or surplus of T.

Scientific and/or engineering opportunity:

The tritium breeding ratio (TBR) is a key metric for devices seeking T self-sufficiency. A calculated TBR above unity implies the facility breeds T at a level closely approaching or exceeding the combination of consumption, uncertainties in the TBR prediction, and T holdups, losses, decay, etc [3-6]. It is believed that ITER will consume almost all T recovered from CANDU reactors (~1.7 kg/y) [10]. Other sources of T exist in the U.S. and abroad, but they are limited in supply, classified, uneconomical, and/or inaccessible for general use [7,8]. The cost of purchasing T is expensive enough to enable defining the mission of DEMO and power plants (e.g., T self-sufficiency) and designing some components around the TBR. Thus, fusion devices generating substantial fusion power and consuming 10s-100s kg of T annually must breed their own T in a blanket to negate the risk of relying on external supplies to provide/control the essential fuel of the machine.

The TBR should be estimated with high fidelity. It is design and breeder dependent and should be established and carefully tailored for each design separately [3] as a small 1% error in the TBR estimation is equivalent to ~1.1 kg of T/FPY for a typical fusion power plant with 2000 MW fusion power. At a T unit cost ranging from ~$30k to ~$118k per gram [9], 1% deficiency implies an additional FPY operational cost of $33-131M to purchase T from external sources. For advanced fusion designs, the TBR requirement reached its lowest value of 1.05 for ARIES-ACT [6] – the most recent power plant study in the ARIES series [10]. The 0.05 breeding margin accounts for known deficiencies in nuclear data (3%), unknown deficiencies in modeling (1%), and T bred in excess of T consumed in plasma (1%). The first margin is derived from recent European experiments to validate the nuclear data for EU blankets. The 3-D model that estimates the TBR should include all engineering and structural details of the blanket and its surroundings as specified by designers using advanced CAD-based 3-D neutronics tools to model fine details of blanket. Nevertheless, a margin of 1% accounts for design elements that could be overlooked during modeling. Strong, optimistic assumptions have been made to limit the last margin to 1%. This excess T is required to provide the startup inventory for a new fusion power plant, to compensate for T holdups in the structure and decay of stored T, and to account for the T lost to the environment [3,6]. Highly efficient T extraction system with redundant components, short times for T reprocessing, and efficient detritiation system are also projected for advanced fusion designs. In the future, the first and second margins will gradually diminish as the nuclear data evaluation improves and more sophisticated 3-D CAD-based codes are developed. An ambitious goal for the net TBR is 1.01, which is achievable with dedicated R&D programs.

Even after a fusion plant is designed and built, there will be uncertainties during the facility's operation that will determine the actual breeding level. Achieving a net TBR of 1.01 cannot be verified until after operating DEMO or power plant with fully integrated blanket, T extraction system, and T processing system. Therefore, any blanket design should have a flexible approach and be able to accept a few necessary changes in order to deliver a net TBR slightly above one. The most practical solution is to operate the DCLL blanket with a ^{6}Li enrichment < 90% and develop a scheme that adjusts the Li enrichment online during operation to compensate for unanticipated tritium production, usage and losses [3,11,12]. This novel scheme helps assure the T self-sufficiency and mitigates the risk of a shortage or surplus of T, but should be tested and matured with R&D programs.

Technology Development and Maturity

A well-planned and executed R&D program is needed to reduce the unknowns involving the T production, storage, processing, etc. A large knowledge gap exists between near-term fusion experiments (such as ITER [13] that generates ~4 g of T/y) and future power plants (that will produce and consume ~110 kg of T/FPY). To advance the fusion energy, a R&D program, involving both analytical studies and lab-based demonstrations, is essential to reduce the breeding margin to ~1% by demonstrating the online adjustment of enrichment, improving and validating the T production predictive capabilities (nuclear data and codes), demonstrating the T recovery and storage processes, and determining the T inventory, holdups, and efficiency of T processing and detritiation systems. Several technologies could assure the T self-sufficiency and lower the TBR requirement from 1.05 to 1.01 for advanced power plants. Small-scale R&D activity, lab testing experiments, and code development involve efforts to:

- Develop the necessary technology and practical scheme to adjust the ^{6}Li enrichment online [11]
- Improve the TBR prediction for the DCLL blanket with better evaluation of nuclear data using 14 MeV neutron integral experiments. The main goal is to improve the cross section data evaluation and diminish the uncertainty in TBR due to nuclear data.
- Improve the TBR prediction by diminishing the uncertainty in calculated TBR attributed to approximations in modeling. High fidelity TBR computations would be established with the state-of-the-art DAGMC code [14-16] that couples the detailed CAD geometry of blanket internals with 3-D MCNP code [17].
- Improve the accuracy of the 1.01 minimum TBR (excluding uncertainties in nuclear data and modeling) by launching R&D programs to:
    - Accurately determine T inventory holdups for all in-vessel and ex-vessel components

  - Increase efficiency, improve performance, and shorten time for T reprocessing and extraction systems for PbLi [1,18]
  - Develop efficient detritiation system
  - Minimize T losses to environment
  - Develop efficient T accountancy system.

Lastly, we describe how the proposed strategic element addresses the four NAS charge factors:

1. **Ensuring U.S. leadership in a field of plasma physics and/or fusion development:**

   The US invented the DCLL blanket concept in the late 1990s [19,1]. The proposed tritium breeding strategy supports the fusion development by allowing US researchers to further enhance the DCLL blanket design, assure its T self-sufficiency, and remain the world leader for the DCLL blanket concept.

2. **Impact on present and future international activities and collaborations by U.S. scientists:**

   To maintain our international competitiveness, we suggest initiating a new international research activity specifically for the DCLL blanket with the Frascati 14 MeV Neutron Generator at ENEA in Italy [20]. In addition, the US could collaborate with the Karlsruhe Institute of Technology (KIT) in Germany [21] to help develop the knowledge base for low T inventory, short processing time, efficient T extraction from PbLi breeder, and sound T accountancy system.

3. **Impact on the health of domestic fusion research at universities, national labs, and industry:** The proposed strategy provides the opportunity to engage diversity of activities at universities (UW and UCLA), national labs (SRNL, ORNL, and INL), and industry (to develop efficient Li enrichment techniques). Furthermore, the program will attract newcomers to UW and provide opportunities to work at the frontiers of neutronics research and code development. The T extraction and processing knowledge base can be tested at the Hydrogen Technology Research Laboratory at SRNL [22] and at the Safety and Tritium Applied Research (STAR) laboratory at INL [23].

4. **Impact of/from unanticipated events or innovations requiring programmatic re-direction:**

   The tritium breeding strategy would be unaffected by unanticipated events in fusion research or innovations to improve the fusion development. It is applicable to all power plant and FNSF concepts (tokamaks, spherical torii, stellarators, etc.), employing the DCLL blanket [24].

References

1. S. Malang et al. (2011). “Development of the lead lithium (DCLL) blanket concept,’’ Fusion Science and Technology, 60, 249.
2. L. A. EL-GUEBALY, L. V. BOCCACCINI, R. J. KURTZ, and L. M. WAGANER, “Technology-Related Challenges Facing Fusion Power Plants,” Chapter in book: Fusion Energy and Power: Applications, Technologies and Challenges. NOVA Science Publishers, Inc.: Hauppauge, New York, USA. ISBN: 978-1-63482-579-5 (2015).
3. 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, 2072 (2009).
4. 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.
5. L. El-Guebaly, A. Jaber, and S. Malang, “State-of-the-Art 3-D Assessment of Elements Degrading the TBR of the ARIES DCLL Blanket," Fusion Science and Technology 61, #4 (May 2012) 321-331.
6. L. El-Guebaly, L. Mynsberge, A. Davis, C. D’Angelo, A. Rowcliffe, B. Pint, “Design and Evaluation of Nuclear System for ARIES-ACT2 Power Plant with DCLL Blanket,” Fusion Science and Technology, 72, Issue 1 (2017) 17-40.
7. The JASON Report on Tritium. MITRE Corporation, JSR-11-345, November 2011.
8. M. Kovari, M. Coleman, I. Cristescu and R. Smith 2018, *Tritium resources available for fusion reactors*, *Nucl. Fusion* **58** 026010.
9. DOE Inspector General Report DOE IG-0632, December 2003; www.ig.energy.gov/documents/CalenderYear2003/ig-0632.pdf.
10. The ARIES Project: http://aries.pppl.gov.
11. L. A. EL-GUEBALY and S. MALANG, “Need for Online Adjustment of Tritium Bred in Blanket and Implications for ARIES Power Plants,” University of Wisconsin Fusion Technology Institute Report, UWFDM-1372 (2009). Available at: http://fti.neep.wisc.edu/pdf/fdm1372.pdf.
12. Morgan, L. & Pasley, J. (2013). “Tritium breeding control within liquid metal blankets,” Fusion Engineering and Design, 88, 107-112.
13. The ITER project: http://www.iter.org/.
14. P. P. H. WILSON et al., “Acceleration Techniques for the Direct Use of CAD-Based Geometry in Fusion Neutronics,” Fusion Engineering and Design, 85, 10-12, 1759 (2010).
15. “DAGMC Users Guide,” University of Wisconsin-Madison Fusion Technology Institute (2008); http://svalinn.github.io/DAGMC/usersguide/.
16. P. Wilson et al., “Predictive Modeling & Simulation for Optimization of Fusion Energy Systems.” Whitepaper on Proposed Strategic Element for US Magnetic Fusion Research, submitted to July 24-28, 2017 Workshop at UW-Madison, WI.
17. MCNP X-5 MONTE CARLO TEAM, “MCNP–A General Monte Carlo N-Particle Transport Code, Version 5.” Volume I: Overview and Theory, LA-UR-03-1987; Volume II: User’s Guide, LA-CP-03-0245; Volume III: Developer’s Guide, LA-CP-03-0284, Los Alamos National Laboratory (2005).
18. P. Calderoni, “Extraction of Tritium from Lithium Based Liquid Metals.” Whitepaper submitted to Fusion Energy Sciences Advisory Committee (FESAC) Transformative Enabling Capabilities (TEC), June 2017.
19. Najmabadi, F. & The ARIES Team. (2003). “Spherical torus concept as power plants–the ARIES-ST study,” Fusion Engineering and Design, 65(2) 143-164.
20. The Frascati Neutron Generator at ENEA, Italy: http://192.107.92.74/fng.
21. Karlsruhe Institute of Technology: http://www.kit.edu/english/index.php.
22. The Savannah River National Laboratory: http://srnl.doe.gov/.
23. Safety and Tritium Applied Research (STAR) at INL: http://nuclear.inl.gov/fusionsafety/experiments/star.shtml.
24. L. El-Guebaly, “Nuclear Assessment to Support ARIES Power Plants and Next Step Facilities: Emerging Challenges and Lessons Learned,” Submitted to Fusion Science and Technology.