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Chapter 6: Power Systems, Science, Engineering & Technology……………………..65

6.1 Introduction

- o Science & Technology Challenges
- o Knowledge Gaps
- o Where overlap with ICF; where unique?
- o Where overlap with MFE; where unique?

Fuel Cycle Technologies

The fuel cycle for an IFE power plant will need to have one or two demonstration facilities in the lead up to a fusion pilot plant that align with reports from the FESAC committee as well as from the NAS Study “Bringing Fusion to the US Grid”. These test facilities would carry out demonstrations of: 1) blanket technologies; and 2) D-T fuel and exhaust processing. It is anticipated that these facilities would allow testing of systems up to TRL 6 or 7. In the fusion blanket community, there is continuing discussion on whether a blanket test facility should utilize only a thermal source without a neutron source or if the facility needs to contain a neutron source to capture all of the relevant physics and materials degradation mechanisms that would occur in a blanket. A thermal blanket test facility would have lower cost and be faster to construct. A blanket test facility with a neutron source would have more cost but would also allow testing of critical phenomena like tritium extraction, tritium production phenomena, including multipliers, and materials degradation with chemical, neutron irradiation, and tritium effects. A D-T fuel and exhaust processing facility would need to define if it would focus on only the main closed-loop fueling cycle or if it would also include technologies for overall facility tritium management. A demonstration plan for the D-T fuel and exhaust processing would likely include testing a full-scale system with non-radioactive simulants (e.g. protium and deuterium) followed by an engineering scale (1/10th to ¼ scale) up to a full-scale demonstration with tritium. Because the fuel cycle for IFE shares similarities with MFE fuel cycle technologies, it is likely that the demonstration facilities will be applicable for both or could be modified to test both IFE and MFE technologies. Both facilities would also be beneficial in training the workforce to operate fuel cycle systems for both IFE and MFE.

6.2 Priority Research Directions (or Need/Opportunities) (3 to 5)

- o Can be posed as a question
- o One paragraph (few sentences) describing the opportunity/gap/need
- o Why is it important? What is the challenge?
- o Why now? What are potential research approaches? What resources needed?
- o How and when will success impact roadmap decisions or future technologies?
- o Connections with other areas (if applicable)

Develop synergistic target/fuel cycle co-design that allows effective target impurity removal within bounding fuel cycle parameters (e.g. - tritium inventory)

The development of a sustainable deuterium-tritium (D-T) fuel cycle for IFE presents distinct challenges that are specific to its operation and approach. Each target introduced into the chamber will introduce impurities such as carbon, hydrogen isotopes, metals, and other elements (e.g. - N or O) depending on target composition. The exhaust processing and other fuel cycle processes will need to remove impurities and provide a pure D-T mixture to inject back into new targets. Additional impurity elements or increases in quantities can require addition and resizing of unit operations within the fuel cycle that increase OPEX and CAPEX costs, tritium inventory, and waste processing considerations. Therefore, collaborative design between targets and the fuel cycle will be essential in developing an integrated IFE plant concept that can produce fusion energy at competitive costs.

6.2.1 Fusion Materials

6.2.2 Impact of chamber and fuel cycle constraints on physics target design

6.2.3 Fuel Cycle Technologies

Partners working on NIF and the LIFE project developed preliminary fuel cycle designs specific for IFE. [1-3] Figure 1 illustrates a simplified version of the fuel cycle design developed for the LIFE project. This design and modeling included the creation of a fuel cycle simulation that was used to assess the impact of any design change on the inventory, footprint, and technology choices of the fuel cycle processes. This design and modeling was based on a relatively modest pre-conceptual effort.

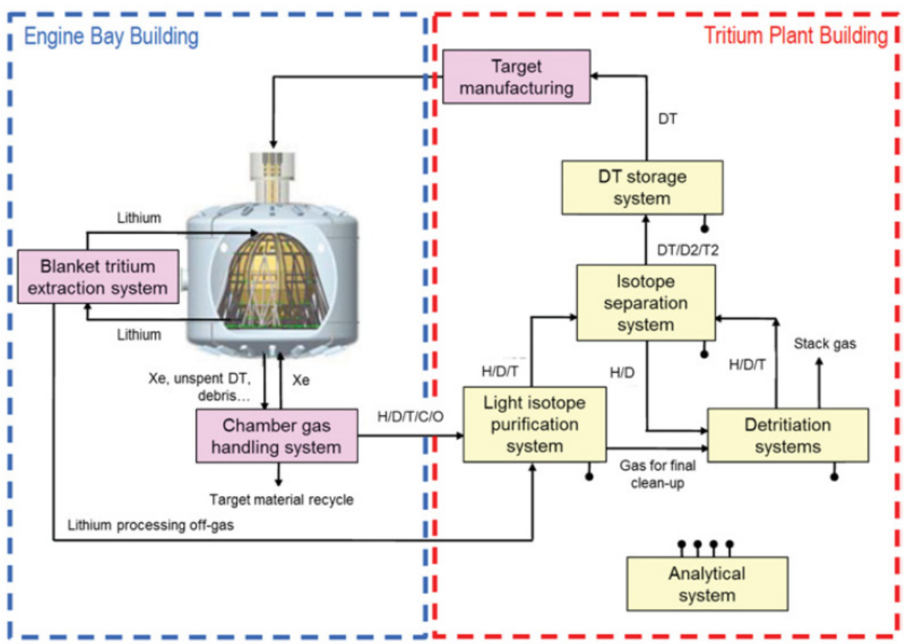

Figure 1. Simplified IFE fuel cycle diagram utilizing a concept developed from the LIFE program. Reproduced from Reyes et. al. [1]

Significantly more detail is needed to support the design of a fuel cycle for an IFE system, but 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 would have been dominated by processes removing the plastic byproducts (protium and carbon). 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, impurities are introduced into the IFE D-T fuel cycle through the use of encapsulants, hohlraums, sweep gases or 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. Tritium cleanup systems would need to be designed 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 (or residence time of tritium) 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. The burn fraction needs to roughly be in the range of ~30% to make IFE feasible from an energy gain perspective. [1] 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.

Fuel cycle technology development for IFE shares many challenges with MFE. For example, development of tritium breeding and extraction as well as blanket technologies are all at a low TRL level, but it is generally envisioned that IFE could use similar solutions to MFE. Most forms of IFE do not utilize magnets, so some blanket concerns from MFE such as magnetohydrodynamics (MHD) in lithium or lithium alloy blankets are not likely to be a factor. Fuel cycle challenges such as real-time accountancy for tritium and tritium clean-up from effluents will be similar but will have adaptations in some part of how they are implements due to tritium injection into targets and storage/movement of targets in the plant.

Exhaust and Hydrogen Isotope Processing

The IFE fuel cycle is a complex chemical process with multiple unit operations which must be performed in a serial fashion using current technology to process exhaust from shots and recover unreacted deuterium and tritium for reinjection into new targets. The use of targets in IFE is a significant differentiator from MFE where D-T is directly injected into the plasma in the form of D-T ice or D-T gas. Though other materials have been proposed, targets typically consist of D-T ice or liquid 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 development of a sustainable deuterium-tritium (D-T) fuel cycle for IFE presents distinct challenges that are specific to its operation and approach. In addition, multiple current generation technologies being proposed for use in a fusion fuel cycle have not been operated continuously for processing of hydrogen isotopes. A sustainable fuel cycle requires that these impurities be quickly separated and efficiently processed to recover tritium that has been incorporated within this stream. Decontamination of exhaust and byproduct impurities is needed to remove residual tritium is necessary to prepare the exhaust for release to the atmosphere.

Research on improved methods of impurity removal with minimum tritium inventory along with materials that can withstand elevated impurity concentrations that would be formed in high burn-up are needed. While similar considerations with impurities and high burn-up fractions may exist in MFE, the specific impurity mixture, separation methods, and process conditions are likely to require solutions that are tailored specifically for IFE.

Tritium Breeding

For an IFE fusion plant, achieving and sustaining a tritium breeding ratio (TBR) greater than 1 will be critical to ensuring tritium self-sufficiency.[4, 5] Achieving this goal will be dependent on the effectiveness of both the tritium breeding and tritium extraction techniques that are chosen. As noted in recent reports from the fusion community [6-8], there is a wide consensus that concepts for tritium breeding and tritium extraction are at a low TRL level (~1-2) and need significant development. It was also noted in the 2013 NASEM report "An Assessment of the Prospects for Inertial Fusion Energy" [9], that breeding blanket and tritium extraction technologies are an area where technologies from MFE and IFE are likely to utilize similar technologies. There are a large number of tritium breeding blanket test concepts that are being considered for testing in ITER and DEMO and this provides a good technical basis for developing breeding blanket technologies for IFE. [10, 11] Reviews of these tritium breeding methods show that the main functions of a breeding blanket are: 1) to breed tritium from lithium and 2) to multiply neutrons such reaction of all fusion neutrons directly with lithium is not necessary. [12, 13] While there are multiple options for multiplying neutrons, the elements that can perform this task most effectively without producing significant quantities of long-lived radioisotopes are Be and Pb. [12, 13] In terms of breeding blankets, the main classes of breeding technologies are solid ceramic breeders and liquid breeding blankets. The liquid breeding blanket category can also be subdivided into liquid metals and molten salts that behave in fundamentally different ways. [12, 13] There are several good reviews that do a very complete job of summarizing the technical challenges in the development of blanket technologies related to ITER. [5, 11, 14-17] Commercial fusion companies have also had renewed interest in using FLiBe as a breeding blanket material. [18, 19] Corrosion, tritium extraction, and other issues associated with FLiBe are areas of active research in both the fusion and advanced fission communities. [20-22] The APS Community Planning Process report [7] recommended several basic research needs related to tritium breeding including:

1. Initiate small-scale tests for a variety of functional breeder blanket materials to advance blanket concept designs
2. Support testing of compatibility between breeder and structural materials required for a viable integrated design
3. Develop models and a multiphysics modeling capability to enable integrated blanket designs

Tritium Extraction

Tritium extraction is a research need that accompanies tritium breeding and that ensures the tritium that is bred within the breeding blanket is extracted at the rates required to ensure tritium self-sufficiency. [4, 5] Additionally, tritium extraction lowers the tritium concentration within the breeding material to minimize tritium transport through undesirable pathways such as diffusion through process containment materials. [17] Methods of tritium extraction depend significantly on the breeding blanket type and can be highly varied. Tritium extraction techniques proposed for use in Li and Pb-Li blankets include permeation against vacuum (PAV), the Maroni Process, and Direct LiT Electrolysis. [23-26] The APS Community Planning Process report [7] recommended a basic research needs related to tritium extraction:

1. Construct bench-scale experiments to test tritium extraction concepts and transport in breeder and structural blanket materials

Direct Internal Recycle

A concept within the MFE community that has gained increasing traction as a way to increase fuel cycle efficiency and decrease the tritium inventory within a fusion energy system is direct internal recycle (DIR). [27] DIR is a concept that fundamentally comes from the preference of the divertor in MFE to exhaust hydrogen isotopes relative to He ash, thereby making it advantageous to have a method to directly recycle a part of the D-T from the exhaust back to the feed without isotopic rebalancing. Implementations of DIR utilizing metal foil pumps to help recover D-T from the exhaust have been proposed and research on those concepts is ongoing for MFE. [28, 29] While DIR has gained significant traction within the MFE community, a similar concept for IFE has not been explored in detail due to the focus within the IFE community on achieving ignition. Direct recycling for IFE would need to reinject and create targets from the recycled D-T mixture. Targets may need to undergo processes such as beta-layering and other processing before injection into the target chamber and the burn fraction in IFE will likely need to be higher in IFE compared with MFE to achieve high gain. It is unclear what issues in energy gain could be caused by variability in the fueling mixture could be caused by utilizing DIR. Despite the uncertainties, direct recycling for IFE could help to lower inventories and might be good to consider for IFE.

6.2.4 System Integration and Design

6.3 High-level conclusions

high potential areas that may advance the field significantly, considerations, potential spin-outs, tie-ins with other cross- cutting areas

- *Sidebars may be included to provide basic, textbook-like material or may highlight a significant recent research result. Sidebars include a paragraph, an image, and perhaps a reference.*

1. Reyes, S., et al., *Overview of the LIFE fuel cycle.* EPJ Web of Conferences, 2013. **59**: p. 11002.
2. Reyes, S., et al., *LIFE Tritium Processing: A Sustainable Solution for Closing the Fusion Fuel Cycle.* Fusion Science and Technology, 2013. **64**(2): p. 187-193.
3. Reyes, S., et al., *Recent developments in IFE safety and tritium research and considerations for future nuclear fusion facilities.* Fusion Engineering and Design, 2016. **109-111**: p. 175-181.
4. Sawan, M.E. and M.A. Abdou, *Physics and technology conditions for attaining tritium self-sufficiency for the DT fuel cycle.* Fusion Engineering and Design, 2006. **81**(8): p. 1131-1144.
5. Abdou, M., et al., *Physics and technology considerations for the deuterium–tritium fuel cycle and conditions for tritium fuel self sufficiency.* Nuclear Fusion, 2020. **61**(1): p. 013001.
6. Engineering, N.A.o., E. National Academies of Sciences, and Medicine, *Bringing Fusion to the U.S. Grid*. 2021, Washington, DC: The National Academies Press. 124.
7. Baalrud, S., et al., *A Community Plan for Fusion Energy and Discovery Plasma Sciences*. 2020.
8. FESAC, *Powering the Future: Fusion & Plasmas*. 2020.
9. Council, N.R., *An Assessment of the Prospects for Inertial Fusion Energy*. 2013, Washington, DC: The National Academies Press. 246.

10. Wong, C.P.C., et al., *Overview of liquid metal TBM concepts and programs.* Fusion Engineering and Design, 2008. **83**(7): p. 850-857.
11. Boccaccini, L.V., et al., *Status of maturation of critical technologies and systems design: Breeding blanket.* Fusion Engineering and Design, 2022. **179**: p. 113116.
12. Aristova, M. and C.A. Gentile, *Comparative Study to Evaluate Candidate Materials for Tritium Production in a Direct Drive IFE Reactor.* Fusion Science and Technology, 2009. **56**(1): p. 475-477.
13. Hernández, F.A. and P. Pereslavtsev, *First principles review of options for tritium breeder and neutron multiplier materials for breeding blankets in fusion reactors.* Fusion Engineering and Design, 2018. **137**: p. 243-256.
14. Abdou, M., et al., *Blanket/first wall challenges and required R&D on the pathway to DEMO.* Fusion Engineering and Design, 2015. **100**: p. 2-43.
15. Rubel, M., *Fusion Neutrons: Tritium Breeding and Impact on Wall Materials and Components of Diagnostic Systems.* Journal of Fusion Energy, 2019. **38**(3): p. 315-329.
16. Smolentsev, S., et al., *Dual-coolant lead–lithium (DCLL) blanket status and R&D needs.* Fusion Engineering and Design, 2015. **100**: p. 44-54.
17. Kessel, C.E., et al., *Critical Exploration of Liquid Metal Plasma-Facing Components in a Fusion Nuclear Science Facility.* Fusion Science and Technology, 2019. **75**(8): p. 886-917.
18. Creely, A.J., et al., *Overview of the SPARC tokamak.* Journal of Plasma Physics, 2020. **86**(5): p. 865860502.
19. Forsberg, C., et al., *Fusion Blankets and Fluoride-Salt-Cooled High-Temperature Reactors with Flibe Salt Coolant: Common Challenges, Tritium Control, and Opportunities for Synergistic Development Strategies Between Fission, Fusion, and Solar Salt Technologies.* Nuclear Technology, 2020. **206**(11): p. 1778-1801.
20. Forsberg, C.W., et al., *Tritium Control and Capture in Salt-Cooled Fission and Fusion Reactors.* Fusion Science and Technology, 2017. **71**(4): p. 584-589.
21. Forsberg, C.W., et al., *Tritium Control and Capture in Salt-Cooled Fission and Fusion Reactors: Status, Challenges, and Path Forward.* Nuclear Technology, 2017. **197**(2): p. 119-139.
22. Forsberg, C.W. and P.F. Peterson, *FHR, HTGR, and MSR Pebble-Bed Reactors with Multiple Pebble Sizes for Fuel Management and Coolant Cleanup.* Nuclear Technology, 2019. **205**(5): p. 748-754.
23. Maroni, V.A., R.D. Wolson, and G.E. Staahl, *Some Preliminary Considerations of A Molten-Salt Extraction Process to Remove Tritium from Liquid Lithium Fusion Reactor Blankets.* Nuclear Technology, 1975. **25**(1): p. 83-91.
24. Moriyama, H., et al., *Tritium recovery from liquid metals.* Fusion Engineering and Design, 1995. **28**: p. 226-239.
25. Humrickhouse, P.W. and B.J. Merrill, *Vacuum Permeator Analysis for Extraction of Tritium from DCLL Blankets.* Fusion Science and Technology, 2015. **68**(2): p. 295-302.
26. Teprovich, J.A., et al., *Electrochemical extraction of hydrogen isotopes from Li/LiT mixtures.* Fusion Engineering and Design, 2019. **139**: p. 1-6.
27. Day, C. and T. Giegerich, *The Direct Internal Recycling concept to simplify the fuel cycle of a fusion power plant.* Fusion Engineering and Design, 2013. **88**(6): p. 616-620.
28. Hanke, S., et al., *Progress of the R&D programme to develop a metal foil pump for DEMO.* Fusion Engineering and Design, 2020. **161**: p. 111890.
29. Peters, B.J., S. Hanke, and C. Day, *Metal Foil Pump performance aspects in view of the implementation of Direct Internal Recycling for future fusion fuel cycles.* Fusion Engineering and Design, 2018. **136**: p. 1467-1471.