2024 TECHNICAL UPDATE

Fusion Blankets Research Objectives

Results from the 2023 Fusion Blankets Workshop

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ABSTRACT

In May 2023, representatives from the global fusion technology community participated in a two-day Fusion Blankets 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 tritium breeding blanket 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 blanket technologies.

Tritium is bred in the blankets when neutrons produced in the D-T fusion reaction interact with lithium. There are four main categories of breeder material proposed for fusion blankets: lithium ceramics, liquid lithium, liquid lead-lithium, and liquid (molten) lithium-containing salts. Each breeder choice presents unique advantages and challenges with regards to blanket geometry, breeding efficiency, chemistry, safety, tritium extraction, and the specific needs of an individual fusion pilot plant concept. Currently, the community makes no recommendation as to which breeder material should be prioritized.

The research objectives (ROs) resulting from the Fusion Blankets Workshop fall into two broad categories. First, the overarching ROs are general and multidisciplinary. They call for the generation of relevant property data, the development of frameworks by which that data can be efficiently shared, quantification of waste streams, and the development of software tools that can be engaged in design. Importantly, the community also highlights the need for experimental facilities in which breeder materials can be studied and blanket technologies assessed.

Second, the topical ROs address five primary categories:

1. **Tritium control.** Subcategories include:
   - Permeation barriers
   - Modeling needs
   - Measurement
   - Extraction systems
2. **Functional materials.** Subcategories include:
   - Flow phenomena
   - Modeling needs
   - Breeder materials
   - Neutron multiplier materials
3. **Structural materials.** Subcategories include:
   - Compatibility
   - Modeling needs

- Activation and waste
- Fabrication

4. **Blanket enabling technologies.** Subcategories include:
   - Thermal management
   - Corrosion protection
   - Lithium supply chains
   - Dual-coolant system needs
5. **Maintenance and integration.** Subcategories include designing for:
   - Safety
   - Integration
   - Maintenance
   - Reliability
   - Manufacturability

The community identified 87 specific topical ROs in total. Taken together, the topical ROs form a goal-oriented research plan to enable effective tritium breeding blankets in fusion pilot plants. During workshop discussions, it was identified that specific blanket designs and breeder choices are likely to be driven by the needs of the private fusion sector. As a result, it was observed that partnership between the private sector, federal agencies, national laboratories, and university research centers is required to ensure that publicly funded breeder-blanket research will be commercially relevant.

Keywords

Blanket enabling technologies
Functional materials
Fusion blanket
Maintenance and integration
Structural materials
Tritium control

ACRONYMS, ABBREVIATIONS, AND INITIALISMS

Be	beryllium
CO_2	carbon dioxide
COP28	28^{th} Conference of Parties to the United Nations Framework Convention on Climate Change
D	deuterium
DOE	United States Department of Energy
FLiBe	lithium fluoride/beryllium fluoride
FLiNaBe	lithium/sodium/beryllium fluoride
FPP	fusion pilot plant
H	hydrogen
He	helium
HF/TF	hydrogen fluoride/tritium fluoride
IFE	inertial fusion energy
IP	intellectual property
Li	lithium
MFE	magnetic fusion energy
MHD	magnetohydrodynamic
Pb	lead
PbLi	lead lithium
PPP	public-private partnerships
RAFM	reduced activation ferritic martensitic
R&D	research and development
SiC	silicone carbide
T	tritium
TBR	tritium breeding ratio
TPB	tritium permeation barrier
TRL	technology readiness level
UK	United Kingdom
U.S.	United States

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1 INTRODUCTION

An efficient, reliable, and safe fusion blanket is essential to the commercialization of deuterium-tritium (D-T) fusion energy (requiring tritium breeding) and also alternative fusion fuel cycles. Both the U.S. Bold Decadal Vision and multiple private fusion programs envision fusion pilot plants (FPPs) operational by the early 2030s that will require robust and operational fusion blanket technology. The requirements of the fusion core blanket will demand the evolution of materials, engineering, and technology to provide reliable and sustained operations.

In D-T fusion concepts, the typical fusion blanket almost entirely surrounds the fusion source, regardless of the specific fusion technology concept. The primary functions are to breed tritium for the D-T fuel cycle, absorb > 90% of the fusion neutron power for thermal conversion, and provide some level of shielding to components behind it. The blanket can also be a pressure vessel because it can reside in vacuum, it often has a plasma facing (or fusion source) component to it (first wall), and it must resist failure under accidents and plasma (or other) transients to the extent possible. The fusion technology concept under consideration (e.g., tokamak vs. stellarator or other magnetic confinement option vs. inertial or magneto-inertial confinement option) can alter the requirements of the blanket and potentially change its integration with other components in the fusion core. In general, fluids will need to flow into and out of the blanket to remove the energy deposited in the blanket, as well as tritium for the D-T fuel cycle. A blanket must be replaceable since it will receive the brunt of the fusion neutron flux and will most rapidly accumulate damage. In general, fluids and their circulation loops are absorbed into the blanket topical area despite being physically situated outside the blanket.

A full, operation-ready fusion blanket has never been built, let alone utilized in a fusion (or any) neutron environment. Notwithstanding, small benchtop D-T irradiations have been performed on some conceptual integrated blanket components. The development of the blanket for fusion energy applications will be a major element in creating a viable fusion energy source. Blanket research has been ongoing for decades, generally at low funding levels, and the global community has gravitated toward a set of blanket concepts for fusion reactors that are combinations of the following materials:

- Water or helium coolant
- Lead-lithium (PbLi) liquid breeder
- Molten salt liquid breeder, including lithium fluoride/beryllium fluoride (FLiBe) or lithium/sodium/beryllium fluoride (FLiNaBe)
- Lithium (Li) liquid breeder
- Lithium bearing solid ceramic breeders
- Reduced activation ferritic martensitic (RAFM) or advanced RAFM structural steel material
- Beryllium (Be) or lead (Pb) neutron multiplier
- Helium purge gas (with solid breeders)

- Functional materials (e.g., silicone carbide (SiC), alumina (Al_2O_3), etc.)
- Tungsten very thin layer on blanket first wall

To accelerate the development of blanket technologies for a range of fusion concepts, 2023 Fusion Blankets Workshop was held (following the 2023 Fusion Fuel Cycles Workshop) from May 24–25, 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 Korea. The goal of this workshop was to gather information from stakeholders in order to support fusion blanket technology development that will enable the community to build a fusion pilot plant with a successful breeder blanket on the timescale of a decade. A successful breeder blanket in a pilot plant will:

- Demonstrate tritium breeding, extraction, and integration with the plant fuel cycle at commercial-relevant scales.
- Use technologies and systems that can be scaled up to a commercial plant.

It is noted that for a fusion pilot plant, full tritium self-sufficiency is ideal but not required.

A full pilot plant design is unknown, nor is it know if there will only be one pilot plant design. It was not the role of this workshop to downselect which breeder material to focus on. A general observation from this workshop is that there is relatively little interest from the U.S. community in pursuing solid breeder concepts. Rather, most interest is concentrated on PbLi and molten FLiBe salt. Interest in liquid Li breeders is also driven by the UK fusion program.

This document summarizes the key research objectives developed at the two-day workshop. A related but separate workshop was held from on the preceding two days on fusion fuel cycle technologies, with tritium extraction form the blanket forming the scope delineation of the two workshops. A full summary of this 2023 Fusion Blankets Workshop is presented in EPRI report 3002029372. Separate documents were prepared from that workshop and are:

- *2023 Fusion Fuel Cycles Workshop Summary: A Summary of the 2023 Fusion Fuel Cycles Workshop Hosted by EPRI in Charlotte, NC on May 22–23, 2023*. EPRI, Palo Alto, CA: 2024. 3002029370.
- *Fusion Fuel Cycles Research Objectives: Results from the 2023 Fusion Fuel Cycles Workshop*. EPRI, Palo Alto, CA: 2024. 3002029371.

This document provides general conclusions from the workshop, over-arching research objectives, proposed framework concepts for new Fusion Blankets 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 BLANKETS WORKSHOP GENERAL CONCLUSIONS

The Fusion Blankets 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 blanket research and development (R&D) activities needed to support commercialization of fusion energy technology. General conclusions from the Fusion Blankets Workshop include:

- Tritium breeding blankets, while critical to the operation of future deuterium-tritium (D-T) fusion energy systems, have not been necessary to support short-pulse fusion research devices to date. This has led to the under-development of blanket technology in the U.S. compared to other countries.
- Related to the above finding, fusion blanket R&D has been primarily a design and simulation-focused research effort. New experimental facilities to address blanket R&D needs through prototypes which then provide critical design feedback are therefore urgently needed to advance this technology on a decadal timeline.
- A low level of sustained investment in fusion blanket R&D has resulted in knowledge gaps arising from lack of familiarity with early R&D work in the field. A concerted knowledge retention and transfer effort is needed to address this.
- Private industry is driving the commercialization of fusion energy in the United States, and public-private partnerships (PPPs) could greatly accelerate the development of all fusion energy concepts.
- In order to deploy fusion on a commercial scale as rapidly as possible, the U.S. Department of Energy (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,[1] should be leveraged and investments that are necessary to close critical gaps should be prioritized.

[1] 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 BLANKET TECHNOLOGIES

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

- Develop a fusion blanket program and partnerships that can address the challenges in blankets used by inertial fusion energy (IFE), magnetic fusion energy (MFE), and other advanced fusion concepts.
- 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) through mechanisms that DOE recently made available such as 30-year IP protection in Cooperative Research and Development Agreements (for certain technologies).
- Foster engagement with community partners, universities, and the private sector to promote domestic and international partnerships to recruit and develop the blanket technology workforce. Workforce development should include a deliberate effort to build a more diverse and inclusive fusion community. Developing blanket technology for a fusion power 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 blanket research progress to take advantage of the rapid developments within public, private, and international research programs and focus future R&D efforts.

4 OVERARCHING RESEARCH OBJECTIVES (ROS) FOR BLANKET TECHNOLOGIES DEVELOPMENT FOR FUSION ENERGY

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

- Determine a framework for collecting data and metadata from tritium breeding, tritium behavior, and materials compatibility experiments relevant to fusion blanket technology. Determine the necessary experimental metadata that must be collected in order for datasets from different experiments to be reliably combined.
- Collect, review, and organize physical property data for relevant blanket materials and technologies across process relevant conditions for different concepts and designs according to the framework determined above. Make the physical property data, including data related to behavior of materials with hydrogen (H), deuterium (D), and tritium (T) easily available via a standardized database.
- Conduct a domestic and global blanket test facilities gaps analysis, cross-referenced against final objectives output from the research objectives identified within this document. Closure of these gaps should focus on how to achieve component-level testing capabilities and identify the minimum set of acceptable environment/performance regimes needed in testing to move towards commercially viable fusion blankets.
- Identify and develop a set of nominal design elements, relevant environment, and performance requirements common to multiple private designs that can be utilized to guide FPP-scale blanket development.
- Quantify waste streams resulting from neutron activation, transmutation, and tritium absorption in blanket materials and their volumes that are anticipated to be generated during the process. Disposal pathways need to be identified and R&D is needed on methods for potential recycling and reuse of these materials.
- Perform risk and budget/planning assessments associated with technology deployment. Thes assessments would address workforce training needs, safety procedures, technology readiness assessment levels for technology deployments, and other relevant areas.
- Develop effective software tools for fusion blanket designs. This means low-fidelity models for rapid iteration, as well as high-fidelity, more computationally intensive models for detailed optimization. Design tools should be flexible, available, and straightforward to use, so that they are available to a wide subset of the fusion community and not just isolated teams.
- Assess how to optimally implement nonproliferation, export control, waste disposal, and community engagement for fusion blankets.

5 TOPICAL RESEARCH OBJECTIVES

Topical Research Objectives are specific to functional categories within the fusion breeder blanket system or specific considerations that need to be addressed related to breeder blankets or their 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 Tritium Control

5.1.1 Permeation Barriers

- **RO 1.1-1:** Define performance requirements for tritium permeation barriers (TPBs), including durability in the thermochemical/mechanical/radiation environment along with anticipated service lifetime. Define where TPBs will be needed in an FPP.
- **RO 1.1-2:** Assess state-of-the-art and identify data gaps. Develop an R&D plan and facility needs so TPBs are ready for FPP deployment.
- **RO 1.1-3:** Develop fabrication/coating processes that enable robust TPBs at scale.

5.1.2 Data and Modeling Needs

- **RO 1.2-1:** Assess what data is needed to design an effective FPP blanket, to what extent existing data in the literature is usable, and to what extent existing fission irradiation and hot cell facilities can be leveraged. In particular, data regarding tritium solubility and diffusivity as a function of temperature and breeder chemistry is needed. Materials performance data in a fusion neutron spectrum is also needed.
- **RO 1.2-2**: Prioritize efficient data collection, data management, and data sharing from repeatable, standardized experiments. It should be possible to effectively combine data from multiple experiments.
- **RO 1.2-3**: Obtaining necessary data will require collaborations on experiments and facilities. Efficient IP standards should be developed which enable effective and mutually beneficial collaborations.
- **RO 1.2-4**: The data and modeling required to operate a plant, not just design it, must be considered. This means assessing what tritium detection and monitoring capabilities are required throughout the plant and assessing whether current technologies are adequate for the radiation environment in a fusion blanket.
- **RO 1.2-5**: Integral-scale tritium experiments and facilities are needed to provide tritium transport model validation data as it is expected that separate effect tests may not be fully predictive of plant-scale behavior.

5.1.3 Measurement and Control

- **RO 1.3-1:** The high radiation environment of fusion, and the resulting highly activated materials, will complicate tritium measurements within an FPP and make in situ measurements difficult. Improving tritium measurement performance should focus on measuring tritium in effluent streams. It should be assessed whether adequate technologies exist, and whether there are instances where in situ measurement of tritium (e.g., in the breeder material of the blanket) will be necessary.
- **RO 1.3-2:** Assess how different breeder materials affect tritium measurement. There is limited experience with liquid tritium breeders in general.
- **RO 1.3-3:** Engage with regulators to understand the likely standards that will be developed, and how much discrepancy will be allowed between the amount of tritium that is bred in theory and the amount of tritium that is measured and extracted.
- **RO 1.3-4:** Establish metrics and design criteria that maximize radiological safety to plant personnel, the public, and the environment.
- **RO 1.3-5:** Communicate and engage with the public around issues of tritium management. Fusion will be integrated in the larger energy market and society. Hence, it is prudent to assess the broader impacts of fusion design choices on economic, safety, environmental, and social factors.

5.1.4 Extraction Systems

- **RO 1.4-1:** There is a general lack of thermophysical data for tritium properties, behavior, and forms within blanket systems that needs to be addressed.
- **RO 1.4-2:** Tritium extraction system (TES) technologies are generally at low technology readiness level (TRL). The best-performing candidates need to be scaled up for the tritium processing throughput an FPP will require. Scale-up of some blanket concepts such as FLiBe, PbLi, and Li are likely to require facilities that can handle all relevant chemical hazards along with any radiation challenges associated with testing with tritium (if applicable). Appropriate facilities for tritium extraction testing scale-up will need to be identified or created and should be capable of handling relevant throughputs.
- **RO 1.4-3:** Assess how impurities and contamination impact the performance of various TES technologies.
- **RO 1.4-4:** *(Extraction from FLiBe)* Tritium's behavior in FLiBe is not well characterized. The data that exists is sparse with little agreement. Tritium breeding and extraction tests in FLiBe are needed; this requires facilities capable of working with beryllium, tritium gas, and tritium fluoride.
- **RO 1.4-5:** *(Extraction from Li)* Because lithium is an effective getter for tritium, efficient TES technologies must be developed that exploit different mechanisms than for the other liquids. There is very limited research on pure-Li breeder blankets, so it is necessary to scale up extraction and permeation testing. As with other lithium experiments, its high chemical reactivity requires careful chemistry control and fire safety systems.

- **RO 1.4-6:** *(Extraction from PbLi)* Additional data on tritium solubility and diffusivity in PbLi is needed. Extraction of tritium from PbLi will be difficult, and proposed technologies are low-TRL. Scaling tritium extraction technologies to FPP-scale is an engineering and materials challenge.

5.2 Functional Materials

5.2.1 MHD, Flow Phenomena, and Coolants

- **RO 2.1-1:** Address long-term stability of solid breeders in respective coolant systems (e.g., helium), including corrosion effects and thermomechanical degradation.
- **RO 2.1-2:** Research materials compatibility with liquid lithium, PbLi, and FLiBe, including both structural materials and thin films and coatings.
- **RO 2.1-3:** Research magnetohydrodynamic (MHD) effects in liquid breeders, especially PbLi and lithium, and how these effects may impact heat and mass transfer, corrosion, and wear within the blanket, manifolds and piping (noting that the higher density of PbLi will result in greater forces on materials). Model how these MHD effects will impact FPP performance. Build experiments capable of testing system behavior with variable geometry for a range of magnetic fields up to high magnetic fields (>5 Tesla).
- **RO 2.1-4:** Develop chemical purification/redox control/impurity removal systems for FLiBe, PbLi, and liquid lithium, leveraging research and development on similar fluid systems in fission.
- **RO 2.1-5:** Develop computational tools that enable liquid breeder blanket designs. These tools should account for conductive walls, MHD effects, heat and mass transfer, turbulence, and tritium behavior. These tools should be widely usable by the community (prioritize ease of access, good documentation, and flexibility).

5.2.2 Data and Modeling Needs

- **RO 2.2-1**: Better data is needed across the board for breeder materials. Data should be collected from repeatable, well-documented experiments. Important data categories include tritium transport, corrosion effects, and MHD effects.
- **RO 2.2-2**: Assess gaps in neutronics data for functional materials. Prioritize gaps based on what is needed for pilot plant design.
- **RO 2.2-3**: Assess gaps in data for neutron multiplier materials (thermophysical, corrosion, neutronics, irradiation stability). Prioritize gaps based on what is needed for pilot plant design.
- **RO 2.2-4**: Develop a framework for collecting MHD data in liquid breeder experiments, such that data from different experiments can be easily compared.

5.2.3 Breeder Materials

- **RO 2.3-1:** *(Developing solid breeder blankets)* There is a large body of research on solid breeder blankets. However, because solid breeders require more structural/functional materials than liquid blankets, a larger percentage of the blanket is non-breeding, and thus, the achievable tritium breeding ratios (TBR) may be too low. Improving TBR of solid breeder blankets is a key research priority. Long-term mechanical stability of solid breeders under irradiation requires more research.
- **RO 2.3-2:** *(Developing FLiBe blankets)* The thermophysical/chemical properties of FLiBe need to be better characterized; the data that exists is sparse with little agreement. Material compatibility with FLiBe needs further research. This requires facilities capable of working with beryllium and tritium. Redox control/chemistry control systems need to be developed for FLiBe. The FLiBe supply chain is also very constrained currently, adding to the difficulty of building FLiBe-based experimental programs.
- **RO 2.3-3:** *(Developing liquid Li blankets)* There is very limited research on pure-Li breeder blankets, so it is necessary to scale up extraction and permeation testing. Lithium is highly reactive, so blanket tests and scaled-up blanket systems will require careful chemistry control and fire safety systems. Sensitivity to impurities is not well understood.
- **RO 2.3-4:** *(Developing PbLi blankets)* MHD effects are central to the performance of PbLi blankets and require further study.
- **RO 2.3-5:** All blanket concepts would benefit from greater attention to engineering integration issues in their design, and measurement of tritium breeding rates under neutron irradiation.

5.2.4 Multiplier Materials

- **RO 2.4-1**: Beryllium poses a health hazard, so research into beryllium and beryllides requires access to specialized facilities. Institutions researching beryllium multiplier materials need access to such facilities.
- **RO 2.4-2**: Assess safety hazards and mitigation strategies associated with large volumes of lead and beryllium at an FPP. Determine needs for remote handling.
- **RO 2.4-3**: Strong supply chains for lithium-6 and/or beryllium are needed, as more lithium enrichment can reduce needs for lead and beryllium multipliers by improving overall TBR of the blanket. Whether enrichment, or use of multiplier materials, is a better strategy should be assessed.

5.3 Structural Materials

5.3.1 Materials Compatibility

- **RO 3.1-1:** Implement a program to understand materials compatibility between proposed structural materials (including lower-TRL fusion materials) and proposed coolants/liquid breeders at relevant temperatures and flow conditions. In situ irradiation during corrosion and tritium effects tests should be leveraged to understand materials durability in environments with multiple degradation mechanisms.
- **RO 3.1-2:** FLiBe corrosion data with structural materials appropriate for the fusion neutron spectrum is very limited. Hydrogen fluoride and tritiated hydrogen fluoride (HF/TF) from tritium breeding or water ingress and other aggressive species pose corrosion risks that must be mitigated with proper redox control, which must be demonstrated at larger scale. Corrosion testing in FLiBe requires beryllium-capable equipment and facilities. It is necessary to develop a good reference electrode for FLiBe to improve the corrosion data from these experiments.
- **RO 3.1-3:** PbLi compatibility may require specialized coatings of structural materials at high temperatures to ensure compatibility. This necessitates an R&D program to demonstrate the reliability and usability of these coatings (e.g., ability to coat a component with complex geometry, long-term radiation stability and adhesion of the coating to the structural material beneath).
- **RO 3.1-4:** There is limited corrosion data for liquid lithium and structural materials. Corrosion experiments need to take precautions regarding lithium's high reactivity with moisture and account for purity of lithium both before and during the testing process.
- **RO 3.1-5:** Develop the qualification requirements and implement a test program for cyclic electromagnetic loading of blanket structural materials and component prototypes.

5.3.2 Data/Modeling Needs

- **RO 3.2-1:** Assess the minimum dataset needed for effective lifetime analysis of how commonly proposed structural materials for fusion will perform in an FPP. Assess what can be addressed with existing data and where a program must be implemented to fill gaps. To the greatest extent possible, match new experiments with existing facilities. Assess when integrated tests are necessary; separate effect tests should be motivated by a clear data need.
- **RO 3.2-2:** Collect sufficient data to model joints and welds in components. Coupon-scale testing of weld fusion and heat affected zones may be performed on the way to full-scale component testing that more accurately represents behavior.
- **RO 3.2-3:** Develop a U.S. Fusion Prototypic Neutron Source, which is important for long-term data needs.

5.3.3 Activation and Waste Considerations

- **RO 3.3-1:** Materials and blanket concept choices have a large impact on activation and waste, and assessments of decay heat and waste generation should be performed early in FPP design processes and as a means of evaluating concepts.
- **RO 3.3-2:** Waste classification regulations need to be updated. Current waste classification regulations are specific to fission with fission relevant materials activated by fission relevant neutron fields. To support the development of fusion, the waste classification regulations will need to be updated to also include fusion relevant materials activated by fusion relevant neutron fields to provide clarity to fusion energy developers and operators so that appropriate selections, design, and end of life waste management can be thoughtfully undertaken.
- **RO 3.3-3:** D-T fusion will generate a large volume of radioactive waste. Significant R&D is needed to develop strategies and technologies to minimize this, through design, waste treatments, and recycling and reuse.
- **RO 3.3-4:** Implications of mixed waste disposal (e.g., activated materials containing tritium and/or beryllium) need to be evaluated.

5.3.4 Fundamental Properties and Fabrication

- **RO 3.4-1:** Promising novel materials (e.g., high entropy alloys, advanced silicon carbide composites) promise good thermomechanical stability under irradiation, low activation, and good materials compatibility. Advancing these materials from lab-scale to large-scale components requires a dedicated R&D program focused on fabrication and machining using these materials.

5.4 Blanket Enabling Technologies

5.4.1 Thermal Management (Heat Exchangers, Pumps)

- **RO 4.1-1:** Research and development into high temperature heat exchangers with tritium permeation barriers. Materials compatibility with primary coolant choices and low level of radiation tolerance.
- **RO 4.1-2:** Research into long term reliable pumps which function under harsh environments with primary coolant material compatibility, tritium compatibility and sufficient throughput scale.
- **RO 4.1-3:** Exploration of power generation cycles fit for fusion application to determine Brayton or Rankine configurations.
- **RO 4.1-4:** Facilities (e.g., experimental loops) for testing balance of plant equipment for different blanket concepts are needed.

5.4.2 Purification and Corrosion Protection

- **RO 4.2-1:** Develop baseline purity standards for liquid breeders. Current datasets from different experiments cannot be compared against each other because the as-received breeder purity varies greatly and is often unreported.
- **RO 4.2-2:** Understand how activation products will affect the chemistry of liquid breeders (e.g., Polonium-210 and Mercury-203 in PbLi).
- **RO 4.2-3:** Certain material/breeder combinations may require the development of robust corrosion-protective coatings.
- **RO 4.2-4:** All blanket concepts will require coolant purification systems to remove impurities and corrosion and activation products. These systems need to be developed and tested in prototypic environments (potentially including neutron activation), and facilities are needed to conduct this testing.

5.4.3 Li Enrichment and Supply Chain

- **RO 4.3-1:** Assess level of enrichment needed for a given FPP and set of operational targets. It is not a given that all FPP designs will require enrichment, or to what level they will require enrichment. Assessment of required Li enrichment level requires modeling of the fuel cycle, particularly neutronics (e.g., determining TBR).
- **RO 4.3-2:** Develop strategies and methods for obtaining Li-6 (e.g., work with molten salt fission companies who need to minimize tritium production in their coolant). Assess existing Li-6 stockpiles in the national lab system.
- **RO 4.3-3:** Understand possible challenges associated with Li-6 enrichment. This includes export control challenges and public perception surrounding use of Li-6 for defense applications.
- **RO 4.3-4:** Analyze the need for an existing supply chain for other potential bottleneck materials including enriched lithium, purified beryllium, reduced activation/neutron transparent structural material alloys, etc. Understand the supply chain development required to facilitate the expansion of fusion energy.
- **RO 4.3-5:** Characterization and mapping of lithium enrichment processes currently used and under development.

5.4.4 Dual Coolant System Needs

- **RO 4.4-1:** Conduct a comparative pumping power assessment for various dual coolants (e.g., helium (He), carbon dioxide (CO_2) and steam), considering the commercial availability or supply chain development required for the critical components (e.g., He/CO_2 compressors).

- **RO 4.4-2:** With the exception of water, dual coolants such as helium are likely to require some new component development and testing, and experimental facilities to enable this. Develop test articles, components and test stands to increase the heat removal capability of helium and other coolants.
- **RO 4.4-3:** With the exception of water-based dual coolant systems, a commercial supply chain for components must also be developed.

5.5 Maintenance and Integration

5.5.1 Design for Safety

- **RO 5.1-1:** Develop safety systems for liquid lithium blankets to prevent explosion or fire in the event of contact with air, water, and/or moisture.
- **RO 5.1-2:** Ensure that fusion researchers and companies follow beryllium safety standards if working with FLiBe or beryllium-based multiplier materials.
- **RO 5.1-3:** Safety implications of material choices and blanket concept selection need to be considered and analyzed early in the design process.
- **RO 5.1-4:** Design for decay heat removal and the installation of other safety systems should be a part of early design integration.
- **RO 5.1-5:** Development of codes, standard, and best practices is needed to address fusion safety issues.
- **RO 5.1-6:** Develop necessary monitoring and surveillance technology for safety, e.g., real-time beryllium detection.
- **RO 5.1-7:** Key safety analysis techniques need to be developed for and/or applied to fusion systems, including failure mode and effects analysis, accident identification and analysis, safety analysis systems models (i.e., software), and software reliability analysis.

5.5.2 Design for Integration

- **RO 5.2-1:** Work with FPP designers to develop draft models of the blanket to assess points of integration. Examples include the interface between the blanket and vacuum vessel; first wall and limiters; blanket and structural mounts; blanket and piping; blanket and diagnostics, etc. The plasma physics teams for FPPs should also be consulted to assess which components related to plasma control will need to be mechanically integrated into the blanket design. Assess challenge points: where does integrating the blanket into the plant raise other engineering challenges?
- **RO 5.2-2:** Ensure that the design of the blanket, and its integration with other components, allows for effective plant maintenance.

5.5.3 Design for Maintenance

- **RO 5.3-1:** Engage with the R&D community, private industry, and relevant vendors to develop efficient, flexible maintenance strategies that maximize learnings from the first of a kind pilot plant that will lead to maximizing commercial plant uptime.
- **RO 5.3-2:** To the extent possible, design pilot plants with maintenance strategies that are as potentially applicable to n^{th} of a kind plants.
- **RO 5.3-3:** Assess likely risk of tritium cross-contamination across interfaces during maintenance. Develop blankets/maintenance strategies that enable one sector or component to be sealed off from others during maintenance.
- **RO 5.3-4:** Assess and develop necessary remote handling maintenance strategies (e.g., to deal with highly activated or chemically toxic materials), which may be informed by existing strategies in other technology domains.
- **RO 5.3-5:** Design blanket components that will undergo minimal misalignment during their lifetime as a result of radiation damage instability, thermal expansion, or movement during maintenance. It should be determined if in situ metrology strategies are needed to detect dimensional changes early.

5.5.4 Design for Reliability

- **RO 5.4-1:** Reliability of fusion systems and components is critical to both the safety and availability of power plants, and therefore to the attractiveness of fusion energy. A greater knowledge of component reliability data is needed in order to ensure a successful demonstration on an FPP and beyond.
- **RO 5.4-2:** Determine the need for and the necessary capabilities to conduct in situ monitoring of structural components to provide suitable protection against structural failures.

5.5.5 Design for Manufacturability

- **RO 5.5-1:** Develop an understanding of the required manufacturing tolerances required for the various blanket system elements, and cross reference with existing manufacturing capabilities for the specific materials.
- **RO 5.5-2:** Develop a gap analysis for the manufacturing capabilities that already exist, compared the manufacturing requirements for the various blanket system elements.

5.6 Cross-Cutting Topics

- **RO 6-1:** Assess the shielding efficacy of the various blanket concepts and determine the need for additional shielding materials to provide sufficient margin.
- **RO 6-2:** Assess and develop the necessary blanket diagnostics systems for blanket system monitoring and control (pressure, temperature, flow, level, tritium accountancy, chemical assessments, etc.).

- **RO 6-3:** Support techno-economic studies to evaluate the various blanket concepts and key performance metrics. With input from the private fusion concept developers, 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 and concept downselection.
- **RO 6-4:** Advance the development of radiation-resistant sensors and instrumentation for FPP blanket systems. This is a cross-cutting topic with the diagnostics R&D community.

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