Critical Safety and Tritium Applied Research Facility Upgrade

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Background

The Safety and Tritium Applied Research (STAR) facility is a unique capability within the US Department of Energy (DOE) complex. This facility offers research capabilities not only needed for answering safety questions regarding tritium inventories in, and permeation through structural components of fusion systems (e.g., divertors, first walls, cooling systems, etc), but also serves as a support facility for developing data needed for licensing ITER and can, if upgraded, provide the support needed for licensing of a Fusion Nuclear Science Facility (FNSF). The STAR facility is a National User Facility of the Office of Science managed and staffed by the Idaho National Laboratory (INL) Fusion Safety Program (FSP). As a National User Facility, it is accessible to university faculty and graduate students, public and private sector scientists and researchers from other DOE laboratories and international collaborations.

Fusion research at STAR is coordinated through the Virtual Laboratory for Technology, which represents the diverse activities of 24 U.S. organizations. The main activities at STAR involve the investigation of Plasma Materials Interactions (PMI) and the related development of Plasma Facing Components (PFC), to which are dedicated the largest experiments in the facility, the Tritium Plasma Experiment (TPE), and the TRitium Ion Implantation experiment (TRIIX). The second area of work regards the tritium breeder, coolant, and structural materials, in particular high temperature fluids such as liquid metals (lithium and its alloys) and molten salts (fluoride based), for which the Tritium Heat Exchanger (THX) and Tritium Lead Lithium Eutectic (T-LLE) experiments are dedicated. Validation experiments are also carried out in support of safety analysis and related code development, in particular for materials chemical reactivity during accident scenarios. The primary experiment in the chemical reactivity area is the Experimental Chamber for Evaluation of Exploding Dust (ExCEED), presently being used to determine the explosion indices of beryllium dust.

STAR is a less than hazard category 3 hazardous materials facility in the DOE complex, with the present capability of handling tritium (< 1.5 g), activated material (e.g. tungsten samples irradiated in the High Flux Isotope Reactor – HFIR), and toxic materials (e.g. beryllium). STAR's 400 m^2 research space (note Figs 1 and 2) is dedicated to research activities directed at the development of safe fusion nuclear technology, with a focus on issues related to the radioactive isotope of hydrogen, tritium (^3H), and has demonstrated a history of international use particularly with regards to ITER and several US/Japan collaborations such as JUPITER, TITAN, and now PHENIX.

Proposed Upgrade

The challenges facing STAR in the future include developing the research data required to quantify the control of tritium in prototypical fusion reactors, even in proposed near-term devices like FNSF. Understanding tritium retention and permeation in strong radiation fields (neutron, gamma or both), and our ability to reduce this permeation with permeation barriers [1], is very limited as can be seen from present day experiences of the Watts Bar tritium-producing burnable absorber rod (TPBAR) project. Understanding the physics that causes the observed reduced effectiveness of ceramic permeation barriers in ionizing radiation fields is extremely important to fusion safety. At this point in time, there is still speculation over whether the reduction is caused by gamma, neutron radiation, or a combination of both. One thing is certain, fusion reactors will have a much larger tritium control problem than fission or the TPBAR project, given the large projected generation rate of ~500 g/day, and large inventories of tritium circulating through the fueling system or contained in structural material in most of the reactor's other systems. However, a large knowledge gap presently exists in our ability to demonstrate tritium extraction from tritium breeding systems, such as flowing PbLi, and permeation of tritium from these breeding systems into high temperature primary and secondary heat transport systems, and subsequently into the reactor building and the environment.

Tritium extraction from PbLi or helium systems to levels that minimize tritium inventories and permeation rates into the reactor building require new technologies, such as the vacuum permeator proposed for the US Dual Coolant Lead Lithium (DCLL) blanket concept [2]. This extraction technique relies on turbulence enhanced mass transport of tritium in the PbLi to the pipe walls of this component, and permeation through these walls to a vacuum environment where elemental tritium gases can be pumped to the fueling system or captured on a getter bed. The efficiency of this extraction system must be greater than 90% to be effective, but to date the physics of this device have not been experimentally proven. However, the benefit from this system is not only in reducing permeation to the reactor building, but the removal of tritium at operating fluid temperatures with the safety advantage of minimizing the mobilization of activated material in the coolant into the extraction system (e.g. Po-210 in PbLi), a problem common to the other proposed systems (e.g., vacuum disengagers or compact mass extractors). To test these systems in prototypical environments, high temperature coolant loops are needed. The US does not presently have these capabilities, which would also be needed to qualify blanket components for an FNSF. The EU [3], China [4], and South Korea [5] all have or are building these capabilities, but the US fusion program has no plan to do so under the present budgetary constraints. Our proposal is to add three small loops dedicated to liquid metals, molten salts, and helium tritium extraction and permeation control research at STAR.

Not only are high temperature liquid metal and molten salt loops required for this research, but micro-sources of neutron and gamma radiation, produced for example from small accelerator driven neutron and gamma sources, must be used to provide the prototypical environments needed to study permeation barrier and tritium extraction performance. The technology of these radiation sources has been under development for decades and is readily available [6, 7, 8]. It is also known, that the Tandem Accelerator used in Nuclear Reaction Analysis (NRA), a diagnostic capability needed at STAR, could also be used with a titanium-tritium target to produce the required micro-sources [9]. It is not the intent of this upgrade to compete with research that can only be conducted at a large accelerator system that generates neutrons for materials damage research (e.g., SNS or IFMIF). The goal here is to build a bench-top scale research capability that affords the users easy access to perform their research. We are well aware that the neutron flux from these sources is on the order of 10^{15} n/m^2-s and DEMO reactors will have fluxes in the 10^{18} n/m^2-s range [10]. Also in a DEMO, these permeation coatings will be exposed to a gamma dose rates of ~3x10^4 Sv/hour, and at temperatures of over 500 °C. Here accelerator driven sources are much closer to DEMO conditions; systems at the Idaho Accelerator Center (IAC) have achieved gamma ray fields with a dose rate of 7.0x10^3 Sv/hr on a target area of 5 cm^2 [11].

A primary experimental device in the STAR facility is the Tritium Plasma Experiment (TPE). This device is the only linear plasma source in the world that can be used to study plasma driven tritium permeation in activated PFC materials, including hazardous materials such as beryllium. TPE was constructed in the mid 1980s and has undergone few upgrades since that time. In order to shorten the plasma run time to a single day when studying permeation in tungsten, the plasma flux in this device must be increased to levels experienced by ITER PFCs, and the exhaust system must be restored to circulate the exhaust back into the TPE plasma chamber. The latter upgrade would greatly lower the risk associated with TPE operation by reducing the quantity of tritium within the TPE confinement system. Given the age of this device, consideration must also be given to a new TPE instead of pushing the present TPE into power regimes for which its aging systems are not able to operate.

Although not widely publicized, in terms of tritium handling capacity STAR is one of largest public tritium research facilities in the world at 1.5 gm. The Tritium Laboratory Karlsruhe (TLK) of the Institute for Technical Physics claims to be the largest at 20 g of tritium [12]. The TLK website cites Japan's Tritium Processing Laboratory (TPL) as the second largest capability now at about 3 g [13]. In terms of floor space available for new research capabilities, STAR is presently overcrowded and in need of an expansion. STAR's total floor space is 400 m^2, whereas that at TLK is reported to be ~1460 m^2.

Finally, for a world class tritium research facility, STAR is woefully inadequate when it comes to material surface analysis capabilities. In fact, there are none. At a minimum, a Scanning Electron Microscope with Energy Dispersive X-ray (EDX) capabilities is needed. The addition of an High Voltage Engineering Three-in-one Tandetron system would not only allow for NRA, but Rutherford Backscattering Spectrometry (RBS), Particle Induced X-ray Emission (PIXE), Elastic Recoil Detection (ERD), and Accelerator Mass Spectrometry (AMS) [9]. These plus existing STAR capabilities would, when combined with the irradiation capabilities of the INL's Advanced Test Reactor located several hundred yards from STAR, would make the STAR a unique world class facility and also a world leading facility for research in this area for decades to come.

Cost of Proposed Upgrade

A tripling of the floor space for STAR is being proposed. This expansion, including larger air detritiation system for a larger STAR, is anticipated to cost approximately $ 5 M based on recent building costs at INL. The NRA system ($2 M including infrastructure), radiation sources ($2 M per source plus infrastructure), and SEM ($1 M) would cost ~$ 7 to 8 M, depending on the approach taken to produce the radiation fields. The small multiple high temperature flow loops (liquid metal, molten salt, and helium) will cost an additional $ 3 M [14], plus $ 1 M in infrastructure for example a tritium tight enclosure for the loops. An upgraded TPE would cost ~$ 1 to 2 M, depending on whether TPE is being modified or replaced. The cost projected to install these systems in technician and staff time is estimated to be $5 M. This brings the total proposed upgrade cost to between $ 22 and $ 24 M as a preliminary estimate.

The annual operating cost will be ~$4 M/year based on a doubling of STAR's present operating costs. The estimated time to construct the build, install the new experimental capabilities, and bring the facility online is ~5 years.

Upgrade Benefit

The STAR facility is already a unique international facility. This upgrade will allow users to access capabilities that will enable the development and licensing of critical safety components for fusion reactors and demonstrate safe tritium production and extraction for next step fusion devices. In theory, these capabilities should also bring funding into the facility from collaborative programs with countries that are involved in the ITER Test Blanket Module Program or presently involved in DEMO design studies.

Priority of this Upgrade

A comprehensive review article on fusion safety and environment concluded that "fusion energy has the potential to deliver safety and environmental (S&E) benefits large enough to be regarded as a major part of the rationale for the fusion-development effort." However, "… Achieving the full S&E potential of fusion will not happen automatically. The safety benefits, especially, appear to range from modest to enormous, depending on the materials used to construct the reactors, other aspects of the reactor design, and, ultimately, the particular fusion reaction that is harnessed" [15]. In the conclusions to this article, four needs and priorities were identified by the author, the third being: "… the community of fusion S&E researchers and the resources available to them are simply too small to carry out the range of studies required even to properly support and benefit from the current and next-generation fusion machines, not to mention the generation of full-scale reactors to follow. As a result, opportunities to help steer fusion development in a timely fashion toward the technology's highest potential are likely to be missed. The resources being devoted to fusion S&E research of all kinds-from the most fundamental laboratory experiments to the integration of safety , environmental, and economic considerations in reactor design-need urgently to be increased". The author of this review is Dr. John P. Holdren, then at the University of California, Berkley. Unfortunately, as is now the case for most fusion research areas, budgetary pressures on FES have resulted in a continual decline (in terms of real dollars) in funding since this assessment was made.

In 2007, an evaluation by a Fusion Energy Sciences Advisory Committee (FESAC) panel identified a number of knowledge gaps in the S&E understanding to a license a US DEMO reactor. The FESAC panel concluded that safety gaps regarding "the knowledge base for fusion systems" is presently "(in)sufficient to guarantee safety over the plant life cycle - including licensing and commissioning, normal operation, off-normal events, decommissioning and disposal" [16]. Extrapolations in present capabilities beyond ITER were identified to exist in five key safety areas. Area 2 is "Understanding and quantifying the fusion source term will be required for licensing activities". The two fusion source terms with greatest uncertainty are dust and tritium. In terms of dust, the key uncertainties are the magnitude of dust generated in the machine, its location and the potential for explosive dust mixtures in the presence of hydrogen and air in certain accident sequences. In terms of tritium, for high temperature breeding blankets, the key tritium issues include accountancy, control and permeation. R&D is needed (e.g., on tritium permeation barriers) to help better define and hopefully resolve the issue prior to DEMO.

Finally, a recent FESAC panel released their findings on materials science and technology [17]. Based on the panel's findings, three topical research themes were identified as grand challenges. The third was: "Harnessing fusion power (tritium science, chamber technology and power extraction)". One of the extraordinary challenges associated with these three themes is: "… tritium must be handled at an unprecedented scale in fusion. Flow rates of many kilograms per day must be effectively processed over an incredible range of temperatures, pressures and material conditions (where vastly different chemical science mechanisms are operative), while observing stringent accountancy and environmental release constraints."

The key scientific grand challenges regarding tritium science cited by this panel that STAR could address are:

CP2. Understand, predict and manage the material erosion and migration that will occur in the month-to-year-long plasma durations required in FNSF/DEMO devices due to plasma-material interactions and scrape-off layer plasma processes.

- What combination of wall thermal conditions, plasma boundary and material choices can be used to assure that the devices do not exceed operational safety limits for in-situ tritium retention and mobile dust?

CP3. Understand the coupled evolution of the plasma and PFCs under prototypical thermal, physical and chemical conditions expected in an FNSF/DEMO.

- How will the ambient and operating temperatures of a FNSF/DEMO affect the structure and fuel/tritium content of migrated and re-deposited material layers and particulates/dust?

- How will elevated temperature simultaneously affect the bulk PFC properties under both plasma and neutron bombardment?
- Will self-annealing effects be important for critical macroscopic quantities such as thermal conductivity and hydrogen trapping/diffusion?

CD3. Comprehend and control the processes that drive tritium permeation, trapping, and retention in neutron radiation damaged materials with microstructures designed to store numerous, nanometer-scale bubbles.

- How do radiation damage and helium gas generation impact tritium storage, retention and permeation in materials?
- Will tritium retention levels saturate with continued radiation damage and transmutation?
- Does the high partial pressure of tritium in lead-lithium breeding coolants require permeation barriers, and are practical barriers even possible in the fusion nuclear environment?

CH1. Develop and validate a predictive capability for the highly nonlinear Thermofluid physics and the transport of tritium and corrosion products in tritium breeding and power extraction systems.

- Can tritium be extracted from PbLi with the required high efficiency to limit tritium permeation below an acceptable level?

A key finding of the panel is: "Public acceptance and safety of fusion energy is strongly dependent upon the ability to reliably control the chemistry and permeation of tritium."

Given these findings, we propose that the FESAC recommend these upgrades to the STAR facility.

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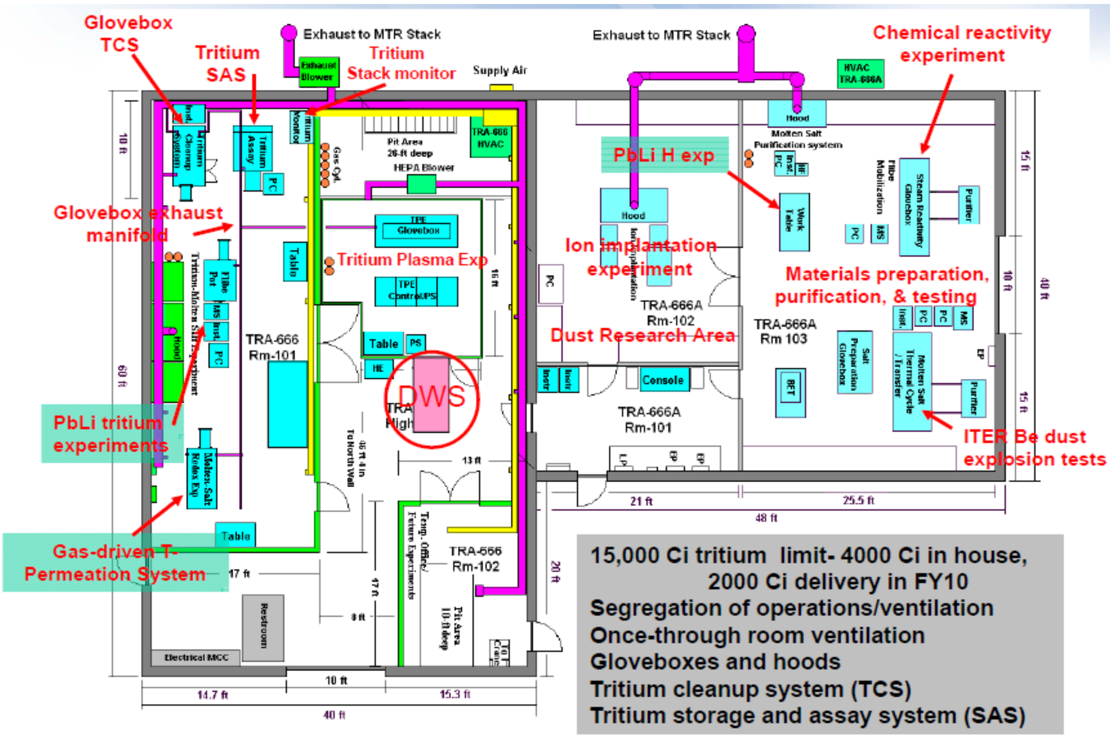

Figure 1. STAR facility floor plan and capabilities.

Figure 2. STAR facility research.