EPRI

2024 TECHNICAL UPDATE

2023 Fusion Fuel Cycles Workshop Summary

A Summary of the 2023 Fusion Fuel Cycles Workshop held in Charlotte, NC on May 22–23, 2023

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3002029370

Technical Update, December 2024

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All or a portion of the requirements of the EPRI Nuclear Quality Assurance Program apply to this product. YES NO

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ACKNOWLEDGMENTS

EPRI edited and published this report.

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This report summarizes key perspectives and insights drawn from discussions by participants during the 2023 Fusion Fuel Cycles Workshop, convened and hosted by EPRI on May 22-23, 2023, in Charlotte, NC. Any views, opinions, and recommendations expressed in this report do not necessarily state or reflect those of EPRI. Any references to specific design information in this report is intended for illustration purposes only and does not imply endorsement.

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This publication is a corporate document that should be cited in the literature in the following manner: *2023 Fusion Fuel Cycles Workshop Summary: A Summary of the 2023 Fusion Fuel Cycles Workshop held in Charlotte, NC on May 22–23, 2023.* EPRI, Palo Alto, CA: 2024. 3002029370.

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Frazer-Nash Consultancy provided extensive support for workshop scoping and planning and coordinated and led workshop facilitation. The Frazer-Nash Consultancy workshop facilitation team consisted of Ben Turner, David McNaught, Emma Johnston, and Nick Walkden.

ABSTRACT

In May 2023, the Fusion Fuel Cycle Workshop was held in Charlotte, North Carolina to identify challenges and solution pathways with a cross-section of fusion industry stakeholders for accelerated fusion fuel cycle development. This workshop aimed to identify technology-agnostic and fusion community-driven research objectives needed to design, build, and operate a successful fuel cycle for a fusion pilot plant on the timescale of a decade. Comprised of expert presentations and extensive discussions in multiple breakout rooms, this workshop culminated in the identification of 85 specific topical research objectives for fusion fuel cycle development, defined in EPRI report 3002029371. Over 170 stakeholders in fusion fuel cycle research and development, representing over 65 institutions and eight countries, attended this workshop.

This Workshop Summary Report summarizes the discussions held in the workshop breakout rooms. It was prepared by the Workshop Planning Committee (see Principal Authors list) based on the detailed notes taken during the breakout discussions by designated EPRI note takers. Breakout room discussions focused on the identification, characterization, and prioritization of challenges relevant to the topics and subtopics listed below. The discussions also brainstormed possible solution pathways.

1. **Fueling and exhaust processing**
    - Fueling system
    - Vacuum pumping system
    - Exhaust processing system
    - Impurity removal system
2. **Isotope processing, rebalancing, and storage**
    - Isotope separation and rebalancing system
    - Isotope storage and handling system
    - Tritium (T) extraction from the blanket system
3. **Confinement processing and tritium accountancy**
    - Detritiation system
    - Tritium recovery from secondary loops and enclosures
    - Tritium monitoring and accountancy

Workshop participants also had the opportunity to define specific development projects to address the identified challenges. The suggested projects are listed in the appendix of this document.

This document is a thorough summary of the workshop breakout discussions and is a reflection of those in-person conversations. It is not intended to represent a complete overview of every topic listed, and there are likely to be additional challenges associated with these topics that were not discussed at the workshop.

Keywords
Tritium
Fusion Fuel Cycle
Fueling and Exhaust Processing
Isotope Processing
Confinement Processing
Tritium Accountancy

ACRONYMS, ABBREVIATIONS, AND INITIALISMS

AI: artificial intelligence

BOP: balance-of-plant

CNL: Canadian Nuclear Laboratories

D: deuterium

DIR: direct internal recycle

DOE: U.S. Department of Energy

D-T: deuterium-tritium (fusion fuel option)

FESTIM: Finite Element Simulation of Tritium In Materials

FLiBe: lithium fluoride/beryllium fluoride

FOA: funding opportunity announcement

FPP: fusion pilot plant

H: hydrogen

HAZ: heat affected zone

H/D: hydrogen/deuterium

He: helium

HVAC: heating, ventilation, and air conditioning

HWR: heavy water reactor

IFC: inner fuel cycle

IFE: inertial fusion energy

ISO: International Organization for Standardization

ISS: isotope separation system

JET: Joint European Torus

Li: lithium

m: meter

MFE: magnetic fusion energy

MFP: metal foil pump

NNSA: National Nuclear Security Administration

NRC: Nuclear Regulatory Commission

Pa: pascal

PbLi: lead-lithium

Q_2: dihydrogen isotopologues

SRNL: Savannah River National Laboratory

T: tritium

TBE: tritium burn efficiency

TCAP: temperature cyclic absorption process

TES: tritium extraction system

TMAP: Tritium Migration Analysis Program

TPBAR: tritium producing burnable absorber rod

TRF: tritium removal facilities

TRL: technology readiness level

U: uranium

U.S.: United States

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1 INTRODUCTION

Both the U.S. Decadal Vision and multiple private fusion programs envision fusion pilot plants (FPPs) operational by the early 2030s, requiring a safe, efficient, and reliable fuel cycle for operation. Many fusion pilot plant concepts under consideration require a deuterium-tritium (D-T) fuel cycle, present a unique set of design considerations for a fusion power system, with safety, performance, and environmental implications. As a radioactive isotope, tritium requires proper handling and processing technologies, and the tritium breeding requirement for ensuring sufficient fuel supply necessitates extraction technologies. Significant research gaps exist on the path to develop robust, safe, and efficient technologies pertaining to tritium fueling, storage, and extraction.

Numerous existing strategic planning reports by or for the fusion energy research community have established fusion fuel cycle technology as an area of significant technological uncertainty on the path to an FPP.[1,2,3] To accelerate the development of relevant fuel cycle technologies, the Fusion Fuel Cycles Workshop was held from May 22-23, 2023, in Charlotte, North Carolina. This workshop aimed to further identify and characterize challenges related to fusion fuel cycles, develop potential solution pathways, and generate actionable research objectives for enabling a fusion pilot plant with a robust fuel cycle on the timescale of a decade.

During the workshop, over 170 participants representative of key researchers and stakeholders for fusion fuel cycle development from over 65 institutions and eight countries were convened. Participants were split into numerous breakout rooms to discuss topics of fueling and exhaust processing, isotope processing, rebalancing, and storage, and confinement processing and tritium accountancy. The rest of this document provides a synthesized overview of the notes taken by assigned note takers during each breakout session. After the event, workshop organizers further synthesized workshop discussions into actionable research objectives for fusion fuel cycle programs, which can be found in the following EPRI report:

- *Fusion Fuel Cycles Research Objectives: Results from the 2023 Fusion Fuel Cycle Workshop*. EPRI, Palo Alto, CA: 2024. 3002029371.

A related but separate workshop was held the following days on fusion blanket technologies, with tritium extraction from the blanket forming the scope delineation of the two workshops. Separate documents were prepared from that workshop and are:

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[1] *A Community Plan for Fusion Energy and Discovery Plasma Sciences: Report of the 2019–2020 American Physical Society Division of Plasma Physics Community Planning Process* (2019-2020). https://sites.google.com/pppl.gov/dpp-cpp.

[2] Fusion Energy Sciences Advisory Committee, *Powering the Future Fusion & Plasma: A long-range plan to deliver fusion energy and to advance plasma science.* (2020). https://science.osti.gov/-/media/fes/fesac/pdf/2020/202012/FESAC_Report_2020_Powering_the_Future.pdf.

[3] National Academies of Sciences, Engineering, and Medicine, *Bringing Fusion to the U.S. Grid* (2021). Washington, DC: The National Academies Press. https://doi.org/10.17226/25991.

- *2023 Fusion Blankets Workshop Summary: A Summary of the 2023 Fusion Blankets Workshop held in Charlotte, NC on May 24–25, 2023*. EPRI, Palo Alto, CA: 2024. 3002029372.
- *Fusion Blankets Research Objectives: Results from the 2023 Fusion Blankets Workshop*. EPRI, Palo Alto, CA: 2024. 3002029373.

The rest of this report summarizes key perspectives and high-level insights drawn from discussions by participants during the two-day workshop, reflecting community priorities for fusion fuel cycle development. Any views, opinions, and recommendations expressed in this report do not necessarily state or reflect those of EPRI.

Workshop Structure

The May 2023 Fusion Fuel Cycles Workshop was broken down into three major discussion streams:

- Stream 1: Fueling and exhaust processing
- Stream 2: Isotope processing, rebalancing, and storage
- Stream 3: Confinement processing and tritium accountancy

Within each stream, there were 3–4 technology subgroupings:

- Stream 1: Fueling and exhaust processing
  - Fueling system
  - Vacuum pumping system
  - Exhaust processing system
  - Impurity removal system
- Stream 2: Isotope processing, rebalancing, and storage
  - Isotope separation and rebalancing system
  - Isotope storage and handling system
  - Tritium (T) extraction from the blanket system
- Stream 3: Confinement processing and tritium accountancy
  - Detritiation system
  - Tritium recovery from secondary loops and enclosures
  - Tritium monitoring and accountancy

Generally, individual participants stayed in stream 1, 2, or 3 for the duration of the two-day workshop. Within their stream, most participants joined one subgroup, though there was some fluidity between groups. Each subgroup saw their technology through four major discussions:

1. Identify and prioritize challenges

2. Characterize & prioritize challenges
3. Develop project pathways to solve challenges
4. Define development projects

This report provides a summary of workshop discussions and is organized by stream and subgroup.

Overview of Discussions

Table 1 provides a summary of insights on challenges, solution pathways, and development projects for each technology subgroup from each workshop discussion stream.

Table 1: Summary of Challenges, Solution Pathways, and Development Projects for Fusion Fuel Cycles Technology Groups

Stream	Technology Subgroup	Challenges	Solution Pathways and Development Projects
1	**Fueling**	• Fueling efficiency • Pellet integrity • Scaled-up, robust fuel injection components • Validated tool set • Fuel recovery • Design requirements	• Testing facilities • Develop fueling control systems (for magnetic fusion energy (MFE) and inertial fusion energy (IFE) systems) • Understand coupling between plasma and fueling requirements • Develop required supply chains
	Vacuum pumping	• Tritium compatibility of pumps • Robust, high-duty-cycle pumps with fusion pilot plant (FPP) scale throughput • Integration of pumps into FPP • Maturity of direct internal recycle (DIR) technology • Species selectivity (He) • General performance requirements	• Modeling of tritium transport in pumping systems • Experimental based pump development program (tritium experiments) • Facility to integrate and test inner fuel cycle subsystems
	Exhaust processing	• Direct internal recycling (DIR) • Concentration/composition monitoring • Throughput and scale of technologies • Solid tritium assay techniques and secondary waste quantification • Design requirements	• Facility to integrate and test inner fuel cycle subsystems • Development of concentration control systems • Development of solid tritium assessment techniques • Physical property database for modeling of relevant particle species

Table 1 (continued): Summary of Challenges, Solution Pathways, and Development Projects for Fusion Fuel Cycles Technology Groups

<table>
<tr><td rowspan="3">2</td><td>Isotope separation & rebalancing</td><td>• Understanding where and how is isotope separation and rebalancing performed in the fuel cycle
• Reducing inventory in the system
• Supply chain concerns
• Accurate measuring of concentrations</td><td>• Generic fuel cycle design needed at FPP scale to map technology selections
• Selection of credible technologies and scaling
• Design, build, or repurpose D-T testing facility</td></tr>
<tr><td>Isotope storage and handling</td><td>• Reliability of storage techniques and materials
• Proliferations risks associated with certain storage materials
• Risks due to over storage and accidental pathways for proliferation risks</td><td>• Development of alternate storage materials and performance characterization against existing technology material
• Develop defined storage toolkit that explains different types of storage for different types of storage tasks and lists key parameters.</td></tr>
<tr><td>Tritium Extraction</td><td>• Determining testing facility requirements and identifying relevant technologies
• Identifying extraction efficiencies and operational duty
• Accident scenarios involving or utilizing the tritium extraction system
• Development of structural materials compatible with breeders</td><td>• Technology down selection and prioritization
• Testing facility development
• Resilient material and component development</td></tr>
<tr><td rowspan="3">3</td><td>Air, water & solid detritiation</td><td rowspan="3">• Large amount of trace tritiated water that needs processing
• Batch vs continuous operation
• Identification and prioritization of solid detritiation techniques
• Regulator and community engagement around hazards
• Waste characterization</td><td>• Advancement of atmospheric detritiation techniques
• Advancement of trace tritium recovery techniques
• Development of solid detritiation techniques</td></tr>
<tr><td>Tritium recovery from secondary loops</td><td>• Techniques to transfer tritium following detritiation from solid water material processing.</td></tr>
<tr><td>Tritium monitoring and accountancy</td><td>• Develop monitoring sensors and predictive controls for balance of plant</td></tr>
</table>

2 STREAM 1: FUELING AND EXHAUST PROCESSING

The following subsections present brief overviews of the technology subgroups within the Fueling and Exhaust Processing workshop stream, followed by results from "Identify and Prioritize Challenges" and "Develop Project Pathways to Solve Challenges" workshop discussion session.

Fueling Systems

In the context of fusion, fueling systems refer to the mechanisms and processes involved in providing and injecting fuel into a fusion device. To sustain a fusion reaction, fuel (typically isotopes of hydrogen, such as deuterium and tritium) must be introduced into the fusion chamber. There are three key components and techniques involved in fueling systems for fusion energy systems:

5. **Fuel injection:** The process by which fuel is introduced into the fusion chamber. The technique varies depending on the fusion approach.
6. **Impurity injection:** Refers to the intentional introduction of trace elements or compounds other than the primary fusion fuel into the plasma of a fusion energy system. Intentionally injected impurities serve various important functions, such as:
   - Plasma confinement and stability
   - Radiation control and mitigation
   - Fueling and plasma profile control
7. **Target fabrication:** The process of creating and assembling the target capsule or pellet that contains the fuel for the fusion reaction.

Fueling Systems: Identify and Prioritize Challenges

The following presents a prioritized list of fueling challenges identified at the 2023 Fusion Fuel Cycles Workshop.

Prioritized list of fueling system challenges

1. **Integrated set of design requirements are needed for an FPP-scale fuel cycle.**
   a. Potential to use milestone awardees fuel cycle designs to put together targets for fueling systems
2. **A plan is needed for a tritium capable facility/facilities to test and develop injection components that work at FPP scale.**
   a. Characterize capabilities that presently exist globally. What is available for use? What can be scaled up? What new facilities are needed?
   b. Leverage existing data and knowledge:
      i. Tokamaks that have burned tritium (e.g., Join European Torus (JET) team)

   ii. Can relevant data from defense applications be accessed and leveraged?
   iii. Leverage learnings relevant for commercial fusion systems from ITER D-T fueling plans.
 c. Tritium handling is expensive and incurs safety and regulatory challenges that need to be derisked for commercial fusion to be a reality. New facilities and/or improving capabilities at existing facilities can help begin that derisking process in the short term.
 d. Example research and development (R&D) includes:
   i. Fuel fabrication improvement (impurity removal,[4] consistency, efficiency of manufacturing)
   ii. Verification of welding and brazing procedures in tritium environments
   iii. Isotope separation testing

3. **Components and fueling systems need to be scaled and reach FPP relevant reliability needs.**
   a. A mature supply chain is needed for ensuring adequate supply of fueling components and fueling pellets.
   b. What computational toolset is required to design and improve these systems? Do new software tools need to be developed and validated?
4. **Fuel delivery needs to be optimized for a certain level of fusion energy yield (minimum set by fuel cycle needs of the FPP).**
   a. Improve fueling efficiency[5] (e.g., pellet delivery for optimal fusion yield)
   b. Fueling injection systems need to be efficient and reliable.
5. **Fuel recovery (e.g., DIR) is likely to be needed.**
   a. The U.S. DOE Milestone-Based Fusion Development Program and existing experiments could start to improve available data for T_2, D_2 and H_2 behavior.
   b. What technology advances are needed for a DIR process to be successfully implemented in an FPP?

Note: DIR pumping challenges are also discussed under the Stream 1: Vacuum Pumping topic.

6. **Fuel fabrication waste recovery to reduce tritium losses needs more R&D.**
   a. Lots of data exists on protium waste recovery, but much less data exists on tritium waste recovery.
   b. Lack of clarity on regulatory and other requirements may introduce uncertainty while systems are designed.
   c. What waste management targets are needed to inform design?

[4] e.g., helium, polymers, protium

[5] Here, fueling efficiency is taken to describe how effectively deuterium and tritium are delivered to the core plasma, such that it becomes possible for them to participate in a fusion event.

Fueling Systems: Develop Project Pathways to Solve Challenges

The following presents a summary of project pathway ideas for fueling and exhaust systems identified during workshop discussion sessions.

Summary of project pathway ideas: fueling and exhaust systems

1. **Project:** Tritium-capable facility[6]/facilities for testing of fusion fueling systems. This facility would ideally have the following capabilities:
    a. Tritium compatibility testing
        i. Provide the ability to test fueling system components at FPP-relevant flow rates.
        ii. Reliability testing of fueling systems.
        iii. Fabrication of fuel medium in a consistent, efficient, and reliable manner.
        iv. Consider community input, impact, and perception.
    b. Development of a fueling control system
        i. Techniques for impurity removal will be needed to demonstrate pellet concentration management.
    c. Demonstration of FPP-relevant fueling system
        i. Needs to demonstrate FPP-relevant flow rates and dynamic control range.
        ii. Long-term engagement between research community, vendors, and private companies will be needed.
2. **Project:** Determine material needs for fueling system and integrate them into public and private fusion materials programs.
3. **Project:** Fueling science development program
    a. Assess and enhance the survivability of cryogenic fuel layer in IFE systems.
    b. Assess and enhance understanding of the coupling between plasma behavior and fueling requirements for MFE.
4. **Project:** Develop supply chain for pellet injection and target fabrication systems for various fusion approaches
    a. Characterize potential supply chain capability.

[6] A "tritium capable" facility could be any public or private facility that meets all applicable regulations (e.g., NRC, NNSA, or other regulator) and safety protocols for work with applicable quantities of tritium to perform specific testing scopes.

Vacuum Pumping

Vacuum pumps are used to remove gasses and particles from the vacuum vessel, reducing the pressure to the desired operating levels. In FPPs, vacuum pumping system will play a crucial role in maintaining the vacuum conditions necessary for the operation. Fusion reactions require a high vacuum environment to prevent energy losses due to collisions between particles and to maintain the high temperatures necessary for fusion. When fusion occurs, various particles are generated, including energetic neutrons and helium ash (helium nuclei produced by the fusion process). These particles can interact with the walls of the fusion core and lead to material damage. By maintaining a vacuum, the number of interactions with residual gasses and chamber surfaces is minimized, prolonging the life of the fusion energy system components.

Fusion energy systems rely on high-purity fuel, such as isotopes of hydrogen (deuterium and tritium). Any contaminants in the vacuum vessel can interfere with the fusion process or reduce energy efficiency. Vacuum pumps help remove impurities and maintain a clean and controlled fusion environment. Overall, vacuum pumping systems are essential in fusion power plants to create and maintain the optimal conditions for efficient and safe fusion reactions.

Vacuum Pumping: Identify and Prioritize Challenges

The following presents a prioritized list of vacuum pumping challenges identified in discussion groups at the 2023 Fusion Fuel Cycles Workshop.

Prioritized list of vacuum pumping challenges

1. **Pumps need to integrate into a given FPP design and be capable of operating at throughput levels that enable tritium self-sufficiency and maintain required plasma conditions for that FPP's fuel cycle**
    a. Anticipated throughput for an FPP needs to be considered, cognizant of all requirements (not just fueling). FPP designers need to model and characterize their anticipated fuel cycle needs to define pump requirements.
    b. Consider the range of species-selective pumping speeds that pumping technology can support and that are sufficient to optimize the TBE for a given plant.
2. **Pumps need to be tritium compatible.**
    a. "Tritium compatibility" levels need definition. There might not be one uniform definition that applies to all pumps, so specificity in requirements for a given pump is important.
    b. An acceptable lifetime for vacuum pumps and the necessity of tritium compatibility needs to be defined. Questions and efforts to consider while crafting said definition include:
        i. What components should be tritium compatible within a vacuum pump?

ii. Evaluation of alternative solutions which lead to performance compromises but improve tritium compatibility or reduce its need.
iii. A review of mercury pumps as a solution.

c. A test bed for exploring tritium compatibility of pumps is needed to explore the solution space.
d. Pumps need to be tritium compatible with respect to lifetime permeation requirements.

3. **Need to design pumps for high-duty-cycle operation and robustness**
   a. Robust pumps which can operate for longer duty cycles will increase the longevity of the overall FPP duty cycle.
   b. Development of pumps with reduced maintenance time and intervention requirements will improve plant economics.
4. **Current pumping technology needs to be scaled up (> 100 Pa m^3/s) to handle FPP throughput levels**
   a. Throughput levels define the fuel cycle mass balance and, as a result, the fuel cycle architecture.
   b. Divertor pressure levels and particle exhaust ratios need to be maintained in a fusion system. This will critically define an exhaust and/or throughput requirements for the fuel cycle.
   c. Continuous operation of pumps is critical to future commercial viability of an FPP.
5. **Design requirements for vacuum pumping systems relevant to an FPP need to be defined**
   a. Relevant throughput scale needs to be modeled for an FPP, coupled with three-dimensional transport of tritium migration through the vacuum pumps.[7]
   b. DIR should be integrated into the vacuum pumping design to ensure tritium self-sufficiency.

Vacuum Pumping: Develop Project Pathways to Solve Challenges

The following presents a summary of project pathway ideas for vacuum pumping systems identified during workshop discussion sessions.

[7] Community experience has previously conducted this level of modeling to rationalize the divertor challenge in FPP design of a spherical tokamak (such as in the Spherical Tokamak for Energy Production program). However, this doesn't merit a digital-twin level of activity.

Summary of project pathway ideas: vacuum pumping

1. **Project: Mature the Direct Internal Recycling (DIR) pumping solution**
    a. Characterize existing DIR concepts and research to evaluate the gap between existing capabilities and a scaled-up DIR system for an FPP.
        i. Explore the current research and development on metal foil pumps and level of technology maturity.
        ii. Explore the current research and development on alternate DIR technology concepts and ascertain level of technology maturity.
    b. Develop an integrated DIR test bed capability
        i. Design, build and commission a DIR test bed facility, designed to demonstrate integrated testing of the DIR technology with all downstream and upstream systems (inner fuel cycle testing) inactively.
    c. Active testing of DIR technologies
        i. Isolated testing of DIR technologies in an active tritium environment to understand any particular isotopic effects.
        ii. Operations should be scaled so that relevance to an FPP is still met (i.e., sufficient magnetic fuel strength and throughputs of tritium).
2. **Project: Develop a tritium compatible vacuum pumping testing facility**
    a. Conduct a characterization survey of existing global tritium testing facilities able to support research and development and assess critical gaps in their capabilities/availability.
    b. Conduct tritium compatibility tests on various pumping solutions and components
        i. Develop a testing plan of existing pumps and low maturity components.
        ii. Identify appropriate facilities with the capability to conduct active testing or if none exist design, build and commission a testing facility.
        iii. Conduct tests and report results with the most likely solution for an FPP.
3. **Project: Define vacuum pumping design requirements for an FPP**
    a. Define required exhaust throughputs (or likely ranges of throughputs) for an example FPP to support and guide vendor engagement.
        i. Look into developing an example design exhaust throughput for the breadth of fusion concepts represented in the milestone award program (e.g., tokamaks, stellarators, IFE)
        ii. Conduct a workshop with vendors to understand current technology limitations and review FPP exhaust throughputs with input from technology vendors.

   iii. Engage vendors to identify key challenges from developing the above set of requirements and develop a FOA process by which all vendors are engaged with driving down the identified challenges.
b. Secure targeted funding to mature exhaust pumping solution for fusion applications
   i. Secure and allocate targeted funding based on work from 3(a). Conduct technical assessments and award partners who can support the breadth of the research effort to ensure vendors are adequately engaged at this stage.
   ii. Hold targeted workshops for industry partners and awardees to develop exhaust pumping solutions aligned with capabilities and defined requirements.

4. Project: Research into Tritium Burn Efficiency (TBE) and fusion exhaust pumping

a. TBE is affected by relative concentrations of species/ash (and relative pumping speeds). There is a need to assess TBE required by a given plant design to support a given operational scheme and determine the corresponding requirements on the plant's pumping systems.

Exhaust Processing

In a fusion fuel cycle, the exhaust purification system refers to the set of technologies and processes designed to manage and treat the waste products and byproducts generated during the operation of a fusion power plant.

The primary waste product in a fusion reaction is helium, which is harmless and non-radioactive. The exhaust of helium ash and its concentration in the divertor have a significant impact on the tritium burn efficiency attainable by the plant, a problem statement localized to MFE.

Unburned tritium, neutron-activated materials, and neutron-activated impurities are also present in a fusion plant. These materials can be hazardous if not managed properly. Their sequestration from the environment (and plant employees) is important to the safe, regulations-compliant operation of the FPP.

The exhaust purification system serves several important purposes:

- **Helium Recovery**: The primary focus of the exhaust purification system is often the efficient recovery of helium gas, which can be valuable and reused for various applications.
- **Tritium Extraction**: Tritium, a radioactive isotope of hydrogen, is generated during fusion reactions. It must be carefully extracted and managed to avoid environmental and health risks.
- **Impurity Removal**: Fusion reactions can produce high-energy neutrons that may activate impurities in plasma gas streams. The purification system must effectively remove these activated impurities to minimize the radioactivity of the waste.

The design and implementation of the exhaust purification system are crucial to ensure that fusion power plants are not only efficient in energy production, but also safe and environmentally responsible. Any remaining waste, such as activated materials and neutron-activated components, must be safely stored, managed, and, if possible, recycled or disposed of in a way that minimizes their impact on the environment and human health.

Exhaust Processes: Identify and Prioritize Challenges

The following presents a prioritized list of exhaust process challenges identified in discussion groups at the 2023 Fusion Fuel Cycles Workshop.

Prioritized list of exhaust processing challenges

1. **Definition of a fuel cycle architecture utilizing DIR technology**
   a. Determine separation effectiveness utilizing the integration of DIR technology.
   b. Demonstrate reduction in overall fuel cycle tritium inventory by the deployment of DIR technology.
2. **Characterization of impurities in fusion concepts and associated impurity removal technologies for exhaust processing**
   - Characterize anticipated impurities generated in different fusion concepts (e.g., MFE, IFE, etc.).
   - Identify key technologies/systems/processes to remove all impurities and engage supply chain stakeholders to determine technology readiness levels.
3. **Develop continuously operating solution for an FPP-scale exhaust processing system and associated process controls**
   - Identify real-time tritium concentration monitoring devices.
   - Determine challenges in operating exhaust processing systems continuously and identify key technology development needs. Highlight the challenges pertaining to MFE and IFE fusion concepts.
4. **Understand disposal pathways and waste management requirements**
   - Determine any solid waste impurities expected in exhaust processing and establish removal processes.
     - What infrastructure is needed?
     - What processes exist? What new processes need to be developed?
     - How to determine tritium levels in solid materials?
     - Engage with regulatory bodies to understand risks to workers and environment
     - Consider public engagement/perception
   - Need to develop infrastructure for waste management and disposal

Exhaust Processes: Develop Project Pathways to Solve Challenges

The following presents a summary of project pathway ideas for exhaust processes identified during workshop discussion sessions.

Summary of project pathway ideas: exhaust processing

1. **Project: High throughput chamber exhaust processing (inner fuel cycle (IFC) loop)**
    a. Develop an inner fuel cycle integrated test bed facility with MFE and IFE exhaust conditions.
        i. Develop a list of requirements for an integrated IFC test-test bed facility.
        ii. Map requirements against landscape of existing facilities internationally.
        iii. Develop/workshop a testing matrix to drive understanding around exhaust processing technologies at an FPP scale.
2. **Project: Modeling to support chamber exhaust processing**
    a. Develop physical properties database to support fuel cycle modeling efforts.
        i. Perform a gap analysis of the physical properties required for design of exhaust processing systems.
        ii. Set up an open-source database with all existing physical properties conducted through literature assessments, vendor engagements, and collaboration with research institutes.
        iii. Conduct experiments required to generate any missing or unavailable data.
        iv. Publish development work publicly to ensure access to information and avoid export control issues.
        v. Utilize and recommend the use of the database to entities designing fuel cycle systems.
3. **Project: Recycling tritium and developing solid detritiation technologies**
    a. Develop non-destructive solid detritiation techniques.
        i. Develop novel and unique technologies to detritiate solid materials non-destructively.
        ii. Conduct lab-scale tests to validate principal of the technology.
    b. Develop a technology maturity roadmap and integrate into the overall fuel cycle and blanket technology roadmap initiative.
4. **Project: Developing post-operations asset recovery and material detritiation processes**
    a. Develop systems for tritium recovery from waste material generated by fusion.
        i. Define user requirements and scale of challenge for an FPP (i.e., rough estimates of solid tritiated waste generated waste)

ii. Produce a conceptual detritiation system deploying existing techniques where possible and engage industry to leverage appropriate design and process experience.
iii. Identify any similar existing processes and leverage knowledge and expertise.

b. Develop a technology maturity plan consisting of experimentation, integrated testing or modeling activity needed.

Impurity Removal

Discussions from this subgroup naturally folded into the other groups after the first breakout session. Refer to the above sections for insights relevant to impurity removal.

3 STREAM 2: ISOTOPE SEPARATION, REBALANCING, STORAGE, AND EXTRACTION

The following subsections present brief overviews of the technology subgroups within the Isotope Separation, Rebalancing, Storage, and Extraction workshop stream, followed by results from "Identify and Prioritize Challenges" and "Develop Project Pathways to Solve Challenges" workshop discussion session.

Isotope Separation and Rebalancing

Isotope separation and rebalancing in the context of fusion refers to the processes and techniques used to manage the isotopic composition of the fusion fuel within a fusion energy system. These processes are essential for maintaining optimal conditions for the fusion reaction, enhancing energy output, and prolonging the fusion system's operational lifespan.

Isotope Separation: Isotope separation involves the selective extraction or enrichment of specific isotopes from a mixture. In fusion, this process is primarily concerned with separating tritium from the fusion fuel mixture in the process exhaust gas stream.

Isotope separation methods may include techniques like cryogenic distillation, chemical processes, or adsorption-desorption processes to isolate and concentrate tritium from the fuel mixture. Once separated, the enriched tritium can be reused in the fusion process.

Isotope Rebalancing: Isotope rebalancing involves adjusting the isotopic composition of the fusion fuel mixture to maintain optimal conditions for the fusion reaction. Over time, the isotopic composition of the fuel can change due to the consumption of isotopes during fusion and the accumulation of waste products. To ensure sustained fusion reactions and maintain desired energy output, the isotopic balance needs to be periodically adjusted.

Isotope rebalancing may involve reintroducing enriched isotopes back into the fuel mixture to restore the desired isotopic composition. This process can help maintain stable plasma conditions and improve overall fusion process efficiency.

Both isotope separation and rebalancing are crucial for managing the fuel composition in fusion energy systems, optimizing energy output, extending operational lifetimes, and ensuring the safety and reliability of the fusion process. These processes are complex and require advanced technologies and careful control to achieve successful fusion outcomes.

Isotope Separation and Rebalancing: Identify and Prioritize Challenges

The following presents a prioritized list of isotope separation and rebalancing challenges identified in discussion groups at the 2023 Fusion Fuel Cycles Workshop.

Prioritized list of isotope separation and rebalancing challenges

1. **Identify where hydrogen isotope separation/rebalancing is performed in an FPP and assess impact on system inventory**
   a. Does the DIR concentration require rebalancing and injection of fresh fuel?
2. **Reduction of tritium inventory within isotope separation and rebalancing system**
   a. High tritium inventories pose safety, regulatory, and efficiency challenges.
   b. Develop the technology further to maximize throughput and minimize inventory of tritium.
   c. Can the technology be taken from batch operation to continuous operation for commercialization?
   d. Since there will likely not be a single FPP design, can isotope separation and rebalancing technology be developed to be compatible with multiple FPP concepts?
   e. What are the technology choices?
3. **What are the supply chain considerations that need to be made for the isotope separation and rebalancing system?**
   a. Are there concerns surrounding export control and licensing that should be considered?
4. **Can one measure the quantity (concentration) of each isotope in the rebalancing stream?**
   a. Is this technology being developed to a sufficient level of accuracy?
   b. Does it measure in real time or does it hinder the continuous nature of the system?

Isotope Separation and Rebalancing: Develop Project Pathways to Solve Challenges

The following presents a summary of project pathway ideas for isotope separation and rebalancing identified during workshop discussion sessions.

Summary of project pathway ideas: isotope separation and rebalancing

1. **Project: Development of generic fuel cycle design for various fusion FPP concepts**
   a. Develop a set of integrated design requirements for the fuel cycles of an MFE and an IFE FPP.
      i. Assess impact of doubling time[8] on FPP designs.
      ii. Determine critical impacting variables/parameters on the operability of a fuel cycle.

[8] Time to double the plant's startup tritium inventory. This allows the startup of a second plant. Faster target doubling times require higher TBRs in the blanket and higher efficiency of tritium processing overall.

b. Design an appropriate isotope separation and rebalancing system capable of meeting requirements defined by 1(a).
    i. Define the system data sheet (e.g. duty requirements, separation factors, dimensions and mass balances).

2. **Project: Technology mapping and data integration**
    a. Develop and implement a standardized database for design and experimental data.
        i. Develop a strategy to standardize all data from pre-existing facilities, highlighting unique isotopic effects.
        ii. Map all stakeholders and ensure adherence to strategy developed.
        iii. Develop a framework for future data integration and ensure effective communication.
    b. Map existing isotope separation/rebalancing and concentration sensor technologies.
        i. Conduct an extensive literature review identifying intellectual ownership, maturity and measured performances of isotope separation/rebalancing and concentration measurement technologies.
        ii. Identify key limitations of the isotope separation/rebalancing and concentration sensor technologies. Determine how these limitations translates to critical risks for the FPP fuel cycle.
3. **Project: Design, build, or modification of a pre-existing deuterium-tritium facility**
    a. Design, build or modify a pre-existing facility to develop an inner fuel cycle test-bed
        i. Capture all design requirements for the IFC test bed from an isotope separation and rebalancing standpoint.
        ii. Design a testbed that mimics the IFC behavior of rebalancing, DIR, injection, and fresh tritium feed from the blanket.
        iii. Build and commission testing facility and develop testing matrix to capture all experimental data to support isotope separation system (ISS) development at an FPP scale.
        iv. Conduct experiments to capture raw data pertaining to:
            1. Tritium/deuterium permeation
            2. Tritium/deuterium diffusion and solubility through different material
        v. Use the testbed as a medium to train and upskill the workforce.
    b. Develop high-throughput, continuous Direct Internal Recycling (DIR pump)
        i. Conduct a scoping study to identify technologies available and down select appropriate technology candidates against requirements for an FPP.
        ii. Mature the technology by lab scale testing followed by integrated system testing and scaled testing.
        iii. See also discussion of DIR in previous sections.

Isotope Storage and Handling

Isotope storage and handling systems in the context of fusion typically refer to the infrastructure and processes designed to manage hydrogen isotopes. Isotope storage and handling systems in fusion encompass several key aspects:

Storage: Both deuterium and tritium need to be stored safely to prevent any leaks or contamination. Tritium, in particular, is radioactive and requires special considerations for handling and storage due to its potential health risks.

Transportation: Isotopes may need to be transported between different facilities, such as from the production site to the FPP. Secure transportation methods that adhere to regulations and ensure the safety of personnel and the environment are essential.

Safety: Given the potentially hazardous nature of tritium and other isotopes, safety protocols and containment measures are of paramount importance. This includes designing facilities with proper ventilation, leak detection systems, and waste management procedures.

In summary, isotope storage and handling systems in fusion research involve various technologies and protocols to manage the storage, transportation, and safe handling of isotopes like deuterium and tritium. These systems must prioritize safety, efficiency, and environmental protection to make fusion a viable and sustainable energy source.

Isotope Storage and Handling: Identify and Prioritize Challenges

The following presents a prioritized list of isotope storage and handling challenges identified in discussion groups at the 2023 Fusion Fuel Cycles Workshop.

Prioritized list of isotope storage and handling challenges

1. **Understand the reliability of storage options, and how structural materials used in storage technology will interact with tritium**
    a. What are the absorption/desorption characteristics of the storage materials being proposed for storing hydrogen isotopes?
    b. What are their stability characteristics under thermal loads?
    c. Are there any aging effects exhibited by the storage material pallet?
    d. How does the structural material of the storage systems interact with tritium?
    e. Are tritium permeation barriers needed? If so, where will permeation barriers be needed?
    f. Are there any embrittlement risks due to the decay effects of tritium or more generally, for hydrogen?
    g. Are the mechanistic behavior of diffusion of tritium through structural material understood?
    h. Can these systems be detritiated so that maintenance or decommissioning activities can be facilitated. If not, what are the alternative maintenance options?

Workshop participants also raised questions regarding possible proliferation risks of storage material and accident pathways due to loss of storage capacity and risks related to public perception, particularly related to the use of depleted uranium as a storage medium for tritium. However, depleted uranium getter beds represent small amounts of fertile uranium and are not relevant to the production of significant quantities of weapons-usable material.

Isotope Storage and Handling: Develop Project Pathways to Solve Challenges

The following presents a summary of project pathway ideas for isotope storage and handing identified during workshop discussion sessions.

Summary of project pathway ideas: isotope storage and handling

1. **Project: Characterization of isotope storage materials compared to depleted uranium bed characteristics**
    a. Characterize hydrogen isotope storage material through existing use at facilities globally.
        i. Identify all facilities which deploy isotope storage systems.
        ii. Establish data sharing activities to characterize technologies with existing data.
        iii. Build a dataset to map performance characteristics of existing technologies.
        iv. Conduct experiments to fill any missing data pertaining to depleted uranium storage material.
    b. Investigate and compare non-depleted uranium material storage options.
        i. Conduct an extensive technology mapping exercise to identify all alternate storage material options.
        ii. Design, build and commissioning a small test bed to explore absorption, stability, and thermal load characteristics of alternate material options.
        iii. Compare data to depleted uranium characteristics and conduct a cost-benefit exercise of maturing alternate technology.

Tritium Extraction from the Blanket

Tritium extraction from the blanket involves recovering the tritium that has been bred within the blanket material as a result of neutron interactions. The tritium that is generated in the blanket needs to be captured and extracted for use as fuel in the fusion reaction. This involves designing a system to collect the tritium-rich gasses or particles that emanate from the blanket. The collected tritium-rich gasses or particles are then subjected to purification processes. This purified tritium can then be used as fuel for the fusion energy system.

Tritium extraction from the blanket is a critical process for the overall operation of fusion energy systems, especially those employing the D-T fuel cycle. It ensures a continuous supply of tritium fuel to sustain the fusion reaction while adhering to safety and environmental considerations due to the radioactive nature of tritium. Effective tritium extraction systems are essential for achieving practical and sustainable fusion energy production.

Tritium Extraction from the Blanket: Identify and Prioritize Challenges

The following presents a prioritized list of challenges identified for tritium extraction from the blanket in discussion groups at the 2023 Fusion Fuel Cycles Workshop.

Prioritized list of challenges: tritium extraction from the blanket

1. **Testing infrastructure for tritium extraction systems (TES) and down selection of technologies**
   a. What information is needed for TES technology down selection? Options are not clear from a performance selection perspective.
   b. Is there currently have enough expertise or resources to adequately explore this area of research?
   c. Does the testing infrastructure exist to increase the technology readiness level (TRL) of TES technologies?
   d. Experimental data is needed to down select technologies and develop models and isotopic effects.
2. **Determining accurate extraction efficiencies and operational duty for tritium extraction systems**
   a. The system needs to be reasonable in terms of duty/energy requirements, as the goal is a power plant that exports energy as a product.
   b. Tritium extraction from the blanket will depend on the breeder material. Which technologies perform best with which material?
   c. Processing time needs to be minimized to support tritium self-sufficiency and overall site inventory.
   d. Low tritium concentrations make extraction take longer.
3. **Coolant impurity and purification challenges**
   a. What impurities will be present in the breeder material?
   b. Will the impurities be subject to neutron activation?
   c. How will purification of the breeding medium be ensured?
   d. Do the impurities negatively impact the performance of the TES?
   e. What processes exist to purify the breeder material?
   f. Are there any significant corrosion and tritium-related effects as a result of impurities?
4. **What accident scenarios (leading to tritium release) can be developed that incorporate the TES?**
   a. Have accident scenarios been developed for the blanket and extraction system?

b. Is this a key area of design that remains unexplored?

5. **What structural material compatibility challenges exist?**
    a. Breeder materials can be aggressive in terms of corrosion and degradation of structural material. What is the best selection for breeder and structural materials to ensure compatibility?
    b. What tests are needed to identify and develop appropriate structural materials?

Tritium Extraction from the Blanket: Develop Project Pathways to Solve Challenges

The following presents a summary of project pathway ideas for tritium extracted from the blanket identified during workshop discussion sessions.

Summary of projects: tritium extraction from the blanket

1. **Project: Technology down selection and data generation**
    a. Technology mapping and down selection for further research and development
        i. Identify all extraction systems technologies for breeding mediums pertaining to FPP concepts.
        ii. Down select technology candidates against developed requirements for an FPP concept.
        iii. Develop simple models to support process design for the tritium extraction system for FPP concepts.
2. **Project: Facility development**
    a. Requirements capture and test facility design development
        i. Identify all testing requirements for breeder options and extraction systems identified.
        ii. Design an integrated user testing facility to deploy multiple extraction systems to generate performance data.
        iii. Conduct a landscape facility assessment to identify appropriate pre-existing test beds that can be repurposed (if any).
        iv. Build, commission, or repurpose facility for testing tritium extraction systems from associated breeder materials.
    b. Conduct testing experiments and model development to support FPP design activities
        i. Develop a testing plan for critical extraction technologies selected.
        ii. Conduct tests to generate required data for model development or validation.
        iii. Develop new models for extraction systems or use validated modeling tools to further the extraction system design in FPP concepts.
        iv. Utilize raw data to model key characteristic behavior of tritium extraction technologies.

3. **Project: Resilient material and component development**
   a. Conduct material assessment tests for tritium extraction systems
      i. Identify and down select key structural, performance and barrier materials needed (if any) for the tritium extraction system.
      ii. Develop a testing plan to generate required data to support design and development of tritium extraction systems.
      iii. Conduct tests and utilize raw data to support overall design activity.

4 STREAM 3: CONFINEMENT PROCESSING AND TRITIUM ACCOUNTANCY

Confinement Systems and Tritium Accountancy

The subtopics for this stream were (1) air, water & solid detritiation; (2) tritium recovery from secondary loops; and (3) tritium monitoring and accountancy. However, these three topics will be combined in a single overarching discussion below. Definitions of these systems are given below before insights from the “Identify and Prioritize Challenges” and “Develop Project Pathways to Solve Challenges” workshop discussion sessions are presented.

Air detritiation systems: An air detritiation system is designed to remove tritium from the air in fusion facilities or research environments where tritium is being handled. This system is particularly relevant in facilities where tritium is used, produced, or handled in various operations, as tritium can be released into the air during these processes.

Water detritiation systems: These systems are used to extract tritium from water sources, particularly from water contaminated with tritium in fusion facilities. Tritium can contaminate water sources due to various processes such as leakage, spills, or as a result of fusion reactions.

Solid detritiation systems: In fusion, this system refers to the process of removing tritium from solid materials that have come into contact with tritium in a fusion facility. Solid detritiation is an essential aspect of fusion research and energy system operation, as tritium can become embedded in various solid materials, potentially posing health risks and affecting the safety of personnel and the environment.

Tritium recovery from secondary loops: Tritium recovery from secondary containment systems in the context of fusion refers to the process of capturing, extracting, and reclaiming tritium within the secondary systems of a fusion energy system. Secondary containment systems are designed to provide an additional layer of safety and protection in case of any potential leaks, spills, or releases of tritium or other materials.

Tritium monitoring and accountancy: In the context of fusion, this refers to the systematic and comprehensive methods used to track, measure, and manage tritium within a fusion facility. These processes are critical for ensuring safety, controlling tritium inventory, and complying with regulatory requirements related to the handling and storage of radioactive materials.

Note: Discussions in stream 3 veered towards general fuel cycle technologies and were not limited to confinement processing and tritium accountancy.

Confinement Systems and Tritium Accountancy: Identify and Prioritize Challenges

The following presents a prioritized list of challenges for confinement systems and tritium accountancy identified in discussion groups at the 2023 Fusion Fuel Cycles Workshop.

Prioritized list of challenges: confinement processes, tritium accountancy

1. **Managing large volumes of trace tritiated water and design of continuously operating tritium facilities**
    a. How can the challenge of detritiating large amounts of trace tritiated water be done efficiently (i.e., with low energy costs)?
    b. How does the fusion community address heating, ventilation, and air conditioning (HVAC) contamination requirements?
    c. What are the waste transportation needs for FPP?
    d. Do modeling capabilities exist to support design of these systems for FPP concepts?
2. **Characterization and removal of tritium from solid components and materials**
    a. Do technologies exist that can non-destructively remove tritium from solid components or materials?
3. **Waste characterization and public engagement around fusion waste**
    a. How to best work with regulatory agencies to understand and communicate the nuances of tritium limits for different waste streams in fusion?
    b. Waste management is a significant cost driver for any FPP.
    c. Community engagement to drive facilitated discussions around waste management and siting.
    d. Currently there is not a comprehensive community engagement strategy that will enable successful siting of fusion, potentially leading to intervention and delay.
    e. There is a need to be transparent with the public and local communities about tritium and waste management to manage long-term reputation and trustworthiness.
    f. Regulatory clarity over life cycle of plant is needed
        i. Regional vs national vs international jurisdiction
        ii. Need to define expected waste output from FPP (e.g., fuel cycle modeling).

Confinement Systems and Tritium Accountancy: Develop Project Pathways to Solve Challenges

The following presents a summary of project pathway ideas for confinement systems and tritium accountancy identified during workshop discussion sessions.

Summary of project pathway ideas: confinement processing and tritium accountancy

Tritium monitoring and accountancy:

1. **Project: Develop monitoring sensors and predictive controls for the balance-of-plant (BOP)**
    a. Develop sensors and monitoring equipment to detect tritium in various states and concentrations:
        i. Mapping activity to determine conditions (pressures, temperatures, and states) in which hydrogen isotope monitors are needed across an FPP.
        ii. Technology review to determine whether all conditions have a specific sensor technology.
        iii. Assess and select technologies which align closely with requirements for an FPP.
        iv. Test selected sensors in appropriate conditions to determine whether they function as hypothesized.
        v. Collect raw data and develop modeling tools to support an FPP control and instrumentation strategy for the fuel cycle.
    b. Develop predictive control software to support balance-of-plant (BOP) activity:
        i. Identify key control variables for BOP and baseline against a generic FPP design.
        ii. Determine sensitivity of feedback required and determine risk pathways.
        iii. Baseline against data generated from testing monitoring technologies.
        iv. Develop and calibrate algorithms/software to integrate into monitoring sensors for the fuel cycle.

Air, water and solid detritiation:

2. **Project: Advancement of atmospheric detritiation systems**
    a. Define performance targets for detritiation system at an FPP scale:
        i. Conduct a mass and energy balance with regulator discharge values to determine scale of detritiation system.
        ii. Explore technologies which are capable of meeting technical requirements and down select appropriate technology.
        iii. Identify key integrative system requirements (e.g., bio shield, tokamak hall, hot cell, and fuel cycle facility).
    b. Mature relevant technologies for atmospheric detritiation.
        i. Develop dehumidifiers for removal of tritiated water vapor from atmosphere at an appropriate scale.
        ii. Explore process change to ensure counter-current wet scrubbing.

iii. Explore prevention in fuel cycle design by minimizing collection of tritiated water.

3. Project: Advancement of trace tritiated water recovery systems

a. Define performance targets for trace tritiated water recovery system at an FPP scale:

i. Conduct a mass and energy balance with regulator discharge values to determine scale of the trace tritiated water recovery system.

ii. Explore technologies which are capable of meeting technical requirements and down select appropriate technology.

iii. Identify key integrative system requirements (e.g., generated trace tritiated water from other systems around the FPP).

iv. What techniques can be deployed to minimize generation of trace tritiated water.

b. Mature relevant technologies for trace tritiated water recovery systems:

i. Identify technologies which can be deployed to meet trace tritium water recovery at an FPP scale.

ii. Explore potential to deploy multiple techniques to reduce duty requirements.

iii. Conduct a design exercise to minimize generation of trace tritiated water.

iv. Determine appropriate safety procedures.

4. Project: Development of solid detritiation techniques

a. Establish baseline techniques for quantifying tritium amounts in different relevant solid materials:

i. Develop novel and unique technologies to detritiate solid materials. Short-term: destructive analysis; Long-term: non-destructive assays that can be used for FPP components without affecting component performance.

ii. Explore technology from other sectors that could be adapted.

iii. Conduct lab-scale tests to validate principal of the technology.

iv. Develop a technology maturity roadmap and integrate into the overall fuel cycle and blanket technology roadmap initiative.

v. Engage supply chain to see potential scalability to FPP fusion concepts.

5. Project: Techniques to transfer tritium following detritiation

a. Identify key challenges in transferring recovered tritium following recovery.

i. Develop rationale for recovered tritium transfer challenges and identify key solutions for development.

Generic project ideas (related to overall fuel cycles development, but discussed during Stream 3 breakout groups)

6. Project: Testing facility for developing tritium accountancy technology

Survey if measurement technologies are robust enough for the FPP environment:

a. Highlight instrumentation needs to be further developed for suitable FPP use.
b. Conduct a review of facilities which are available for simulated FPP-environment testing and validation.
c. Upgrade existing facilities.
d. Build new facilities capable of validating performance in expected environment.
e. Calibration and validation
f. Document consolidated experiences and share with the community.
g. Engage regulators to make sure accuracy is sufficient.
h. Determine batch vs continuous operation requirements:
    i. Need high availability of measurement technology (redundancy)
    ii. Sensor placement determined by process control needs and risk assessment

7. **Project: Revise International Organization for Standardization (ISO) criteria for design of ventilation system**
    a. Revise and update ventilation system standard to include tritium:
        i. Identify standards pertaining to tritium and upgrade them to address tritium challenges.
        ii. Specify performance definitions relevant to test facilities and FPPs.
8. **Project: Confinement strategy and HVAC integration**
    a. Ensure facility designs incorporate containment strategy.
        i. Segregate into zones that can be isolated from HVAC
9. **Project: Tritium targets in a D_2O reactor**
    a. Assess viability of breeding T in existing Heavy Water Reactors (HWRs) for increased supply chain availability.
        i. Conduct a neutronic cost benefit analysis to determine whether it is commercially viable to breed tritium in HWRs.
10. **Project: Expand tritium removal from CANDU reactors**
    a. Introduce new tritium removal facilities (e.g., Pt LePreau, India, Romania)
        i. Explore the commercial and geopolitical discussion to remove tritium from HWRs in facilities like Pt LePreau, India, or Romania.
        ii. Utilize new removal facilities as a basis to test tritium removal technologies.

5 CONCLUSIONS

Prompted by rapid fusion power plant deployment timelines and significant existing technology gaps, the May 2023 Fusion Fuel Cycles workshop convened over 170 researchers to identify challenges, research gaps, and potential solution pathways for fusion fuel cycle development. Throughout the workshop, extensive discussion was had in breakout rooms regarding pertinent topics for fusion fuel cycle technology: fueling and exhaust processing, isotope processing, rebalancing, and storage, and confinement processing and tritium accountancy. Subtopics within these three overarching groupings were also explored in breakout room discussions. The workshop resulted in community-prioritized research objectives as well as development project ideas to potentially solve major challenges for fuel cycle systems. This report provided a full synthesized summary of breakout room discussions, and its companion report "Fusion Fuel Cycles Research Objectives: Results from the 2023 Fusion Fuel Cycle Workshop" (EPRI Report 3002029371) provides key conclusions pertaining to research priorities to address technical gaps. While significant effort is needed to address critical technology development needs, this workshop provided an opportunity for relevant stakeholders to prioritize specific gaps and efforts to help most effectively shape fusion fuel cycle research programs.

A APPENDIX: PROJECTS IDEAS

Throughout the workshop, participants had the opportunity to fill out project idea templates aimed at addressing challenges identified during the workshop. These project idea templates were a method implemented by the organizers to collate the ideas of development work given the context of discussions within the workshops. A lightly edited transcription of those project templates is given below. Any mention of specific organizations or capabilities in this section do not imply endorsement.

What	Details	Implementation
Fuel cycle modeling		
Fuel cycle model development		
Fuel cycle dynamic modeling	• Collect physical properties used in fuel cycle design to support overall modeling	• Community outreach for data • Validate data • Develop toolkit
Develop fuel cycle model	• Maximize throughput, minimize inventory	• Get inputs on conceptual FPP design to develop model • Validate with performance data from sub systems • Optimize fuel cycle design
Gap analysis of analytical tools for fusion fuel cycle	• Determine where fundamental research is required and what needs testing in a tritium environment	• Identify stakeholders, have them identify requirements • Identify available technologies • What solutions are already available? • What gaps exist? • What knowledge from existing experiments/facilities can be applies? • Manage IP conflicts • Make sure knowledge is shared
Parasitic load assessments of fusion fuel cycle technologies	• Assess energy requirements, associated emissions, and waste streams of fuel cycle	• Benchmark against established processes/data • Progress to full sustainability assessment of fusion fuel cycle • Develop framework to assist in technology selection • Define “sustainability” with input from stakeholders • Use software like ORION

Facility development to collect data for fuel cycle modeling		
Tritium property testing facility and mod-sim framework	• Understand fundamental tritium behavior and properties by leveraging experiments and simulation	• Create open-source data library / public research record on materials and tritium interactions • Use simulations to fill in gaps from experiments • Understand impact of impurities • LIBRA, SRNL; Finite Element Simulation of Tritium In Materials (FESTIM), Tritium Migration Analysis Program (TMAP)
Build fuel cycle demonstration facilities	• Expose components, systems to fusion-relevant conditions • Study interfaces between components • Test component reliability	• Build full system in non-tritium environment first • Build subsystems for testing tritium extraction and compatibility • Build at reasonable scale • Get validation needed for confident design of FPP
Tritium extraction from blanket/breeder		
Modeling		
Integrated modeling of tritium extraction from breeder	• Unify/model existing experimental work on tritium extraction from breeders and develop predictive capability of extraction performance	• Model with existing data sets • Predict extraction efficiency, mass transfer coefficients • Incorporate new data • Follow-on facility build
Experiment/facility		
Rapid tritium extraction development facility	• Rapidly test extraction techniques at small scale • Model validation for scaled up performance predictions • Integration with FPP design • Assess TES for all breeder materials of interest • Improve TES efficiency for blankets	• Small-scale testing of TES systems • Rapid iteration on TES design • Develop models with data from facility • Start with D/H, get to T • Derisk FPP program
Tritium extraction innovation	• Develop tritium extraction technologies for an FPP for FLiBe, PbLi	• Thermophysical property measurement • Model tritium transport with convection and complex flow fields • Hydrogen/Deuterium (H/D) experiments at relevant conditions

Electrolytic tritium extraction in loop system and modeling for scaleup	• Tritium loop to test extraction capabilities	• Design loop, extraction architecture • Purification system • Optimize with modeling • Demonstrate extraction capability
Tritium extraction investigation for gas-liquid contactor	• Model extraction efficiency from this technology, investigate scalability	• Use existing data to develop computation tool • Carry out design optimization and scalability studies
Isotope separation, DIR		
General program		
Continuous isotope separation/rebalancing	• Demonstrate continuous hydrogen isotope system with FPP-relevant throughput	• Develop membranes and electrodes • Demonstrate scalability • Create models • Test with H and D first, then T • Determine which proton conductors work with FPP
Lab scale scoping for technology down selection for isotope processing/rebalancing	• T extraction from low - concentration breeder materials • H isotope extraction efficiency; inventory management; budget; scalability	• Gather data for comparing of TES options with trace levels of tritium • Develop correlations for scaleup • Proof of concept development of extraction technologies • Small scale experiments
Chamber exhaust stream species separation	• Create suite of technologies that enable segregation of different exhaust species prior to processing • Enable tritium recovery from exhaust and detritiation of waste	• Evaluate existing technology and its scalability • R&D for gaps • Evaluate impurities likely for each FPP candidate • Test facility for demonstration of mixed gas exhaust separation • Metal Foil Pump (MFP) cryogenic absorbers, etc.
Develop ISS for rebalancing	• Develop optimized system for rebalancing • ISS with fast response balancing system, not just high purity T_2 separation	• Continue development of ISS systems • Identify other separation materials to optimize kinetics over purity • Need system inputs (throughput, flow rate) • Demonstrate separation factor • Build on existing ISS knowledge
Develop analytical techniques for rebalancing	• Analytical technique to measure hydrogenic species isotopologues	• Define expected requirements/environmental conditions for analytical equipment • Identify appropriate technique

	• Rebalancing system control	• Develop the technology to align with FPP requirements
Specific technology development program		
Develop **Raman spectroscopy** accountancy aligned with rebalancing	• Develop Raman spectroscopy for Q_2 analysis in fusion rebalancing conditions	• Quick analysis of isotope concentrations • Prototype and validate
Raman spectroscopy for speciation	• Improvements to facilitate real time measurements at higher sensitivity, speed, reliability	• Improve signal collection • Materials compatibility • Easy operation for non specialists
Temperature Cyclic Absorption Process (TCAP) technology scale-up and parallelization	• Benchmark throughput limits of a single TCAP column • Assess viability of parallel TCAP column • Optimize column design, materials, heat transfer • Provide reliable ISS to FPP • Improve TCAP throughput	• Improve heat transfer of column • Improve absorption kinetics with materials modification • Model multiple TCAP columns operating in parallel • Optimize column shape • Utilize existing research data, including SRNL TCAP (lots of work done, needs scale up) • Currently: small workforce, export control issues • License TCAP to fusion developers
Process intensification and modeling of **TCAP** isotope separation	• Create modular, scalable TCAP design to increase heat/mass transfer and decrease plant T inventory	• Model system, develop modular approach to column design • Integrate into plant design • Test H/D, then D/T
High throughput direct internal recycling continuous **pump**	• Develop and mature technology concepts for demonstration in pilot environment (TRL 3→5) • Reduce T inventory	• Scoping study of concepts • Downselection • Technology maturation, design, demonstration
Development of **pressure swing adsorption** as an alternative ISS/rebalancing technique	• Advance TRL for alternative separation technologies with potential for high throughput processing	• Demonstrate high throughput, efficiency • Identify materials • Do testing in H/D first • Need throughput requirements
Proton conductor hydrogen isotope separation for rebalancing	• Establish DIR and hydrogen isotope rebalancing simultaneously	• Build on existing work • Ceramic proton conductors

Laser-based hydrogen isotope separation	• Build prototype of laser-based ISS to increase efficiency/throughput	• Use approach for uranium-235 (U-235) and apply to hydrogen? • Proof-of-concept development
Exhaust processing		
Exhaust processing modeling of high throughput chamber exhaust processing	• Model performance of unit operations relevant to FPP scale with respect to throughput and inventory	• Identify nondimensional parameters and scaling factors • Define validation curves, correlations needed to design exhaust processing system • Need validation experiments
Exhaust processing (high-throughput)	• Improve and implement technologies needed for exhaust processing	• Want to reduce inventory and increase throughput • Need experiments to demonstrate technical feasibility of DIR technologies (MFP, cyrosorption, permeation) • TRL 4-5 now • Leverage existing capabilities, including those at KIT, UKAEA, SRNL
Process controls		
Overall fuel cycles controls		
Predictive Facilities Controls	• Model predictive control for balance of plant • Develop validated systems code for balance of plant model • Develop feedback controls • Need for regulatory approval of plant	• Develop models concurrent with experiments • Get defined fuel cycle from industry • uncertainty analysis • Incorporate material property data from experiments • Utilize well-understood control algorithms
Testing facilities for analytical tools	• Upgrade existing testing facilities or build new ones to validate technologies in representative environment	• Ensure analytic systems meet regulator requirements • Identify existing facilities, competencies, and partners • National labs, industry partners • Figure out IP conflicts
Develop analytical techniques for rebalancing	• Analytical technique to measure hydrogenic species isotopologues • Rebalancing system control	• Define expected requirements/environmental conditions for analytical equipment • Identify appropriate technique • Develop the technology to align with FPP Requirements

Tritium monitoring/controls		
Technology development for instrumentation and monitoring	• Establish monitoring technology toolbox that meets regulatory requirements and supports continuous operation	• Gap analysis of monitoring requirements and available technology • Prototype and validate technologies • Demonstrate ability to meet requirements (need testing facility) • Demonstrate robustness • Build on knowledge from batch testing • Find other fields that have worked on similar problems • Consolidate materials compatibility data • Assess supply chain / provide feedback to supply chain analysis • Have beta versions of instruments ready for integrated pilot plant tests
Testing of tritium analytics in fusion relevant conditions	• Test technology for measuring isotope ratios and tritium concentrations in fusion relevant conditions	• Controlled testing of concentration tolerance, memory effects • Test in full tritium loop • Test established and novel technology
Materials compatibility		
Database creation		
Tritium materials standards workflows	• Create community standard workflows and facilities for tritium materials qualification for facility model	• Gap analysis on tritium materials interactions data; review literature • Describe risk categories/embrittlement/permeation • Create standard qualification workflow • Identify D, T facilities across public/private entities
Tritium specific materials compatibility database	• Assemble database of tritium compatible construction materials • Define gaps between existing data and device requirements	• Assemble public-private team, determine strategy • Assess gaps • Experimental plan to fill gaps • What do FPP designers absolutely need?
Tritium compatibility		
T-specific materials compatibility	• Low-level T uptake effects on polymers	• Understand limitations of polymeric seals and components in BOP operations

	• Downselect best materials for low concentration tritium applications	• Utilize CANDU experience and polymer data • Carry out experiments on loops
Modeling retention and permeation	• Modeling permeation vs surface area, pressure, temperature • Modeling for solids and liquids	• Experiments in neutronic damage vs tritium traps, how it impacts permeation • Model pellet penetration vs trajectory locations • Tritium retention and recovery at different operating phases
Effect of tritium uptake on welded joints	• Gap analysis: information on effects of T uptake in heat affected zone (HAZ) • Effect of T uptake on structural integrity/weld properties	• Literature/data review for gap analysis • Accelerated aging tests • Tritiated weld samples, burst testing of tritiated welds, material property testing • Input into fusion materials database (if it exists)
Heat exchanger vs tritium extraction tradeoff	• Develop HX to interface with tritiated primary coolant without HX becoming a tritium sink	• Deliver T to fuel cycle and deliver heat -- not immediately compatible goals • Consider coatings, dual-cooled concepts
Corrosion effects		
Functional material compatibility with liquid breeder materials	• Perform functional material compatibility testing on identified challenges with Li, PbLi, FLiBe • Emphasis on how impurities impact compatibility	• Flowing experiments • Impurity experiments • Off-normal operation conditions • Literature survey/info gathering first • Determine static and flowing experiments needed to evaluate compatibility • What material/breeder combos are of critical interest?
Detritiation		
Atmospheric detritiation		
Atmospheric detritiation R&D program	• Consider upstream tritium pathway and impact on FPP design/requirements • Identify potential air detritiation systems	• Identify challenges in room-temperature air detritiation, assess technology gaps • Consider available technology vs. requirements for FPP • Work with FPP designers to understand design requirements on their end • Define R&D program for scale-up or development of new technology

Atmospheric detritiation R&D program	• Provide tritium-capable test facility for detritiation development	• Want to avoid large inventories of tritiated water • Test identified technologies for detritiation • Validation data for room air detritiation systems • Valuable to all FPP developers
Atmospheric detritiation R&D	• Develop specific columns and dehumidifiers for removal of tritiated water vapor from atmosphere through counter current wet scrubbing	
Atmospheric detritiation R&D / wet scrubber technology	• Develop specific columns, dehumidifiers for removal of tritiated water vapor from atmosphere	• Counter-current wet scrubbing • Enable confinement of tritium, sequestration • Experimental demonstration • Final active barrier for tritium releases, important for regulation
Water detritiation		
Engineer molecule that preferentially binds to tritiated waste	• Develop molecule that preferentially binds to tritium and aids removal of tritium from low-concentration tritiated water	• Need technologies for removal of T from water when it's at low concentration • Could this be a pathway to fix that?
Waste detritiation (e.g., solid)		
Management of tritiated waste	• Develop comprehensive set of technologies for managing waste from fusion facilities	• Utilize existing industry lab capabilities (tritium capability; separation processes; work with HWR operators) • Literature review, test plan, deployment of test plan
Successful recovery and detritiation method for end of life components	• Nondestructive methods for tritium recovery • Detritiation for waste stream	• Need facility for recovery studies
Recycling tritium and detritiation	• Minimize level of T in waste for disposal, recover T for reuse, improve T recovery from components	• Research on current state of the art, explore existing tritiated components • Facilities to study tritium entrapment • Extraction/recovery studies • Lessons learned from JET and other devices
Modeling of membrane detritiation technology	• Provide mechanistic understanding of membrane detritiation process to guide design	• Modeling development and validation • Uncertainty quantification • Design analysis

		• Use TMAP8, existing 1D membrane models
Short term and long-term solid T assay	• Establish baseline technique for quantifying tritium inventory in solids	• Short term: destructive assays, generate data • Long term: develop non-destructive assay techniques • Implement predictive artificial intelligence (AI) modeling with validation datasets from experiments
Tritium-capable facility development		
Design and requirements determination for revision of ISO 17873	• Revise ISO 17873 (criteria for design and operation of ventilation systems) to include tritium	• Needed for good FPP design, uncertainty reduction • Working group needed • Don't make a standard that is too prescriptive on what technologies could be used for detritiation • Doesn't necessarily need to be a regulation, but provides guidance
Hydrogen risk assessment for FPP	• Hydrogen codes and standards that work for tritium and enable design flexibility of FPP	• Avoid a situation where FPPs have to follow hydrogen codes that do not apply to them • National labs: help advocate to H_2 standard bodies • This is already an issue at tritium labs
Design requirements determination for confinement strategy and HVAC integration	• Ensure facility designs incorporate a tritium confinement strategy into the design • Segregate tritium into zones that can be isolated from HVAC for detritiation	• Consider HVAC and overall building in FPP design • Need relevant design details from private sector • Leverage ITER, CANDU expertise • Private companies, facilities designers need to do this
Tritium confinement/ development of selective membranes for tritium separation	• Test selective membranes, an alternative to conventional methods like molecular sieves • Useful for facilities handling large quantities of tritium (catch excess tritium in ventilation system)	• Boron-nitride, graphene type materials • Take academic initial results and scale it to more industry-relevant levels • Utilize existing industry capabilities
Economics, supply chain		
Parametric relation study involving regulation, economics, technology	• Reduce uncertainty for how regulation/economics/ technology interface	• Parametric relationship development • Understand technology development options • Focused topical working groups • Not using fission as a baseline

		• Identify how regulations impact cost of plant • Need more info on how tritium likely to behave in plant
Supply chain assessment (detritiation)	• Develop reference plant for MFE/IFE supply chain	• Develop generic bill of materials for MFE and IFE fuel cycle • Show functional component breakdown, specific component breakdown • List components and requirements • Assess gaps (what is available, what needs to be developed or scaled up) • Work with FPP developers to understand fuel cycle plans
Pellet injection supply chain development		• Supply chain development • Engage suppliers/vendors • Scale up pellet injection to what is needed by FPP
Supply chain development for detritiation systems	• Develop supply chain in time for FPP	• Which subsystems and technologies don't have an associated supplier?
International cooperation and communication	• Everyone needs to be aware of existing facilities and capabilities	• Lots of knowledge in CANDU / Canadian Nuclear Laboratories (CNL) system, JET/UKAEA • Don't reinvent the wheel
Tritium supply for FPP startup		
Expanding tritium removal from new CANDU reactors	• Introduce new tritium removal facility (TRF) plants at CANDU reactors that do not currently have them • Supplement tritium availability for startup of FPP	• International agreement on need for tritium to support fusion needed • Design and deploy TRF at CANDU facilities without them • Develop economic model to justify this • Align regulators, CANDU operators • TRFs at CANDUs: also learning opportunities for FPP
Feasibility study on tritium targets in D2O reactor	• Assess viability for breeding T in existing HWRs for more availability • Relax constraints on tritium doubling time	• Neutronics study • Assess logistics • Tritium Producing Burnable Absorber Rods (TPBARs) info • Regulatory feedback

Proliferation, uranium use		
Develop non-uranium storage for tritium storage	• Improve public acceptance by minimizing uranium usage at FPP	• Raise TRL level of non-uranium storage options • Literature review and assess options • Plan to scale up most promising
Characterizing non-proliferation impacts of U bed for tritium storage	• Characterize impacts of U-bed for nonproliferation, determine protocols for avoiding proliferation issues	• Identify actual proliferation risk • Identify programmatic controls to reduce risk
Detritiation of getter beds	• Waste management, detritiation of storage beds, decommissioning • Better safety case, regulatory compliance • Facilitate Y/N decision on uranium getter bed use	• Understand behavior of U beds, and formation of impurities under operational conditions • Develop methods for detritiation of used beds • Develop methods to reclaim getter bed materials • Experiments on getter beds • Separate, purify valuable elements
Public acceptance		
Screening tool for public acceptance, export control, regulatory compliance	• Create screening tool (web app) teams can use to evaluate public acceptance, regulatory compliance, and export control issues of their system	• Use publicly accessible data

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3002029370

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