Materials science R&D required for the design of inertial fusion energy tritium breeding blankets

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EXECUTIVE SUMMARY

This white paper includes new measurements, modelling, and diagnostic development required for developing the tritium breeding blankets and fuel cycle infrastructure for inertial fusion energy (IFE). Because tritium is not produced in sufficient quantities, either naturally or as a by-product of fission reactors, to support the needs of a large-scale D-T IFE test facility or fusion reactor, it must be generated on-site. Fusion blankets are designed to handle this crucial function, and as a result are configured to surround the main chamber where the D-T reactions take place. In addition, blankets are intended to provide a means of absorbing energy deposited by the neutrons for power generation and to shield other critical sub-systems from the fusion environment. Several competing blanket designs have been developed and are planned for testing on the ITER magnetic fusion energy (MFE) experimental reactor. While some of the experience from ITER may translate well to blanket design for IFE, to date a complete tritium breeding system has yet to be demonstrated, and many significant technology challenges remain.

In this white paper, we describe several areas of R&D that are required to advance IFE blanket technology: (a) hydrogen isotope uptake and diffusion/permeation through blanket materials, (b) surface chemistry at gas-solid and liquid-solid interfaces, and (c) separation of tritium from exhaust gases. While the above list is not intended to be exhaustive, significant near-term progress is possible in each of these proposed research areas through new laboratory-scale experiments, development of novel diagnostics, and modelling. The information provided by such work would be invaluable for evaluating different proposed blanket designs. Several options for experimental and modelling research on these topics are discussed herein.

I. BACKGROUND

Tritium breeding has been recognized as a high priority for fusion R&D in several recent community-driven studies [1,2]. In part, this is in recognition of the substantial technical

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challenges that remain in this area; in the recent APS community report, breeding blanket technology is currently estimated to be at a TRL level between 1-2. Fortunately, this appears to be an area that is well-suited for collaboration between the IFE and MFE research communities. While the details of an IFE blanket design may differ from one optimized for MFE, there is considerable overlap in the foundational research needed to bring these concepts forward. In fact, 7 of the 8 near-term recommendations outlined for blanket development within the recent APS-DPP-CPP report "will equally benefit any fusion concept including tokamaks, stellarators, inertial fusion energy, and alternate concepts." [1]

As highlighted in the APS report, many of the early-stage design choices will likely be driven by materials science. Tritium can be bred through neutron reactions with Li, and current blanket concepts under consideration include solid breeders (e.g. porous ceramics) as well as liquid metals or molten salts. In addition, there are many options for the surrounding structural materials and cooling methods. (Several of the different concepts, including Dual Coolant Lead Lithium (DCLL), Helium Cooled Lead Lithium (HCLL), and Helium Cooled Ceramic Breeder/Pebble Bed (HCCB/PB), are discussed in a recent overview by Kessel and co-workers [3].) Being able to select between the various options, however, will require a much deeper understanding of materials performance in a fusion environment that includes exposure to high temperatures, tritium gas, and 14 MeV neutrons.

Beyond the blankets themselves, there are many other aspects of the infrastructure to process tritium that must be considered. Operational experience with previous D-T campaigns in IFE experiments at NIF (LLNL), the Z-Machine (SNL), and the Omega facility (University of Rochester) can provide useful guidance. However, the tritium requirements for a demonstration IFE plant will far exceed the requirements for these facilities, and tritium permeation and retention in materials will have to be modelled with unprecedented precision to ensure that proposed designs can meet safety and regulatory limits. In addition, efficient, high throughput methods of separating unused D and T fuel from other exhaust gases are needed to ensure efficient refueling.

This white paper includes proposals for experiments and modelling that would help close some of the gaps discussed above. The experimental work proposed could be carried out in the near-term (i.e. within the next 5 years) and would greatly solidify our ability to design breeding blankets for IFE.

II. PROPOSED R&D ACTIVITIES

A. Improving the experimental data for hydrogen diffusion and trapping

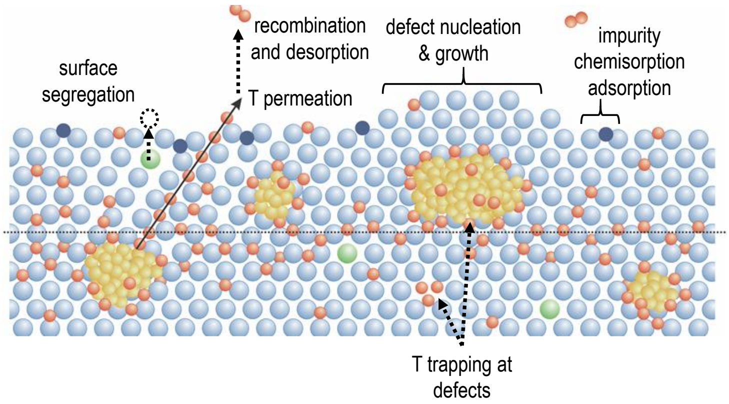

Fig. 1: Physics governing tritium permeation and diffusion through materials

Tritium permeation through blanket materials and its interaction with defects produced by neutrons could significantly impact the operation of an IFE demonstration plant. In addition, super-permeable membranes have been cited as a means to separate out tritium from other exhaust products. There are several approaches to bridge the gaps in our understanding that can be undertaken immediately using existing experimental facilities. High energy ion bombardment can be used to simulate the effects of 14 MeV neutron damage. The Ion Beam Laboratory at SNL offers a wide range of irradiation capabilities for ion damage of materials and can tailor the damage distribution and dpa level as needed. At the same time, these materials can be dosed with hydrogen gas, allowing it to diffuse into the material and occupy defects within the bulk material. Diagnostics for hydrogen isotope depth profiling (typically up to several μm into the material), e.g. Nuclear Reaction Analysis (NRA), can be used to assess the concentration of trapped hydrogen within the material.

In addition, several hydrogen science facilities are available within the U.S. FES program (at SNL, INL, ORNL, and SRNL) that can provide valuable measurements on gas-driven permeation rates through materials. Instrumentation for high-resolution, high-sensitivity thermal desorption spectroscopy, also available at many of these laboratories, allows the binding energy of hydrogen isotopes to defects to be ascertained. Such measurements are needed to improve the quality of the experimental database being used to assess loss of tritium through permeation and trapping in blanket materials.

B. Quantify surface effects responsible for H recombination and release

Much of the important physics of interest for blanket systems occurs at gas-solid and liquid-solid interfaces. As previously discussed, large uncertainties exist in the reported permeabilities through materials proposed for use in blanket systems. While there are several potential causes, surface effects (particularly impurity adsorption) are often the most important contributors to inconsistencies in the literature data. In addition, materials compatibility is a major concern, especially in the interaction between the lithium-based materials (especially liquid metals) used for tritium breeding and adjacent solid structural materials.

Experimental work focusing on the interaction between hydrogen isotopes and chemisorbed impurity species is recommended to better understand these phenomena. Determining the effects of chemisorbed/co-deposited impurities and species segregation calls for precise quantification of surface composition and chemistry. The best general-purpose tools for this application are x-ray photoelectron (XPS) and Auger electron spectroscopies (AES). Both techniques sample over a depth of ~ 5 nm from the surface; XPS also provides information on the local chemical environment. The presence of surface impurities has been shown to strongly affect hydrogen chemisorption and release from the material. Low energy ion beam techniques are uniquely sensitive to hydrogen and provide sensitivity to the top 1-2 monolayers of the surface. Temperature programmed desorption is also recommended to determine the binding enthalpies of chemisorbed species, along with vibrational spectroscopies (e.g. high-resolution electron energy loss spectroscopy (HR-EELS) and Fourier transform infrared (FTIR) spectroscopy). In addition, ion beam analysis techniques are well suited for determining the penetration of liquid metals such as Li into structural materials. Secondary ion mass spectrometry (SIMS) is also quite suitable for this purpose.

C. Opportunities for modelling and simulation

A variety of models will be needed to design tritium breeding modules for IFE, spanning a wide range of time- and length-scales. The requisite models span a diverse set of disciplines, ranging from continuum thermal modelling to atomic-scale simulation of material response to the fusion environment.

Considerable progress can be made with modelling techniques that are already available or under development. Thermomechanical modeling software (commercial and in-lab), radiation transport codes (MCNP, GEANT4, etc.), and molecular dynamics software (e.g. LAMMPS) will all play a role in optimizing tritium breeding blanket designs. Atomistic methods such as density functional theory can provide basic information on surface chemistry and hydrogen chemisorption. New algorithms and techniques for developing interatomic potentials are being developed through ongoing ASCR-FES SciDAC programs (PSI-2 and FusMatML). Developing a suitable workflow with a number of these available modeling techniques, specific to IFE conditions and constraints, is recommended.

D. Development of new techniques for characterization in harsh environments

The fusion environment is exceedingly harsh, presenting challenges to materials characterization techniques. Developing solutions to these issues is not trivial, but there are several options that could be pursued within the scope of an IFE blanket/fuel cycle program. With the above problems in mind, one of the main themes of this proposal is extending surface analysis techniques beyond their typical applications, e.g., single-crystal systems under ultra-high vacuum conditions, into the much more complex realm of blanket materials in a radiation environment.

In this initiative, we propose several new strategies to develop much higher fidelity surface diagnostics suitable for harsh environments. Surface analysis techniques traditionally have been applied to UHV environments, largely because electrons and low energy ions are scattered as they pass through gas at elevated pressures. This attenuates the detected signal and increases its energy spread. Synchrotron-based ambient pressure XPS provides guidance on how to proceed by using differential pumping along the beam line and detector paths and minimizing the length of travel taken by the beam within the high-pressure environment. Laboratory-based XPS systems of similar design are now becoming more widely available. A similar approach could potentially be adapted for LEIS/DRS techniques, and a proof-of-concept instrument is currently under development for this purpose.

III. OUTLOOK

Because breeding blankets for both IFE and MFE are at such an early stage of development, they are far behind many other technologies required to develop a demonstration fusion reactor. It is therefore crucial that a broad program to support research in this area be pursued with high urgency. The blanket system configuration must be integrated with many other subsystems and will likely dictate many aspects of the final design, especially the internal surface area that can be devoted to laser and diagnostic ports. Because of this, blankets must be considered in the earliest design stages of any major D-T test facility or IFE demonstration power plant. Many design decisions / trade-offs hinge on physical parameters which are unknown or have not been established with high confidence. The R&D activities outlined here would provide some of the basic information needed to make these decisions, including down-selection between different blanket concepts.

A sustained program of foundational R&D in blanket research for IFE is needed. Many of the proposed activities outlined above could be initiated immediately. Development and testing of the proposed new experimental and modelling techniques described here would likely require an initial effort spanning ~5 years.

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