Common Challenges Facing Future MFE and IFE Power Plants

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Introduction

The pursuit of fusion energy to solve the world's dependence on fossil fuels has generated multiple approaches. Two leading scientific approaches involve magnetic confinement of a DT plasma and inertial confinement (laser driven) of a DT plasma. Each with the ultimate goal of producing more usable energy than what is required to create the fusion reaction. Both approaches also must breed tritium fuel from blankets containing lithium to produce more T fuel than is consumed in the fusion reactions.

While the technologies to create magnetic confinement and inertial confinement fusion reactions have very different scientific and technological challenges to create a fusion reaction, there are many fundamental areas of commonality.

- Power generation - the conversion of fusion energy to electrical power that can be economically supplied to the grid
- DT is the fusion fuel for MFE and IFE where the T must be produced by the reactor
- Radiation Safety
- The fusion reaction is created using a DT plasma
- Low Temperature Science and technology
- High temperature Science and technology
- Materials for the fusion nuclear regime and reaction facing surfaces

Power Generation

ITER, NIF, and LMJ are all large MFE and IFE facilities dedicated to creating the fusion reactions at or above scientific breakeven conditions. None of these facilities have capabilities to convert fusion energy to usable power. Once scientific feasible fusion technology is demonstrated at one of these facilities, converting that capability to generate net power in a fusion pilot plant at a commercially attractive price is a major challenge.

The product of the fusion reaction is the same regardless of the approach. 14 MeV neutrons and 3.5 MeV 4He are the byproducts that have to be turned into thermal energy to produce electricity in a power plant. Both MFE and IFE have to solve many of the same problems.

- When does a power plant need to break even on cost per gigawatt?
- What is the cost target per gigawatt that makes fusion power economically viable?
    - Is that achievable with the 1^{st} plant, 2^{nd} plant n^{th} plant?
- Optimizing the use of 14 MeV neutrons

    - What neutron capture technology needs to be developed to capture as much of the energy as possible in a first wall and T breeding blanket – even a few percent into the environment can be a radiological problem
- How will the energy from 14 MeV neutrons be optimized and controlled to achieve both tritium breeding and thermal energy for power generation?
- Managing the 4He and other chamber particles
    - In magnetic fusion alpha particles lose their energy to the plasma and help keep the plasma hot. For IFE they could get imbedded in the wall and create embrittlement concerns. In either case they eventually get pumped out with the unburned DT fuel and have to be separated.
    - How will it be disposed of?
        - Up the stack?
            - How will tritium cross contamination with waste He be addressed?
        - Can it be recycled or reused in the power generation cycle?
- How would water be heated?
    - Where is the most efficient location for water circulation?
        - Liquid first wall?
        - Remote water loop?
            - Ex: High pressure He circulation to remote water loop
- Are there other methods to generate electricity other than boiling water?
    - What balance-of-plant ideas or options are there?
    - Are there methods that can be developed to leverage the plasma and directly generate electricity from it?
    - Smoothing the electric power output of cyclic fusion power generation
- Power plant life and maintenance
    - How does the plasma and 14 MeV neutrons affect the life of power plant components?
    - Maintenance of highly activated materials means all remote handling. How can remote vacuum connections (or other components) that are tritium contaminated or activated be handled?
    - What material properties are affected by the plasma and neutrons?
    - How can fatigue and hydrogen embrittlement of materials be managed and mitigated
    - What is the life cycle of primary components?
    - What is the life cycle of a power plant?
    - What happens when a power plant is decommissioned?

DT Fuel

DT is the fusion fuel for MFE and IFE. The logistics of managing the fuel supply on a scale required to fuel a power plant are challenging. DT handling has been limited to the research community and research quantities. Handling tritium on an industrial scale creates new challenges.

Vast quantities of tritium will be required daily to fuel a fusion reactor. Tritium needs to be bred from the fusion reaction to generate enough fuel for to keep the reactor operating.

- Tritium breeder materials and technology on an industrial scale are relatively new systems that will require continuous development and improvement.

Minimizing the tritium inventory at a power plant requires significant technological development to keep the inventory secure and the risk to the workers, population, and environment low.

ITER has developed a fuel cycle that is a building block for future power plants. There are several challenges in the DT fuel cycle. A primary challenge is the DT fuel that is not consumed during the fusion reaction needs to be purified and recycled in an efficient manner to minimize the inventory and capital cost of a power plant.

- DT purification is a slow process with today's technology. It requires contamination removal, isotopic separation (protium removal), and recombination (creating the desired D:T ratio). Tritium inventory is required to compensate for the time that is necessary to process breeder and recycled fuel.
- What is the tritium inventory required for a DT fusion economy, and is it feasible?
- Breeder technology that does not require tritium separation and purification would minimize the need for tritium processing and allow direct mixing of tritium and deuterium into the fuel cycle
- Fast separation of unused DT fuel and process gases and contaminants from the reactor can allow recycled DT to go directly back into the fuel cycle
    - Are there high volume, passive methods of isolating hydrogen and its isotopes from other elements and molecules
- Minimizing contaminants from process piping and components from getting into the fuel supply (C, N2, H2O scavenging from tubing and chamber walls)
    - Are there materials or coatings inert to tritium scavenging that can keep contaminants out of the fuel cycle?

DT contamination of the facility and environment are additional concerns.

- Prevention - are there barrier materials or coatings that can address tritium permeation through materials.
- Mitigation – what industrial scale cleanup technologies, methods, and protocols should be standard at all facilities?

DT compatible components are typically custom, made for particular organization or use, and made to that organization's standards. These DT compatible components incur significant cost due to custom standards. A single international standard for tritium compatible materials, components, handling and processes is needed. This can enable:

- Commonality and compatibility of materials, protocol, and systems across global facilities
- Global tritium safety standards and behavior
- Development of commercially available tritium compatible valves, mechanisms, and sensors
- Cost reductions for tritium compatible components and systems

DT targets for IFE are very challenging. The process of layering and characterizing a DT capsule is time consuming, expensive, and needs significant development to achieve industrial scale production. MFE pellet technology is comparatively inexpensive and already capable of industrial scale target production.

- Are there ways to leverage MFE pellet technology to IFE targets?

Radiation Safety

IFE and MFE facilities must deal with the same radiological hazards

- 1e29 14 MeV neutrons per year per GW output.
    - Is there adequate neutronics modelling capability to understand transport in a fusion reactor plant?
- Beta decay of tritium
- Tritium contamination of materials
- Methods to accurately account for tritium inventory in plant sub systems
- Activated structures
    - What impact does the half-life of activated materials that can create thousands of tons of material for low-level burial have?
- Are plant operations and maintenance possible with human beings?
    - What remote operations are possible with current technology?
    - What technology needs to be developed for remote operations?

Global standardization of radiation safety for fusion power plants and a regulating organization would be beneficial for

- Power plant operational standards
- Power plant design
- Component design
    - Manufactures can develop globally compliant components, reducing fabrication cost and cycle time

Plasma Facing Materials

Magnetic and inertial fusion interact differently with the DT plasma, however the plasma still interacts with the environment surrounding it. The development of a comprehensive handbook of materials for use in plasma environments, including material degradation effects, impacts on fatigue life, material life cycle, and best practices for material interactions with the plasma would benefit MFE and IFE. The ORNL MPEX device is designed to support this, but it is a steppingstone to industrial scale exposure.

Low Temperature and High Temperature Science and Technology

Fusion power plants and research facilities require the use of materials, components, and methods at extreme temperatures. Technology for extreme temperatures is constantly being developed for use in applications other than fusion energy.

- How can current technologies be leveraged?
- Material properties at extreme temperatures are often limited, limiting the choice of materials for engineers. How can more materials be added to the database of materials for use in extreme environments?

- Designs for components, mechanisms, and systems to operate at extreme temperatures are often custom and expensive.
- Tritium permeation in materials in extreme environments

How can the commercial market be engaged to help develop low cost, turnkey solutions?

Conclusion

Fusion Energy has great promise but comes with significant challenges. Challenges that are common to MFE and IFE power generation and power plant operation can be addressed in a common effort, regardless of the technology that will power the fusion reaction. Ultimately, the energy consumer is concerned with cost/kW. How does the fusion energy development path, IFE or MFE, achieve consumer cost expectations?