COMBINED FUEL CYCLE MODELING AND PROCESS DEVELOPMENT FOR IFE

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1. EXECUTIVE SUMMARY

The development of a sustainable deuterium-tritium (D-T) fuel cycle for inertial confinement fusion energy (IFE) presents distinct challenges that are specific to its operation and approach. The distinguishing characteristic of IFE is the laser-driven compression of a target. There are two fundamental approaches for IFE, Direct and Indirect drive IFE. Direct drive IFE is where a spherical capsule is targeted directly by many lasers simultaneously to compress the D-T through ablation of the encapsulating material. For indirect drive IFE, this spherical capsule is further placed within a metal hohlraum and the lasers are focused on the inside surface of the hohlraum creating X-rays which then cause a similar effect to the direct drive approach. Though other materials have been proposed, D-T ice is typically encapsulated within protiated (C-H) or deuterated (C-D) polymers. These polymers can react to form combustion products (CO_2, CO, and water), carbon, hydrocarbons, and other impurities upon laser irradiation and subsequent fusion reactions. Thus, a significant portion of the target material composition is not D-T, creating a unique condition where the impurity flow is comparable to and may significantly exceed the unburned fuel flow. The fuel cycle is really a complex chemical process with several unit operations which must be performed in a serial fashion using current technology. A sustainable fuel cycle requires that these impurities be quickly separated and efficiently processed to recover tritium that has been incorporated within this stream. The fuel processing plant must blend this recovered D-T with tritium extracted from breeding materials into new targets in order to close the fuel cycle. This requires pressurization, storage, and potentially transportation of the gases to a fuel fabrication facility so that targets can be sufficiently produced to satisfy a fuel injection rate of ~1-20 Hz. The target preparation process will have a substantial impact on fuel cycle design and is just one example of how IFE places unique demands on tritium process systems. It is critical that the D-T fuel cycle be integrated into the co-design of IFE through combined modeling and process development. The size and cost of the fuel cycle will be dependent on the number and quantity of different byproducts produced in the reaction of the target. Modeling of the fuel cycle in an iterative process with the target design will aid in making informed decisions in both the design of the fuel cycle and the target. This will be critical in ensuring that the fuel is both feasible as well as cost effective. This model will also indicate which unit operations should be targeted for further development to make the fuel cycle more cost effective and feasible.

2. BACKGROUND

SRNL has previously worked with NIF and the LIFE project to help in the design of fuel cycle systems. This work included the creation of a fuel cycle simulation using Aspen Plus (outlined in Figure 1) that was used to assess the impact of any design change on the inventory, footprint, and technology choices of the fuel cycle processes. The hierarchical simulation allowed for varying levels of modeling detail within the fuel cycle.

While a base configuration for the model has been developed, the level of process modeling detail is at a very coarse level that was appropriate for the very broad scope of design changes being investigated at the time. Significantly more detail is needed to support the design of a fuel cycle for an IFE system, and the simulation would need to be altered and run for variations of an IFE device that are proposed. An example of how important design decisions can be in the development of a fuel process is illustrated by an early suggestion in the LIFE program to utilize plastic hohlraums for indirect drive fusion. With the proposed compositions, process separation efficiencies, and recycle requirements, the fuel cycle simulation was able to determine that the fuel cycle would have been dominated by processes removing the plastic byproducts. Those gases would have been several orders of magnitude higher than the hydrogen (Deuterium/Tritium) gases needed for fusion. The impact of plastic hohlraums on the fuel cycle ruled out designing a fusion engine employing plastic hohlraums. While this topic is not specifically in debate today, there are suggestions to use plastic foam in targets instead of hollow targets with D-T ice in order to facilitate a more uniform reaction. A fuel cycle simulation is necessary to determine if any gains in fusion from these materials would be overshadowed by their impacts on the fuel cycle size, complexity, and energy costs.

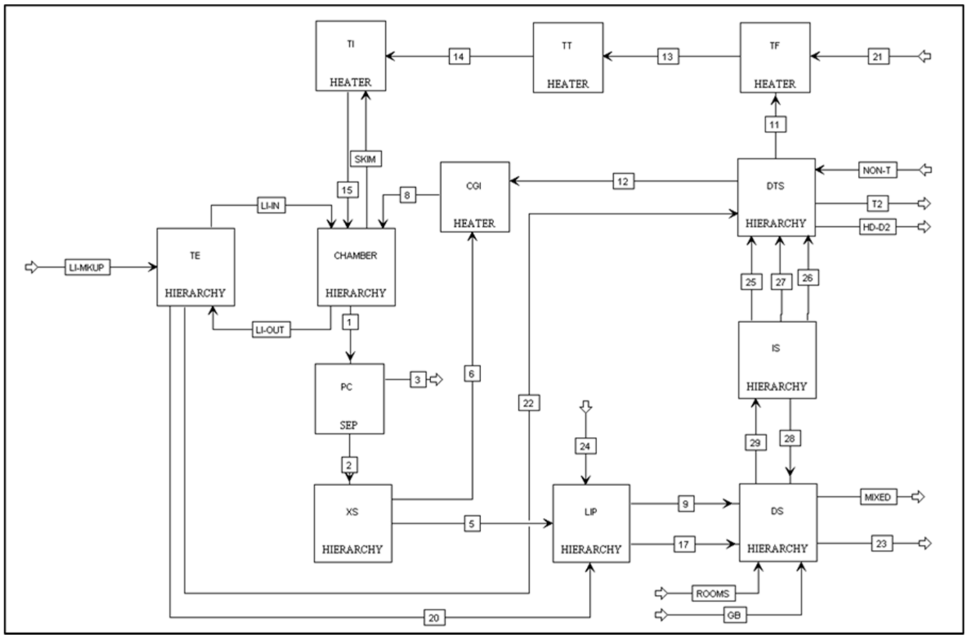

Figure 1. Outline of Fuel Cycle Simulation Elements in the fuel cycle process model developed by SRNL for work with NIF and on the LIFE project

As described above, impurities are introduced into the IFE D-T fuel cycle through the use of encapsulants and hohlraums, but they may also be introduced via other process and through air in-leakage throughout the system. Such impurities may include gaseous products such as ammonia, tritiated water, tritiated hydrocarbons, or other compounds. These impurities need to be decomposed to recover tritium before they can be released to the environment. SRNL has decades of experience developing tritium cleanup systems for all fuel cycle technologies as outlined in Figure 2, including the recent development of palladium membrane reactor (PMR) catalytic reactors for impurity removal. However, these systems and catalysts would likely need to be redesigned and adapted for the impurity profiles that will be encountered in an IFE system. In addition to impurity processing and removal, other tritium processing components, such as isotope separation and confinement systems, will likely need to be scaled and adapted to IFE requirements. It is expected that this will be an ongoing, iterative process led by modeling and IFE community engagement.

The most fundamental fuel cycle parameter is the fuel's burn fraction (β) in the fusion engine. Among a variety of other factors, the burn fraction directly relates the required engine fuel input to the specified net power generation rate. This relationship can be examined in Equation (1).

$$\beta = \frac{\dot{N}^{-}}{T_f} \qquad \text{Equation (1)}$$

In the above equation, $\dot{N}^{-}$ is the burn rate and T_f is the fueling rate or the fraction of available fuel that is experiencing burnup. The burn rate is directly proportional to the net power generation of the engine.

As the burn fraction decreases, the flow of fuel to the engine increases, as does the exhaust from the engine. This increases the size of every section of the fuel cycle, which has four (4) critical outcomes:

1. More energy is required to operate the larger sections, so fuel flow must be further increased to maintain the specified net power generation rate
2. Inventory increases directly with the size of the plant
3. Increased inventory also increases tritium decay requiring increased tritium breeding ratio
4. Changes in the fuel cycle composition can have non-linear effects on fuel cycle processes, possibly exacerbating effects of modifications

The recent NIF shot N210808 had a burn fraction of 1.8%, and if this were in a IFE system, then ~98.2% of the tritium and deuterium would have to go back through the fuel cycle. In discussions with target designers and researchers at LLNL and the Naval Research Lab (NRL), the burn fraction needs to roughly be in the range of 20-35% to make IFE feasible from an energy gain perspective. Understanding the trade-offs in target design, operating conditions, and other factors needed to achieve high burn-up fractions will need to be factored into the fuel cycle design and operation.

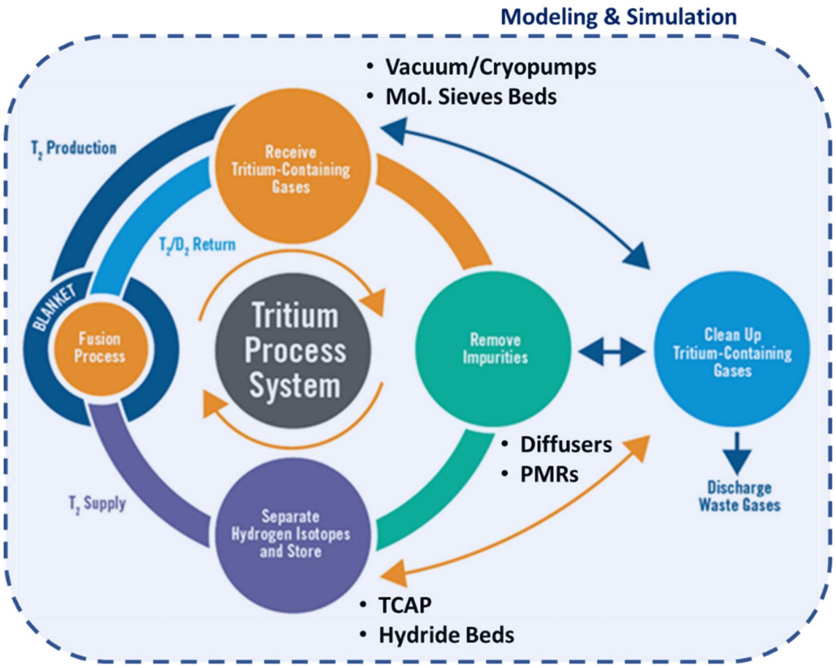

Figure 2. D-T Fuel Cycle Technologies and Modeling that Need Improvements for IFE Technologies.

3. RECOMMENDATIONS

An IFE fuel cycle simulation program needs to be conducted in parallel with IFE process design with feedback back into the overall process design process. A fuel cycle simulation is necessary to determine how elements of the fuel cycle are affected by changes in target design, operating conditions, and other engine design factors. The benefits of an improved engine design must consider the resulting changes in the fuel cycle design to ensure a viable plant can be developed. As fusion engine design matures and the process technologies in the fuel cycle are chosen, the process modeling detail will increase. The fuel cycle simulation develops from analyzing fusion engine design impacts into a design support tool for building the actual fusion plant. Simulation models will develop to the point they are used for equipment sizing and scenario evaluation for operational planning and safety evaluations.

In addition to incorporating fuel cycle considerations into the design process, it is recommended to include an expert(s) on fuel cycle technologies onto leadership teams guiding the development of IFE concepts so that fuel cycle considerations are given appropriate weight in program decisions.

WHITE PAPER TEAM AND EXPERTISE

Dr. Jim Becnel is in the Hydrogen Isotope Process Science Group at SRNL is an expert on tritium process modeling and has worked on the development of fuel cycle models for IFE systems and the exhaust separations for ITER. His experience working on IFE process modeling includes modeling the fuel cycle for the LIFE program. Dr. Becnel is highly experience in the development of flowsheet and process models for tritium processes at SRS.

Dr. George K. Larsen is a principal scientist in the Hydrogen Isotope Process Science Group at SRNL, where he provides tritium science expertise. His research covers all aspects of tritium processing, from basic to applied science and has been conducted in support of both NNSA and DOE Office of Fusion Energy Science. Dr. Larsen is also a PI on ARPA-E and INFUSE projects related to the tritium fuel cycle.

Greg Staack is a fellow engineer in the Hydrogen Isotope Process Science Group at SRNL and has spent many years negotiating R&D activities in a Tritium Facility. His research covers all areas of tritium processing, including hydrides, materials for tritium service, and tritiated particulates. He is the Task Lead for Hydrogen Storage tasks for NA-192 and Regenerable Bed Development.

Dr. Holly Flynn is a post-doctoral researcher in the Hydrogen Isotope Process Science Group at SRNL and an expert on tritium processing. Her research covers all areas of tritium processing, including hydrides and simulation and has been conducted in support of both NNSA and DOE Office of Fusion Energy Science.

Dr. Lucas M. Angelette, a senior engineer for Hydrogen Isotope Process Science at SRNL, has significant background in impurity processing for tritium and has focused much of his research on gas adsorption systems and hydrogen permeation systems in tritium processing systems. He is also the Task Lead over the Impurity Removal tasks for NNSA NA-192 and PI of the Pd-Ag braze development PDRD at SRNL.

Dr. Brenda L. Garcia-Diaz, the Advisory Program Manager for Fusion Energy at SRNL, is the PI on an ARPA-e/FES GAMOW project for scale-up of the Direct LiT Electrolysis process for tritium extraction. She is also the Lab PI on an INFUSE program with Commonwealth Fusion Systems (CFS) to mitigate molten salt corrosion in concentrating solar power systems. She was a member of the NASEM Committee that authored the report "Bringing Fusion to the US Grid" and she has managed the group in SRNL that performs the tritium effects on materials research.

Dave Babineau, the Director of the Tritium Technology Division at SRNL, has 33 years of experience in design, operations and commissioning of tritium breeding, purification, isotopic separation, and extraction systems. He has approximately 15 years of experience in the SRS Tritium Facility and 15 years in SRNL. For 2 of the years in SRNL he took a 2-year company approved leave of absence to work that the ITER International Organization in Cadarache France as the Tritium Plant Section Leader providing him with relevant fusion fuel cycle experience. He is on the board of directors for the Fusion Power Associates and participated in both the APS Community Planning Process as well as being a panelist for the NASEM Committee for "Bringing Fusion to the US Grid".

Savannah River National Laboratory is the leading DOE laboratory for tritium processing research and development. It has expertise in design, fabrication, modeling, and deployment of advanced technologies for deuterium-tritium fuel cycle technologies for both NNSA and fusion energy applications. SRNL is leading the design, fabrication, and delivery of the tokamak exhaust processing system for ITER and have been working closely with ITER on fuel cycle systems for over 12 years. SRNL invented and has advanced isotope separation technologies such as the thermal cycling absorption process (TCAP) to be a leading solution for isotope separation for fusion energy. SRNL has also developed a variety of modeling solutions for the fusion fuel cycle including process models, detailed heat and mass transfer models, as well as models for system control. The models developed by SRNL include an Aspen fuel cycle process model for the LIFE program. Additionally, SRNL has significant expertise and unique testing capabilities is in tritium effects on materials. This includes the ability to load sample using gram level tritium inventories and the ability to characterize both the mechanical properties and microstructure of the tritium exposed samples.

4. REFERENCES