**A tritium research program in support of burning plasma science and fusion energy**

P. W. Humrickhouse1, M. Shimada1, P. Calderoni1, L. C. Cadwallader1, and B. J. Merrill1

1Idaho National Laboratory

**Email of first author:** paul.humrickhouse@inl.gov

**Executive summary of proposed strategic element:**

Tritium is the fuel of D-T fusion reactors, and it has long been understood that procurement and perpetuation of an adequate tritium supply for future burning plasma devices is a critical issue. Devices that operate beyond (or alongside) ITER will need to breed a comparable amount of tritium to what they burn; the bred tritium must in turn be extracted for re-use as fuel. This is complicated by the propensity of tritium to permeate through high-temperature materials, and the need to tightly control both permeation losses and tritium inventories for environmental, safety, and safeguards (tritium accountancy) reasons. ITER’s 4 kg maximum tritium inventory (~1.5x1018 Bq) is almost twice the radioactivity released from Fukushima Daiichi (0.8x1018 Bq), and releases of tritium to the environment or public exposures will eliminate any political advantage fusion has over other energy systems and fail to meet fusion’s promise of safe and clean energy.

While there are long-established physical models for estimating permeation, they presently lack any real predictive power as a result of very large uncertainties in the underlying parameters. Investigation of the influence of such uncertainties in just a couple of the relevant transport properties in the recent FNSF study [[[1]](#endnote-1)] resulted in tritium permeation loss estimates differing by about two orders of magnitude. It is difficult to design tritium extraction and confinement systems when the demand on them is so uncertain, and reliance on conservatism or bounding estimates may result in component and system designs that are unnecessarily costly and complex, or simply unrealizable. For these reasons a robust research effort supporting tritium science, from the fundamental transport phenomena progressing to multiple-effect, integral scale experiments, is needed to support the realization of burning plasmas and fusion energy.

**Scientific and/or engineering opportunity:**

Some of the most fundamental aspects of tritium transport important to future facilities have proved difficult to quantify. Consider, as an illustrative example, the analysis of the FNSF design referenced above. In principle, estimating tritium permeation and inventory in this (or any other) design depends on relatively few transport properties, albeit ones that must be known for all the materials in the system: the diffusivity, solubility, dissociation and recombination rates at interfaces, and radiation damage-dependent trap concentrations and energies, all temperature dependent. Though some of these such as diffusivity and solubility are in principle easy to measure in small experiments, such experiments are frequently not very repeatable; a well-known and particularly important example is the tritium solubility in lead-lithium, measurements of which span several orders of magnitude for reasons that are not understood. The first step in understanding tritium transport in a complex environment, then, is identifying the reasons for such large discrepancies in fundamental parameters, through review of legacy data, performance of new experiments, and establishment of standards for their execution to demonstrate and ensure repeatability.

Once these fundamental issues have been resolved, meaningful multiple-effect experiments can be undertaken. This includes investigation of the influence of radiation damage on tritium transport, an area in which important work is already ongoing [[[2]](#endnote-2)], and demonstration of coupled transport phenomena underlying most tritium extraction concepts. In a liquid breeder, for example, these involve transport of tritium in the liquid, release to another medium (e.g. a purge gas or solid permeation membrane), and diffusion or convection out of the system. Concepts such as compact mass extractors [[[3]](#endnote-3)], droplet sieves [[[4]](#endnote-4)], and vacuum permeators [[[5]](#endnote-5)] are not new, and some theoretical estimates of their effectiveness are very promising. But these have not been demonstrated experimentally, and there is presently no plan to do so in the U.S., though experiments are now being pursued elsewhere in the world.

The final stages of such a program should progress toward testing at prototypic scales and in geometries and environments approaching the complexity of fusion. This would include elements such as: 1) in-pile fission reactor loops for demonstration of on-line tritium breeding and extraction systems; 2) investigation of the influence of magnetic fields and resultant MHD flows on tritium transport; and 3) testing of blanket segment prototypes in both radiation and magnetic fields.

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

In contrast to other ITER members Europe, Japan, Korea, China, and India, the United States is neither a participant in the ITER TBM program nor do we have a DEMO (or comparable next step device) program. Necessary tritium-related research and development is being driven by TBM and DEMO design data needs in these other countries but is simply not being performed in the U.S., and as a result we are not leaders in this field. An interesting empirical confirmation of this fact is found in the attendance demographics at the recent Symposium on Fusion Engineering, in which only one of 18 oral presentations related to tritium breeding and extraction was given by member of a U.S institution, that being an analysis of a foreign DEMO blanket design. Pursuit of an actual next-step device and initiation of a robust tritium science program in the U.S. as proposed here would begin to rectify this.

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

Many of the activities that would be envisioned under such a program are particularly well suited to international collaborations. One of the fundamental problems outlined above is the uncertainty associated with fundamental tritium transport properties and the non-repeatability of experiments performed to measure these. Resolution of such issues would be well served, for example, by international benchmark activities wherein each party performs measurements of standard materials in their own experimental facility. Such collaborations would be valuable in identifying the underlying reasons for such discrepancies and in standardizing measurement procedures.

**3. Impact on the health of domestic fusion research at universities, national labs, and industry**

We noted above the comparatively low level of U.S. participation in this area of research, and a more robust program can only improve this, at both national laboratories and universities. This is not presently an area in which industry participates significantly, but a program supporting experiments that progress toward components and prototypes should increase industry participation in their construction.

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

Some of the ideas discussed here (e.g. for tritium extraction systems) are not new, but their successful realization would change the fusion landscape. The purpose of the recommended program is to *drive* these and other such innovations in the area of tritium science.

**Additional Considerations:**

Two final points should be emphasized. The first is that the proposed research is necessary regardless of whether U.S. fusion research has an explicit energy mission, or is focused solely on burning plasma science; a burning plasma is fueled by tritium, and its continued operation will depend on breeding and managing tritium. Secondly, the committee has been charged with evaluating scenarios in which the U.S. either is, or is not, a member of ITER; while much tritium science will certainly be learned in ITER, its primary purpose is not blanket or tritium science; it will operate at lower temperatures and at a much lower duty factor than future devices, and does not breed tritium except in the TBMs. The proposed R&D program is therefore equally necessary regardless of future U.S. participation in ITER.

1. [] P. W. Humrickhouse and B. J. Merrill, “Tritium aspects of the Fusion Nuclear Science Facility,” *Fusion Engineering and Design* (2017), doi:10.1016/j.fusengdes.2017.04.099. [↑](#endnote-ref-1)
2. [] M. Shimada, G. Cao, T. Otsuka, M. Hara, M. Kobayashi, Y. Oya and Y. Hatano, “Irradiation effect on deuterium behavior in low dose HFIR neutron-irradiated tungsten,” *Nuclear Fusion* **55** (2015) 013008. [↑](#endnote-ref-2)
3. [] N. Alpy, T. Dufrenoy, and A. Terlain, “Hydrogen extraction from Pb–17Li: results with 800 mm high packed column,” *Fusion Engineering and Design* **49–50** (2000) 775-780. [↑](#endnote-ref-3)
4. [] F. Okino, K. Noborio, Y. Yamamoto, and S. Konishi, “Vacuum sieve tray for tritium extraction from liquid Pb–17Li,” *Fusion Engineering and Design* **87** (2012) 1014-1018. [↑](#endnote-ref-4)
5. [] P. W. Humrickhouse and B. J. Merrill, “Vacuum permeator analysis for extraction of tritium from DCLL blankets,” *Fusion Science and Technology* **68** (2015) 295-302. [↑](#endnote-ref-5)