2024 TECHNICAL UPDATE

Fusion Fuel Cycles Research Objectives

Results from the 2023 Fusion Fuel Cycles Workshop

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3002029371

Technical Update, May 2024

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ACKNOWLEDGMENTS

EPRI edited and published this report.

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This report summarizes fusion fuel cycle research objectives identified 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: *Fusion Fuel Cycles Research Objectives Results from the 2023 Fusion Fuel Cycles Workshop.* EPRI, Palo Alto, CA: 2024. 3002029371.

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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, representatives from the global fusion technology community participated in a two-day Fusion Fuel Cycles Workshop. During this workshop—and in the months leading up to it—participants worked to identify the key research objectives that are required to bring fusion fuel cycle technology to a sufficient level of maturity so that it can be deployed successfully in deuterium-tritium (D-T)-fueled fusion pilot plants. The U.S. Bold Decadal Vision for fusion calls for commercially relevant fusion technology in the 2030s. To realize this, significant strides must be made to develop robust, safe, and efficient technologies pertaining to tritium fueling, storage, and extraction.

The research objectives (ROs) resulting from the Fusion Fuel Cycles Workshop fall into two broad categories. First, the overarching ROs are general and multidisciplinary. They call for the generation of relevant property data, the identification of target performance metrics, techno-economic evaluation of fusion fuel cycles, and assessments of workforce and safety requirements. The overarching ROs specifically highlight the need for scalable exhaust processing and detritiation methods.

Second, the topical ROs address three primary categories:

1. **Fueling and exhaust processing.** Subcategories include:
   - Fueling
   - Vacuum pumping
   - Exhaust processing
2. **Isotope processing, rebalancing, and storage.** Subcategories include:
   - Isotope separation, rebalancing, storage, and handling
   - Tritium extraction
   - Tritium compatibility with materials
3. **Confinement processing and tritium accountancy.** Subcategories include:
   - Tritium removal and recovery
   - Management of tritiated waste
   - Modeling
   - Analytical tools
   - Regulation and nonproliferation concerns
   - Demonstration facilities

The community identified 85 specific topical ROs in total. Taken together, the topical ROs form a goal-oriented research plan to enable robust fuel cycles in fusion pilot plants. The community makes no recommendation as to what the specific design of a fusion fuel cycle should be; instead, the ROs are intentionally generalizable to many different fusion pilot plant concepts.

Importantly, the community emphasized the leadership of the private fusion sector with regards to fusion pilot plant design and overall commercialization efforts. During workshop discussions, it was observed that partnership and communication between the private sector, federal agencies, national laboratories, and university research centers is required to ensure that publicly funded fuel cycle research will be commercially relevant.

Keywords

Confinement processing
Fueling and exhaust processing
Fusion fuel cycle
Isotope processing
Tritium
Tritium accountancy

ACRONYMS, ABBREVIATIONS, AND INITIALISMS

COP28	28th Conference of Parties to the United Nations Framework Convention on Climate Change
D	deuterium
DIR	direct internal recycling
DOE	U.S. Department of Energy
FLiBe	lithium fluoride/beryllium fluoride
FPP	fusion pilot plant
H	hydrogen
HT	tritiated hydrogen gas
IFE	inertial fusion energy
IP	intellectual property
JET	Joint European Torus
MFE	magnetic fusion energy
PPP	public private partnership
R&D	research and development
RAMI	reliability, availability, maintainability, and inspectability
RO	research objective
T or ^3H	tritium
T_2	tritium gas
TF	tritium fluoride
TRL	technology readiness level
U.S.	United States

CONTENTS

1 INTRODUCTION

A safe, efficient, and reliable fuel cycle is important for the commercialization of fusion energy. Many fusion concepts under development will require a robust deuterium-tritium (D-T) fuel cycle, and alternative fusion fuel cycles also have isotope processing needs. Both the U.S. Bold Decadal Vision and multiple private fusion programs envision fusion pilot plants (FPPs) operational by the early 2030s. The requirements of the associated fueling systems will require the evolution of fuel handling technologies, in particular regarding tritium, to assure reliable and sustained operations.

Tritium (^3H) and fuel systems present a unique set of design considerations for a D-T fusion power system, with safety, performance, and environmental implications. Tritium is radioactive and has properties similar to, but distinct from other hydrogen isotopes such as protium (^1H). Tritium gas (T_2) undergoes isotope exchange with common hydrogen compounds, such as hydrogen gas (forming HT), and water (forming HTO), both of which can enter the biosphere if not fully contained or recovered. Hydrogenic gases (Q_2 i.e.: H_2, D_2, T_2 HD, HT, DT) can be challenging to contain due to their ability to diffuse through and accumulate within pressure boundary materials. Ensuring worker and public safety as well as minimizing environmental impact in fuel cycle operations and waste disposal are critical requirements to achieve at the outset of commercial fusion.

Existing tritium handling systems have been developed for the small number of tritium-fueled fusion energy sciences experiments (such as JET and ITER), and as a waste management system in certain fission installations, particularly in heavy water reactors. The tritium handling systems required for fusion power plants will represent an evolution and major innovation of these systems. Operations will be effectively continuous, with circulating flow rates on the order of kilograms of tritium per day, and total tritium inventories on the order of hundreds of grams.[1] These performance targets will be enabled by tritium pumping, handling, separation, purification, and accountancy technologies adapted for fusion power plants. Furthermore, to resupply fuel used in the fusion reaction itself, the requirement of tritium breeding in D-T systems necessitates tritium extraction from the blanket at a rate on the order of tens of grams of tritium per day.[2]

To accelerate the development of relevant fuel cycle technologies, the Fusion Fuel Cycles Workshop was held from May 22-23, 2023, at EPRI in Charlotte, North Carolina. Participants included representatives from federal agencies, private fusion companies, universities, and national labs from the U.S., Canada, the United Kingdom, Italy, France, Germany, Japan, and

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[1] Illustrative order of magnitude estimates are based on analysis presented in Samuele Meschini *et al* 2023 *Nucl. Fusion* **63** 126005 and Ferry *et al* 2023, PPPL Introduction to Fusion Energy and Plasma, "Introduction to fusion power plant fuel cycles and tritium breeding blankets."

[2] Order of magnitude estimates for tritium extraction from the blanket is based on a generic gigawatt-scale plant, an estimated 15 MeV of energy released per individual fusion reaction, and the approximate 3 grams per mole molar mass of a triton.

Korea. The goal of this workshop was to gather information from stakeholders in order to support fusion fuel cycle technology development that will enable the community to build a fusion pilot plant with a robust fuel cycle on the timescale of a decade. A full summary of this 2023 Fusion Fuel Cycle Workshop is presented in EPRI report 3002029370. A related but separate workshop was held from on the following days on fusion blanket technologies, with tritium extraction form the blanket forming the scope delineation of the two workshops. Separate documents were prepared from that workshop and are:

- *2023 Fusion Blankets Workshop Summary: A Summary of the 2023 Fusion Blankets Workshop Hosted by EPRI 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.

This document provides general conclusions from the workshop, over-arching research objectives, proposed framework concepts for new Fusion Fuel Cycle Research and Development (R&D) Centers within the U.S. Department of Energy (DOE) Office of Science Fusion Energy Sciences program, and detailed topical research objectives. These conclusions and research objectives were drafted by organizing committee members and reviewed by workshop participants. Any views, opinions, and recommendations expressed in this report do not necessarily state or reflect those of EPRI.

2 FUSION FUEL CYCLE GENERAL CONCLUSIONS

The Fusion Fuel Cycle Workshop Research Objectives documented in this report represent observations and general conclusions drawn from structured and moderated sessions seeking input from subject matter experts on fusion fuel cycle R&D activities needed to support commercialization of fusion energy technology. General conclusions from the Fusion Fuel Cycles Workshop include:

- Private industry is driving the commercialization of fusion energy worldwide, and public-private partnerships (PPPs) have already been invaluable for private programs. In the space of fusion fuel cycle R&D, PPPs are expected to greatly accelerate the development of all fusion energy concepts.
- Early fusion fuel cycle technology development (proof-of-concept, prototyping, etc.) can be performed with protium and deuterium in standard laboratories, but validation in a relevant environment will require testing with tritium prior to deployment in a pilot plant to de-risk them and mature readiness levels.
- De-risking fusion fuel cycle technologies by demonstration with tritium will be necessary to support deployment of these technologies. Tritium facilities will require appropriate spatial, inventory, and throughput scales and the corresponding safety infrastructure to enable safe use of the required tritium inventories and chemical formats. These facilities should offer flexible testing configurations with both standalone and integrated fusion fuel cycle loop testing.
- Leverage pathways for partnerships with the U.S. National Laboratories and international laboratories. The tritium production, processing, and modeling expertise that reside at these institutions represents decades of investment and expertise, constituting a valuable resource for advancing fusion fuel cycle science and technology.
- In order to deploy fusion on a commercial scale as rapidly as possible, the U.S. DOE and other publicly funded fusion R&D efforts–both in the U.S. and internationally–should coordinate closely with one another and with the private fusion industry to make efficient use of limited public funds. International cooperative R&D agreements, like the one announced at COP28,[3] should be leveraged and investments that are necessary to close critical gaps should be prioritized.

[3] COP28 refers to the 28th Conference of Parties to the United Nations Framework Convention on Climate Change, held from November 30th-December 12th, 2023, in Dubai, United Arab Emirates.

3 FRAMEWORK CONCEPTS: DEVELOPING FUSION FUEL CYCLE TECHNOLOGIES

Framework Concepts are suggestions from the Fusion Fuel Cycle Workshop participants on developing the framework for a new Fusion Fuel Cycle R&D Center within the U.S. DOE Office of Science Fusion Energy Sciences program. Key Framework Concepts identified at the Fusion Fuel Cycles Workshop include:

- Develop fusion fuel cycle collaborations and partnerships that can address the challenges in fuel cycles used by inertial fusion energy (IFE), magnetic fusion energy (MFE), and other advanced fusion fuel cycles, including issues related to tritium processing technologies, nonproliferation, and export control.
- Support PPPs as part of DOE's milestone program and other funding opportunities. Organize workshops, knowledge seminars, industry days, and technical exchange meetings. Streamline partnering mechanisms and work with companies to alleviate concerns related to intellectual property (IP).
- Foster engagement with community partners, universities, and the private sector to promote domestic and international partnerships to recruit and develop the fusion fuel-cycle technology workforce. Workforce development should include a deliberate effort to build a more diverse and inclusive fusion community. Developing fuel-cycle technology for a fusion pilot plant requires expertise from many disciplines. This provides a pathway to include research groups that have not historically participated in fusion technology development in key research and funding opportunities.
- Periodically reevaluate fusion fuel cycle research opportunities to take advantage of the developments within public sector research, international collaborations, and the private sector.

4 OVERARCHING RESEARCH OBJECTIVES (ROs) FOR FUSION FUEL CYCLE TECHNOLOGIES DEVELOPMENT FOR FUSION ENERGY

Overarching Research Objectives address research gaps common across fusion fuel cycle topics and are of high importance to the advancement of fusion fuel cycle technologies for the deployment of fusion energy. These Overarching Research Objectives include the following:

- Experimentally characterize, review, and organize physical property data for relevant fusion fuel cycle materials across process relevant conditions for different concepts and designs. Make the physical property data including data related to behavior of materials with H, D, and T available to the community through publications, databases, and other relevant mechanisms.
- Identify and develop a set of nominal design elements and performance requirements common to multiple private designs that can be utilized to guide FPP-scale fusion fuel cycle development.
- Develop techno-economic studies to evaluate the various fusion fuel cycle concepts and key performance metrics, including requirements for reliability, availability, maintainability, and inspectability (RAMI). With input from the energy industry and fusion science and technology experts, identify the most promising concepts to guide technology selection and to inform directions of technological development.
- Develop exhaust processing and detritiation techniques that will enable fusion energy production to scale economically. Explore methods for regeneration or recycling of fusion fuel cycle materials such as getters, and adsorbents as well as advancing water detritiation systems.
- Perform risk and budget/planning assessments associated with technology deployment. These assessments would address workforce training needs, safety procedures, technology readiness assessment levels for technology deployments, supply chain, and other relevant areas.
- Assess how to optimally implement nonproliferation, export control, waste disposal, accident scenarios, and community engagement for the fusion fuel cycle.

5 TOPICAL RESEARCH OBJECTIVES

Topical Research Objectives are specific to processes within the fusion fuel cycle or specific considerations that need to be addressed related to the fusion fuel cycle or its operation. These research objectives are organized by topics and sub-topics to the greatest extent possible but may have some applicability across topics as well where complex interactions are expected.

5.1 Fueling and Exhaust Processing

5.1.1 Fueling

- **RO 1.1-1:** Develop fueling design requirements for an FPP-scale fusion fuel cycle.
- **RO 1.1-2:** Develop requirements for tritium R&D facilities to test and develop fueling components at FPP scale.
- **RO 1.1-3:** Develop and scale fueling technologies to FPP-relevant conditions and demonstrate reliability.
- **RO 1.1-4:** Develop synergistic target/fusion fuel cycle co-design to identify target materials and processing methods that have minimum impact on the fusion fuel cycle and allow for inventory reduction.
- **RO 1.1-5:** Optimize fuel delivery to achieve required fusion yield for FPP design requirements.
- **RO 1.1-6:** Design, develop, and demonstrate a fueling control system and any storage system needs for disruption mitigation or other off-normal operations.
- **RO 1.1-7:** Develop impurity removal and processing of tritiated impurities during fuel formation processes.
- **RO 1.1-8:** Develop survivable cryogenic fuel layer for IFE applications.
- **RO 1.1-9:** Study the coupling between plasma behavior and fueling requirements to better understand their interactions in advanced fueling systems.
- **RO 1.1-10:** Develop tritium sensing requirements for fueling that can provide information on process conditions in the fueling system as well as provide information about tritium inventory.
- **RO 1.1-11:** Based on needs and requirements for direct internal recycling (DIR), plan tritium R&D facilities that can develop, test, and demonstrate DIR technologies alone or in combination with other fusion fuel cycle systems.

5.1.2 Vacuum Pumping

- **RO 1.2-1:** Develop pumping design requirement for an FPP-scale fusion fuel cycle.
- **RO 1.2-2:** Study the tritium compatibility requirement for pumping technologies and develop solutions that can solve tritium compatibility related challenges within the pumping train.

- **RO 1.2-3:** Develop and optimize pumping systems that are more robust and that can handle high duty cycle and continuous operation.
- **RO 1.2-4:** Scale pumping technologies to the throughputs needed for an FPP-scale fusion fuel cycle.
- **RO 1.2-5:** Mature DIR pumping solutions.
- **RO 1.2-6:** Plan for a tritium R&D facility to test and develop pumping components at FPP scale.

5.1.3 Exhaust Processing

- **RO 1.3-1:** Characterize the physical properties, non-dimensional scaling relationships, validation curves, and system integration factors that will enable process model development to support chamber exhaust processing design and operation. Model the performance of components and develop process modeling frameworks relevant to FPP scale in processing rates and inventory.
- **RO 1.3-2:** Evaluate the need and requirements for DIR of hydrogen isotopes.
- **RO 1.3-3:** Develop a fusion fuel cycle architecture for DIR of hydrogen isotopes from exhaust.
- **RO 1.3-4:** To the extent possible, determine the separation efficiency of DIR technologies.
- **RO 1.3-5:** Demonstrate reduction in tritium inventory by integration of DIR technology.
- **RO 1.3-6:** Characterize anticipated impurities generated in different fusion concepts including IFE and MFE.
- **RO 1.3-7:** Develop improved impurity removal techniques (e.g., target debris, palladium membrane reactors, getters) that can purify gas streams while minimizing inventory for different fusion concepts.
- **RO 1.3-8:** Develop continuously operating, high throughput exhaust processing system at the scale needed for a fusion plant. Reduce the tritium inventory and increase processing rate. The development should demonstrate the feasibility of all technologies throughout the exhaust processing system.
- **RO 1.3-9:** Identify or develop real-time concentration monitoring, diagnostics, sensors, or devices for locations in exhaust processing critical to process monitoring, control, or tritium accountancy.
- **RO 1.3-10:** Develop an understanding of the needs for tritiated waste processing infrastructure and waste disposal pathways needed to support operation of fusion plants.

5.2 Isotope Processing, Rebalancing, and Storage

5.2.1 Isotope Separation and Rebalancing

- **RO 2.1-1:** Develop a fusion fuel cycle architecture for the integration of isotope separation/rebalancing with DIR, storage, and fueling to accomplish critical tasks like protium removal from the process and rebalancing the isotope mixture.
- **RO 2.1-2:** Investigate isotope separation methods that have the potential to reduce tritium inventory while rebalancing isotopes, pursuing multiple methods in parallel and de-risking any particular method.
- **RO 2.1-3:** Minimize tritium inventory in the isotope separation system through process intensification that improves heat and mass transfer, increases kinetics, and reduces system volume.
- **RO 2.1-4:** Scale-up the processing rates of low tritium inventory isotope separation technologies to meet the needs of a fusion fuel cycle.
- **RO 2.1-5:** Develop improved models for isotope separation systems that both help to guide system integration as well as assist with further technology development.
- **RO 2.1-6:** Define the sensing needs in the isotope separation and rebalancing system for tritium accountancy and process control.
- **RO 2.1-7:** Perform validation of the isotope separation methods with tritium at the required flow rates in a tritium R&D Facility.

5.2.2 Isotope Storage and Handling

- **RO 2.2-1:** Identify candidate materials that can achieve the process requirements for hydrogen isotope storage materials to be used in a continuously operating fusion fuel cycle (e.g., charging/discharging rate, capacity, thermal stability, degradation/aging effects). Utilize databases of existing materials from other DOE efforts such as the hydrogen storage material center of excellence.
- **RO 2.2-2:** Define detailed operating characteristics for hydrogen isotope storage beds such as required heat transfer rates, storage capacity, dead volume, material lifetime, acceptable heel quantity of tritium, regeneration requirements (if applicable), need to be able to perform tritium accountancy functions, etc.
- **RO 2.2-3:** Define the needs for structural materials used in hydrogen storage bed housing including resisting embrittlement, ability to operate for extended periods and cycles at elevated temperatures, and the ability to support regeneration of the hydride beds if needed.
- **RO 2.2-4:** Identify the waste streams and disposal pathways/processes for the hydrogen storage materials and detritiation requirements during maintenance and/or decommissioning.

5.2.3 Tritium Extraction from Breeder Materials

- **RO 2.3-1:** Define the operational requirements for the tritium extraction system including blanket material flow rates, extraction efficiencies, tritium concentration monitoring requirements, and other applicable performance metrics.
- **RO 2.3-2:** Identify primary tritium extraction methods and systems of interest and system architectures for fusion fuel cycle integration that have the potential to meet private-sector fusion pilot plant timelines or that could be viable alternatives for first-of-a-kind plants or future fusion plants.
- **RO 2.3-3:** Identify and measure fundamental properties (e.g., phase diagrams, solubilities, mass transport properties, heat transfer properties) of major blanket systems and dissolved species needed for engineering of tritium extraction systems. Standardize data collection methods and develop efficient methods (e.g., databases) to share property data throughout the fusion community.
- **RO 2.3-4:** Perform an architectural analysis of the blanket loop to understand the trade-offs in locating tritium extraction relative to other blanket components such as the primary heat exchanger. The analysis should consider the tritium permeability of the primary heat exchanger.
- **RO 2.3-5:** Characterize tritium extraction process efficiency and develop mass and energy balance models that can be used to evaluate tritium inventory, parasitic loads, and by-product. Examples of these byproducts include tritiated gas (e.g., HT, HTO, TF, T_2) or tritiated compounds (e.g., tritiated metals).
- **RO 2.3-6:** Characterize tritium extraction process material compatibility with liquid breeder materials through testing in static conditions, in flow conditions, with the presence of impurities, and during off-normal operations.
- **RO 2.3-7:** Develop tritium extraction models that both help to guide integration of the fusion fuel cycle and blanket as well as assist with further technology development.
- **RO 2.3-8:** Identify the waste streams and disposal pathways/processes for the tritium extraction process and component requirements during maintenance and/or decommissioning.
- **RO 2.3-9:** Create research infrastructure (labs, facilities, etc.) to enable more rapid development of tritium extraction technologies and where concepts can start with non-radiological testing and progress to testing with tritium. Testing should also progress from static testing to loop testing up to high TRL level demonstrations of tritium extraction systems.

5.2.4 Tritium Compatibility of Materials

- **RO 2.4-1:** Perform an analysis on existing data for tritium compatible materials related to fusion plant design and operation, and identify methods (e.g., databases) to compile and organize the information. Identify gaps between existing data and anticipated requirements for commercial fusion facilities and facilities with the potential to close the gaps.
- **RO 2.4-2:** Perform tritium compatibility analyses relative to fusion materials on materials joining methods, novel methods of material fabrication being developed (e.g., additive manufacturing), testing on samples in specific configurations and/or stress profiles. Compile and organize the data into formats that are useful for the community.
- **RO 2.4-3:** Define the needs for tritium permeation barriers as well as develop and characterize permeation barriers for various use scenarios and substrate materials.
- **RO 2.4-4:** Develop improved models for tritium permeation and retention in fusion relevant materials. Modeling should include both solids and fluid systems.
- **RO 2.4-5:** Characterize the interplay between neutronic damage and tritium trapping as well as how these factors impact tritium permeation.
- **RO 2.4-6:** Develop an understanding of tritium retention and recovery during different operating phases of a fusion plant.
- **RO 2.4-7:** Perform an assessment of facility and/or capability needs for tritium materials research including both assessments for operational and waste disposal and detritiation needs. Develop the facilities to support tritium materials research needs for all aspects of fusion energy.
- **RO 2.4-8:** Develop and demonstrate methods to recycle, regenerate, or reuse tritiated materials such as vacuum pump oil, hydrogen storage materials, isotope separation catalysts, equipment structural metals, or tritiated gasses within the fusion fuel cycle process in order to reduce waste streams of tritiated material produced within an FPP.

5.3 Confinement Processing and Tritium Accountancy

5.3.1 Tritium Removal, Tritium Recovery, and Tritiated Waste

- **RO 3.1-1:** Assess the ability of existing technologies to perform atmospheric detritiation and define the gaps in the technologies needed for detritiating room-temperature air. The assessment should include evaluation of technologies developed for ITER along with systems and operating experience at global tritium handling facilities. Investigate detritiation processes that do not generate tritiated water.
- **RO 3.1-2:** Develop specific technologies (e.g., columns, dehumidifiers) for removal of tritiated water vapor from the air in various spaces and/or scenarios during the operation of a fusion pilot plant.
- **RO 3.1-3:** Develop improved methods and technologies (e.g., adsorbents or molecules that preferentially bind to tritium) that can remove and/or recycle tritium at low concentrations from liquid water.

- **RO 3.1-4:** Identify and develop improved getter materials for use in fusion fuel cycle processes for removal of tritium or other process impurities. Identify potential pathways for waste minimization, recycling of materials, or other methods to reduce tritiated waste streams from the use of getters.
- **RO 3.1-5:** Perform an assessment of the set of available technologies for managing different waste streams during operation of fusion plants and identify gaps where technology development is needed for fusion plant operation.
- **RO 3.1-6:** Assess technology development needs in detritiation of solid materials that investigates lessons learned at JET, other fusion devices, and other global tritium handling facilities.
- **RO 3.1-7:** Develop improved methods for solid material detritiation and recycling of recovered tritium that minimize tritium levels in solid waste for disposal.
- **RO 3.1-8:** Develop improved techniques for quantifying tritium inventory in solid materials (including tritiated dust) that can be used in both short-term and long-term measurements including destructive and non-destructive assays.
- **RO 3.1-9:** Develop predictive models for tritium inventory in solid waste systems that are validated with experimental data and utilize state-of-the-art predictive technologies (e.g., artificial intelligence) to help improve predictions of relevant quantities such as tritium content or tritium concentration with time.
- **RO 3.1-10:** Develop a waste disposal pathway/methodology to handle tritiated waste from commercial fusion plants that can handle the volumes of waste materials of different types that are planned to be generated during the operation of a fusion plant. This would include coordination between regulators and disposal facilities to develop a fusion waste classification.
- **RO 3.1-11:** Communicate and engage with the public around issues of tritium management.

5.3.2 Modeling

- **RO 3.2-1:** Develop modeling resources (e.g., curated physical properties databases including uncertainties and meta-data) that have good validation of input data and that can be used by the community to develop more robust fusion fuel cycle modeling.
- **RO 3.2-2:** Develop integrated mass and energy balance process models that can be used to optimize process flow rates and to assess energy requirements, parasitic loads, minimize tritium inventory, assist in technology selection, and optimize fusion plant performance.
- **RO 3.2-3:** Develop modeling tools and methods to support real-time tritium accountancy and validate models with data on batch and flowing systems.
- **RO 3.2-4:** Develop fusion fuel cycle modeling tools to support discussions with regulators and can incorporate aspects relevant to regulation such as environmental transport of tritium and other considerations.
- **RO 3.2-5:** Develop accident scenarios modeling involving tritium transport and release to the atmosphere and improve modeling of tritium intake in the biological systems and food chain.

5.3.3 Analytical Tools

- **RO 3.3-1:** Perform an assessment and gap analysis of analytical tools for the fusion fuel cycle that can identify process requirements, available technologies, and can apply operating experience from global tritium facilities and fusion demonstration systems. Consider if the gaps are best addressed by advancing existing tritium technologies, incorporating existing technologies not yet applied to tritium, or developing entirely new technologies.
- **RO 3.3-2:** Develop a process monitoring toolbox that meets regulatory requirements and supports continuous operation of fusion plants. Integrate knowledge from batch testing, testing in other fields with similar problems, and consolidate material compatibility data. Assess the supply chain for sensors that would be needed in different parts of a fusion plant.
- **RO 3.3-3:** Develop improved spectroscopic or sensing methods (e.g., Raman spectroscopy) for detecting relevant species in process streams at relevant concentrations in real time.
- **RO 3.3-4:** Develop improved spectroscopic or sensing methods that can support real time tritium accountancy and quantification of material mass balances within the process at the required accuracy. Improvements may include higher sensitivity, speed, and reliability.
- **RO 3.3-5:** Develop, demonstrate, and validate the use of distributed sensor integration (e.g., sensor fusion) to improve the accuracy of sensing and measurements and calculated tritium accountancy frameworks that rely on these measurements.

5.3.4 Regulation, Nonproliferation, Supply Chain, Community Engagement

- **RO 3.4-1:** Provide technical support to regulators in providing materials property data, data on assumptions in accident scenario analysis, operating experiences or lessons learned, standard fusion fuel cycle configurations, or other information to support the development of a regulatory framework for fusion.
- **RO 3.4-2:** Develop guidance on nonproliferation risks for companies and lists of materials exclusions that would be necessary to ensure nonproliferation goals are met in terms of the potential for material irradiation, diversion of hydrogen isotopes (deuterium and/or tritium) that are export controlled, or other proliferation pathways that are identified to be potentially significant.
- **RO 3.4-3:** Perform a parametric relation study to reduce the uncertainty in how regulation, economics, and technology relate to fusion commercialization. This will involve understanding how technology development options will impact overnight cost of plant, lifecycle plant cost, and/or other relevant metrics.
- **RO 3.4-4:** Develop reference plants for MFE and IFE with a generic bill of materials that includes both functional and specific component requirements that can be used to develop the supply chain for fusion plants.

- **RO 3.4-5:** Analyze the tritium start up needs for fusion plants in the context of global availability and conduct cost-benefit and trade-off analysis for various methods of tritium production. Understand how potential new facilities for tritium production could supplement tritium availability from fusion plants to support the expansion of fusion energy.
- **RO 3.4-6:** Develop a model plan and resources to support community education, engagement, and acceptance around the fusion fuel cycle, fusion waste, and other topics that can be used in communities where fusion plants are being sited, constructed, and operated.
- **RO 3.4-7:** Create a screening tool for public acceptance, export control, and regulatory compliance that can help evaluate issues related to fusion plant permitting, construction, operation, decommissioning, or other issues.

5.3.5 Fusion Fuel Cycle Demonstration Facilities

- **RO 3.5-1:** Develop tritium R&D facilities that can help to understand fundamental tritium behavior and properties by leveraging experiments and simulations.
- **RO 3.5-2:** Create tritium R&D facilities that can demonstrate and validate the performance of components and subsystems as well as study interfaces. These facilities would also have capabilities for testing component durability and would deliver validated data that can provide confidence in fusion fuel cycle design for fusion plants.

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