2024 TECHNICAL UPDATE

2023 Fusion Blankets Workshop Summary

A Summary of the 2023 Fusion Blankets Workshop held in Charlotte, NC on May 24–25, 2023

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EPRI Project Manager
D. Grandas

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EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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Principal Investigators
D. Grandas
A. Sowder

This report summarizes key perspectives and insights drawn from discussions by participants during the 2023 Fusion Blankets Workshop, convened and hosted by EPRI on May 24-25, 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.

The following individuals contributed to the preparation of this report:

Principal Authors

Sara Ferry	MIT Plasma Science and Fusion Center
Mohamad Abdallah	Tokamak Energy
Brenda Garcia-Diaz	Savannah River National Laboratory
Paul Humrickhouse	Oak Ridge National Laboratory
Davin Young	Commonwealth Fusion Systems

Contributing Authors

Aditi Verma	University of Michigan
Andrew Sowder	EPRI
Ant Hollingsworth	Commonwealth Fusion Systems
Ben Lindley	Realta Fusion
Brad Nelson	Type One Energy
Brian Grierson	General Atomics
Brian Wirth	University of Tennessee, Knoxville
Chase Taylor	Idaho National Laboratory
Colin Baus	Kyoto Fusioneering
Dale Hitchcock	Savannah River National Laboratory
Dave Babineau	Savannah River National Laboratory
David Weisberg	General Atomics
Dennis Whyte	MIT Plasma Science and Fusion Center

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Diana Grandas	EPRI
George Larsen	Savannah River National Laboratory
Giulia Rela	Commonwealth Fusion Systems
Guinevere Shaw	Department of Energy
Heena Mutha	Commonwealth Fusion Systems
Holly Flynn	Savannah River National Laboratory
Ivan Maldonado	University of Tennessee, Knoxville
J. Steven Brantley	Zap Energy
John Canik	Type One Energy
Kathrin Abraham	Canadian Nuclear Laboratories
Larry Baylor	Oak Ridge National Laboratory
Masashi Shimada	Idaho National Laboratory
Michael Christenson	Zap Energy
Michael Segal	Commonwealth Fusion Systems
Mike Gorley	UK Atomic Energy Authority
Pravesh Patel	Focused Energy
Rachel Lawless	UK Atomic Energy Authority
Richard Pearson	Kyoto Fusioneering
Sam Suppiah	Canadian Nuclear Laboratories
Soha Aslam	Thea Energy
Susana Reyes	Xcimer Energy

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ABSTRACT

In May 2023, the Fusion Blankets Workshop was held in Charlotte, North Carolina to identify challenges and solution pathways with a cross-section of fusion industry stakeholders for accelerated fusion blankets development. This workshop aimed to identify technology-agnostic and fusion community-driven research objectives needed to design, build, and operate a successful blanket 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 87 specific topical research objectives for fusion blanket development, defined in EPRI report 3002029373. Over 180 stakeholders in fusion blanket research and development, representing over 70 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. **Tritium control.** Subcategories include permeation barriers, modeling needs, measurement, and extraction systems.
2. **Functional materials.** Subcategories include flow phenomena, modeling needs, breeder materials, and neutron multiplier materials.
3. **Structural materials.** Subcategories include compatibility, modeling needs, activation and waste, and fabrication.
4. **Blanket enabling technologies.** Subcategories include thermal management, corrosion protection, lithium supply chains, and dual-coolant system needs.
5. **Maintenance and integration.** Subcategories include designing for safety, integration, maintenance, reliability, and manufacturability.

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

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

ACRONYMS, ABBREVIATIONS, AND INITIALISMS

Al: aluminum

ALARA: as low as reasonably achievable

AM: advanced manufacturing

Ar: argon

ATR: Advanced Test Reactor

Be: beryllium

Bi: bismuth

°C: degrees Celsius

CFD: computational fluid dynamics

CFS: Commonwealth Fusion Systems

CO_2: carbon dioxide

Cr: chromium

CTE: Coefficient of Thermal Expansion

D: deuterium

DBA: design basis accidents

DBTT: ductile-brittle transition temperature

DCLL: dual coolant lead lithium

DIR: direct internal recycling

dpa: displacements per atom

EU: European Union

F: fluorine

FCC: face centered cubic

Fe: iron

FeCr: ferrochrome

FERMI: Fusion Energy Reactor Models Integrator

FLiBe: lithium fluoride/beryllium fluoride

FPNS: fusion prototypic neutron source

FPP: fusion pilot plant

H/D: Hydrogen and Deuterium

H: hydrogen

He: helium

HF: Hydrogen Fluoride

HFIR: High Flux Isotope Reactor

Hg: mercury

HX: heat exchanger

IFE: inertial fusion energy

IP: intellectual property

JET: Joint European Torus

Li: lithium

LIB: liquid immersion blanket

LM: liquid metal

LOCA: loss of coolant accident

MeV: megaelectron volts

MHD: magneto-hydrodynamics

MIT PSFC: Massachusetts Institute of Technology Plasma Science and Fusion Center

ML: machine learning

MSRE: Molten Salt Reactor Experiment

N: nitrogen

Nb: niobium

O: oxygen

ORNL: Oak Ridge National Laboratory

Pa: pascal

Pb: lead

PbLi: lead lithium

PFC: plasma facing components

PRA: probabilistic risk assessment

PRF: permeation reduction factor

Q_2: dihydrogen isotopologues

QA: quality assurance

QC: quality control

RAFM: reduced activation ferritic martensitic

R&D: research and development

RAMI: reliability, availability, maintenance, inspectability

SiC: silicon carbide

SNS: Spallation Neutron Source

STEP: Spherical Tokamak for Energy Production

Sv: sieverts

T: tritium

TBR: tritium breeding ratio

TES: tritium extraction system

TF: tritium flouride

Ti: titanium

TiC: titanium carbide

TPB: tritium permeation barriers

TRL: technology readiness level

U.S.: United States

UK: United Kingdom

V: vanadium

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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, reliable, and operation-ready fusion blanket. Many fusion pilot plant concepts under consideration require a deuterium-tritium (D-T) fuel cycle, requiring a fusion blanket surrounding the fusion source, breeding tritium for the D-T fuel cycle, absorbing > 90% of the fusion neutron power for thermal conversion, and providing some level of shielding to components behind it. To meet these requirements, an evolution of materials, engineering, and technology is needed to develop a blanket that can ensure reliable operation. In addition to the blanket's functional requirements, it must resist failure under accidents and plasma transients, generally accommodate fluid flow, and be replaceable due to rapid damage from neutron flux. Significant research gaps exist on the path to develop operation-ready blanket technologies pertaining to tritium breeding, extraction, and integration with the plant fuel cycle at commercial-relevant scales.

Numerous existing strategic planning reports by or for the fusion energy research community have established fusion blanket technology as an area of significant technological uncertainty on the path to an FPP.[1,2,3] To accelerate the development of relevant blanket technologies, the Fusion Blankets Workshop was held from May 24-25, 2023, in Charlotte, North Carolina. This workshop aimed to further identify and characterize challenges related to fusion blanket technologies, develop potential solution pathways, and generate actionable research objectives for enabling a fusion pilot plant with an operations-ready blanket on the timescale of a decade.

During the workshop, over 180 participants representative of key researchers and stakeholders for fusion blanket development from over 70 institutions and eight countries were convened. Participants were split into numerous breakout rooms to discuss topics of tritium control, functional materials, structural materials, blanket enabling technologies, and maintenance and integration. 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 blankets programs, which can be found in the following EPRI report:

- *Fusion Blankets Research Objectives: Results from the 2023 Fusion Blankets Workshop*. EPRI, Palo Alto, CA: 2024. 3002029373.

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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.

A related but separate workshop was held the previous days on fusion fuel cycle technologies, with tritium extraction from the blanket forming the scope delineation of the two workshops. 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.

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 blanket 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 Blankets Workshop was broken down into five major discussion topics:

- Tritium Control
- Functional Materials
- Structural Materials
- Enabling Technologies
- Maintenance and Integration

Within each overarching topic area, there were 4 technology subgroupings:

- Tritium Control
  - Permeation barriers
  - Modeling needs
  - Measurement
  - Extraction Systems
- Functional Materials
  - Flow phenomena
  - Modeling needs
  - Breeder materials
  - Neutron multiplier materials
- Structural Materials
  - Material compatibility
  - Modeling needs
  - Activation and waste

  - Fabrication
- Enabling Technologies
  - Thermal management
  - Corrosion protection
  - Lithium supply chains
  - Material compatibility
  - Dual coolant requirements
- Maintenance and Integration
  - Designing for Safety
  - Designing for Integration
  - Designing for Maintenance
  - Designing for Reliability

Each subgroup saw their technology through four major discussions:

1. Identify and prioritize challenges
2. Characterize and 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 topic and subtopic.

Overarching Themes

Some broad themes that were evident during workshop discussions are outlined in Table 1.

Table 1. Overarching themes discussed in breakout discussions during the 2023 Fusion Blankets Workshop.

A Fusion Materials Compatibility Database
There were many questions surrounding structural and functional material choice for each breeder concept. PbLi, FLiBe, and Li are all corrosive (pending chemical conditions). For any proposed material and breeder, it is important to consider how the material degrades against: • Temperature • Displacements per atom (dpa) • Radiation field • Impurity levels • Magnetohydrodynamics (MHD) flows • Flow rate • Redox potential The minimum dataset needed to successfully complete a blanket design must be assessed, and then existing data should be surveyed to see where gaps are for materials of interest. It is noted that existing data might be insufficient if it is not connected to an experiment that is easily repeatable and well characterized. Next, a plan is needed to close open gaps. This includes surveying existing facilities that could be easily modified or upgraded (e.g., a PbLi loop with the ability for high-field magnets to be installed), so that the need to build new facilities is minimized (which adds a time delay to getting data). In parallel, a framework for data collection needs to be developed. This goes beyond simply answering “what data must be collected?” and includes careful characterization of the experiment itself (e.g., impurity levels in the fluid, volume of fluid, crucible material). The framework may even extend so far as to determine a standard set of experimental procedures for corrosion tests. The framework should be able to meaningfully compare datasets from different experiments to generate a complete picture of material behavior. Researchers participating in these programs would need to upload their public data to this database. To the extent possible, the database itself should be open-source and straightforward to access. Scattered, independently run, single effects tests for a small subset of breeders and materials may not successfully support pilot plant development. A targeted, strategic, and efficient campaign aimed at providing fusion companies and fusion researchers with the data required to move forward with pilot plant design is needed.

Table 1 (continued). Overarching themes discussed in breakout discussions during the 2023 Fusion Blankets Workshop.

Tritium Properties/Kinetics Database
Currently, only minimal data exists for how tritium moves through liquid breeders (solubility/diffusion) and how it interacts with structural and functional materials (permeation). The data that does currently exist varies by multiple orders of magnitude for the same set of conditions. A strategy is needed for improving the understanding of materials compatibility through the use experimental investigation of tritium behavior in different material/breeder combinations.
Acceptance Of Reasonable Uncertainty in a Pilot Plant Design
To maintain an aggressive timeline, key blanket research and development (R&D) needs to begin immediately. Many workshop participants wanted to be able to fully constrain experiments to be in line with the final design of a pilot plant. However, waiting until final FPP design information exists may result in a delay in the deployment of fusion energy. Activities must be able to start presently. It is possible to use tools that currently exist to perform reasonable scoping studies on various high-level plant and blanket designs (e.g., fuel cycle modeling) in order to estimate target performance metrics.
Maintenance Must Be Considered Early in the Design
As the learning curve is progressed upon in terms of both operations and component design, a pilot plant is expected to have higher maintenance outages frequencies in early phases of operation. Efficient maintenance is key to a successful pilot plant mission and will be critical to the commercial viability of fusion power plants. A blanket that is effective at breeding tritium, but which will take many months to fix if it breaks, is not necessarily a better solution than a blanket that is less efficient for tritium breeding but can be maintained on a faster timeline. In general, to have efficient maintenance, blanket design must be completed considering how maintenance will be undertaken. Retrofitting a maintenance strategy onto a finalized design may lead to delays once operation begins.

The following sections will provide insights from discussions occurring in the different breakout sessions at the workshop.

2 TRITIUM CONTROL

The tritium control breakout session had four main tracks: permeation barriers, data and modeling needs, tritium measurement and control, and tritium extraction. Note that the tritium extraction session is the most directly integrated with the 2023 Fusion Fuel Cycles Workshop held on May 22-23, 2023. Tritium accountancy and management throughout the fuel cycle (which includes the breeder blankets) is a core challenge. Insights from participant discussion in each breakout session track are described below.

2.1 Permeation Barriers

Tritium permeation barriers (TPBs) require low hydrogen (H) permeability, dense microstructure, minimal defects due to fabrication, good adhesion to the structural material beneath, and good stability with regards to the thermal, chemical, and radiation environment. Radiation damage, in particular, must not degrade the material's ability to block tritium permeation (at least, not beyond some acceptable level). TPBs are characterized with the permeation reduction factor (PRF). Examples of TPBs include coatings (e.g., via chemical vapor deposition, dip-coating) or structural materials chosen in part for their high PRF (e.g., certain ceramics, TiC).

Below are key points raised during this breakout session.

- Limited data is available on TPBs.
- In order to direct R&D, explicitly defined requirements for the TPB are needed.
  - For a given concept/component/application, determine:
    - Thermochemical environment
    - Radiation environment
    - Component geometry
    - PRF is needed
  - Assess what data exists in the literature and whether data are usable.
  - Plan experiments to address data gaps, and/or to validate a new TPB material.
- Once the requirements for TPBs have been determined for a variety of blanket concepts and components, it should be possible to determine the range of testing conditions needed in a test facility.
  - Temperature range
  - Breeder of interest
  - Radiochemical environment
  - Mechanical stresses
- Note that a facility that can handle tritium will be needed. Earlier research stages can likely start with hydrogen and deuterium H/D, reducing challenges associated with tritium.

- Such a facility can be used to determine fundamental permeation data for various materials, and to test properties like durability of a given TPB/coating.
- This facility or these facilities should be able to start with small-scale coupons and H/D, such that focus is only place on the highest-performing TPBs for scaled-up tests in tritium.

- What are the general requirements for TPBs in a given FPP concept? Once component, material, and performance needs are assessed, the TPB supply chain gaps can be determined for a given FPP concept and plans can be made to address these gaps.
  - Which components need a TPB? What TPB fabrication techniques will be needed? Are there commercial vendors capable of executing these fabrication techniques?
  - What different TPB materials are needed?
  - What surface area is needed?
  - Can blankets be designed such that tritium permeation is reliant on a minimal number of permeation barriers, by having a realistic strategy which involves tritium permeation to secondary containment zones which can then clean up the permeated tritium, and thereby reduce the number of surfaces that need to be permeation barriers?
- TPBs (and TPB/structural material combinations) may be agnostic to breeder material in certain instances. However, there may be some TPBs that are incompatible with a given breeder fluid, due to corrosion.
  - Ability to collect large amounts of fundamental permeation data on different TPB systems is important.
  - Collect data and ensure it is repeatable (good metadata). Create an open-source database.

2.2 Data and Modeling Needs/Validation

The overall takeaways from this breakout room conversation were as follows:

1. An effort should be established to assess what data is needed to design an effective FPP blanket, where literature/existing experimental data is usable, and where the gaps are.
2. An experimental plan needs to be made to address the data gaps.
3. Create a data management framework to govern a database that many stakeholders contribute to. Focus is on high-quality, repeatable data with good metadata describing the conditions under which the data was collected.
4. Use data to validate simulations.

More details for data and modeling needs are below:

- What data gaps need to be addressed before a working FPP blanket can be designed? Assess gaps for:
  - Tritium solubility

- Tritium diffusion
- Fundamental material properties of breeder material:
  - In a radiation environment
  - Across a wide temperature range
  - In the presence of impurities
  - In the presence of magnetic fields
- Structural/functional material properties, especially as it pertains to tritium interactions
- Isotope exchange rates
- Trap density and energy
- Surface adsorption/desorption
- Generally, property evolution in a fusion neutron spectrum
- Integral effects. Experience with radionuclide transport in high temperature gas-cooled fission reactors suggests that no amount of separate effect data can lead to a predictive model for reactor systems. Integral effect data (and facilities to collect it) are needed for this.

- What is the strategy for closing the gaps which efficiently ensures an appropriate leveraging of existing resources?
  - What facilities exist?
    - It may be possible to consider facilities outside of the universities and national laboratories
  - What facilities can be modified or upgraded?
  - What new facilities are needed?
  - What data gaps need to be closed first?
    - What data will take the longest to collect?
- Prioritize efficient data management and data sharing
  - Minimize uncertainties
  - Experiments should be repeatable, and conditions of experiments should be clear.
  - The database should be organized, open sourced, and available to anyone.
  - A framework for how data should be organized is needed.
- Address modeling and simulation gaps for better fuel cycle/blanket design
  - Need fully integrated multi component models with open-source interfaces.
  - High and low fidelity models are needed: low fidelity for rapid iteration, and high fidelity for detailed optimization
  - Need better mechanistic testing models
    - Understand key transport phenomena
  - Integrated multiphysics modeling framework for blankets

  - What are the challenges in creating a single "ideal" software tool? Are there common challenges between blanket concepts, or are multiple tools needed?
  - Will projects like the Fusion Energy Reactor Models Integrator (FERMI) result in flexible design tools that are open source and have a low barrier to entry?
- How to manage financial, intellectual property (IP), and bureaucracy barriers to standing up new test facilities?
  - IP rules between institutions and countries can create roadblocks to effective collaborations when combining resources to create a new facility. It is important to consider these rules from the beginning and create an efficient strategy.
  - Integrated tests are needed, but some compromises in the fidelity and level of integration will need to be made. What can be learned from lower cost options, like an aneutronic facility with injected tritium? How to include capability to handle any liquid breeder at high temperatures and high magnetic fields?
- Technical considerations related to collecting data:
  - Other radiological sources make detection of tritium complicated depending on location within FPP. Tritium is a low-energy beta emitter, so consideration is required to understand where other sources are likely to prevent detection of tritium's signature radiation.
  - Consider gaps in measurement capability:
    - What tritium detection/monitoring capabilities are absolutely needed at each part of an FPP?
    - What measurement technologies currently exists and what still needs to be developed?
    - How much fidelity is needed to have confidence in tritium accountancy and in the fuel cycle performance?
    - What level of fidelity is needed for regulation?
    - What learnings and parallel efforts can be leveraged from the fission community?

2.3 Measurement and Control

Note: see also the discussion in 2.2. Data and Modeling Needs**.**

- The fusion environment makes measurement challenging:
  - High radiation environment and activated materials complicates measurements. Tritium is not the only signal.
  - High temperatures make tritium even more mobile. It is likely to seep into many plant locations (like pump oil) that might not be actively monitored, creating an accountancy challenge.
  - There should be as much focus as possible on measuring tritium in effluent/extraction streams. In situ measurements in the blanket will be challenging. This may necessitate a

research effort to develop tritium-capable sensors that can quantify concentrations within the breeder material.
    - Assess what on-line in situ measurement strategies are available and if they could work in the fusion environment.
  - To the extent possible with existing facilities, validate/test FPP measurement strategies in a nuclear environment.
  - It will be important to understand how high magnetic fields will impact fluid flow and pumping.
- The **breeder choice** affects the measurement strategy.
  - Solid breeder: tritium (T) needs to saturate through pellets first. There is a need to quantify this lag time and incorporate it into models.
  - Less experimental research exists for liquid breeders.
  - Tritium is "easier" to remove from some breeders than others.
- Need frameworks for quantifying measurement uncertainty and requirements
  - Minimal data available from integrated breeding tests. These will provide a better understanding the challenges ahead.
  - What will regulatory standards look like? What amount of uncertainty will be acceptable? There will be some (and possibly a large) discrepancy between how much tritium is expected to breed and how much is extracted and stored.
  - Need a concept agnostic framework
  - Tritium dust might be an important loss term (and a safety hazard).
  - How much inventory is releasable?
- What level of validation and detection is needed to reassure the public near a plant? How can the public be engaged in the FPP plans?
- Safety first, accountancy second
- Measurement technology scaleup
  - Focus on exhaust
  - Can tritium management technologies developed for fission be scaled up for fusion throughput levels?
  - What can be learned about the technology development philosophy used by the chemical processing industry?
  - Research into inferred measurement techniques should be undertaken (other reactions that can be related to tritium production, but which are maybe easier to measure)

2.4 Extraction Systems

This breakout group focused on tritium extraction systems (TES) technology for the four main breeder choices. Below are what workshop participants considered to be the top challenges associated with tritium extraction from each breeder, as well as an overview of the other challenges identified by the group.

Concept-agnostic challenges that were identified included:

- There is a lack of accessible fusion energy-relevant thermophysical data for tritium in general.
- There is a need to study how impurity/contamination impacts TES.
- Easy access does not exist for tritium-capable facilities capable of testing TES from different breeders.
- TES are generally low technology readiness level (TRL), at least at the scale needed for an operating FPP.

Top Challenges for FLiBe

- Thermophysical properties of tritium and fluoride salts are not well-characterized.
  - Need better data on diffusivity and solubility of tritium
  - What causes variation in reported data?
- Need verified tests of tritium extraction, with a larger scale test that validates long-term operation.
  - No verified tests so far
- Structural materials will be a challenge. Extraction system materials choice may affect system chemistry and extraction efficiency.

Other Issues for FLiBe

- Extraction issues
  - Low overall concentration of T in FLiBe might make extraction difficult
  - Need large extractor surface to lower the T concentration
  - Heat exchanger (HX) concentration limit
- Chemistry issues
  - Redox control
  - FLiBe purity
  - Tritium fluoride (TF) production is a corrosion hazard
  - Materials choices; galvanic corrosion

- Safety issues
  - Hazards associated with beryllium (Be)
  - Containment of molten FLiBe
  - Activated corrosion products
- Need to characterize thermophysical properties of FLiBe, T radiochemistry
- Supply chain:
  - Limited beryllium supply
  - Uranium impurities in beryllium ores
  - FLiBe production
  - FLiBe purification

Top Challenges for PbLi

- Tritium solubility uncertainty (there are four orders of magnitude uncertainty for T in PbLi)
- Scaling from lab test to an FPP. Proposed technologies are low TRL.

Other Issues for PbLi

- Extraction (general)
  - Need better T diffusivity and solubility data
  - Low extraction efficiency requires large systems
  - Need to consider corrosion effects
  - Need to model and test tritium residence time in a given system
  - Gas-liquid contactors
    - Complicated hydraulics
    - Need to understand pumping/form losses and heat loss
  - Vacuum sieve tray
    - Need to understand role of impurities
    - Need to understand pumping/form losses and heat loss
    - R&D on nozzle reliability
    - R&D on scale-up
  - Vacuum permeator
    - Basic membrane material performance and compatibility R&D still needed
  - Getters
    - Energy-intensive
    - Supply chain difficulty
    - Not steady-state

- Safety
  - Transmutation products; Polonium-210
- Waste management:
  - Meeting waste disposal rating of less than 1 for bismuth isotopes
- Cost
  - Vanadium (V) and niobium (Nb) are expensive
  - Alpha-iron (alpha-Fe) is cheaper, but worse permeability
  - Vacuum pumping: high energy cost
  - Getters: high energy cost
- Characterize T chemistry in relevant conditions within three years
- Infrastructure to allow engineering-scale tests

Top Challenges for Li

- Low TRL levels associated with this breeder (and breeding experiments)
  - Need tests of permeation
  - Need tests of extraction
- Lithium is reactive: safety hazard, plus impurities have a significant and not yet fully understood impact on the behavior in this system
- Lithium is a getter for tritium, and therefore it is fundamentally difficult to remove tritium from Li. Different strategies are needed for tritium extraction for Li breeders than for all other breeders.

Other Issues for Li

- Need to understand sensitivity to impurities and corrosion products
  - Limited R&D on impurity detection
- High hydrogen solubility
- Can H/D data be extrapolated to model T in the lithium system?
- Lithium vapor pressure
- Safety standards

Top Challenges for Solid Breeders

- Uncertainty in long-term mechanical stability of solid breeders in a neutron environment
- Uncertainty in impurity generation
- Temperature gradients within the blanket could pose a challenge
- Modeling for tritium transport phenomena
- Need fusion-relevant neutron source
- Separation of T from helium (He), impurities in gas stream

3 FUNCTIONAL MATERIALS

“Functional material” is a general term that describes materials used in the plant which are not structural or significantly load-bearing, but which play an important role in some plant function. This typically refers to breeder and multiplier materials, but could include other materials such as insulators, tritium permeation membranes, or tritium permeation barriers (discussed above in the tritium control section). The workshop’s functional material breakout session had four tracks: MHD/flow phenomena/coolants, data and modeling needs and validation, breeders, and multipliers. Insights from participant discussion in each breakout session track are described below.

3.1 MHD, Flow Phenomena, Coolants, and Breeders

For each breeder material, key challenges were identified:

- Solid breeders
  - Thermal performance
  - Thermal expansion mismatch
  - Material compatibility (steel/ceramic)
  - Corrosion and aging management of high-temperature structural materials
- Lithium
  - Insufficient data exists for how tritium behaves in liquid lithium, or regarding compatibility of liquid lithium with structural materials to inform blanket material specifications
  - Coating (anti-corrosion, TPB) degradation
  - Impurity removal
  - Strongly impacted by MHD effects
- PbLi
  - Interactions with structural materials
  - Coatings as a tritium permeation barrier strategy and a corrosion protection strategy
  - Need higher structural strength from materials due to PbLi density
  - Radiation damage in structural and compatible materials
  - Thermal compatibility
  - Strongly impacted by MHD effects
- FLiBe
  - Corrosion/impurities
  - FLiBe is challenging to work with so there is limited information about its behavior in a fusion-relevant environment. There are significant data gaps and uncertainties regarding tritium solubility and diffusivity in FLiBe.

- Byproducts and impurities from tritiated hydrogen fluoride (HF), oxygen reactions
- Structural material activation
- Disposal of waste
- May be affected by MHD effects at some level, though confirmation is needed

Breeder-agnostic solution pathways were considered:

- Need test facilities with high temperature breeders (>450 °C), high magnetic fields (>5 Tesla) to test components, pumping solutions, and validate codes.
- May need a separate low complexity facility with good diagnostics for the sole purpose of developing a code validation dataset.
- Want to develop a computational fluid dynamics (CFD) code that account for conductive walls, heat transfer, and turbulence.
  - In general, need more computational capability in multimaterial environments
  - Need code to be easy to for a workforce to use (prioritize open-source, flexibility, ease of use, good documentation)
  - Need to integrate MHD effects into the code (and need validation data).

3.2 Data and Modeling Needs and Validation

This conversation focused on data and modeling needs for three broad categories: breeder materials, multiplier materials, and MHD effects.

Breeder materials

- Significantly more data, and data of a higher quality from what currently exists for breeder materials in representative conditions expected in an FPP, is required to make informed design decisions. For example, these data would include thermophysical properties, neutron irradiation response, chemical properties, materials interactions, and waste considerations. Experiments should be undertaken which are repeatable and suitably well characterized in order for data from different experiments to be reconcilable.
- Current critical data gaps which should be addressed include:
  - T transport
  - Materials degradation
  - Neutronic cross sections
- Need facility access to produce these data.
  - FLiBe: need beryllium-capable facilities
  - Need tritium-capable facilities for certain datasets
  - Need high temperatures, high magnetic fields
  - Strategic integrated tests may result in better information than multiple separate single-effect tests

    - New facilities should be flexible so that they can be modified and expanded to address future data gaps
    - Sufficient, robust computational models can complement validation data from large-scale fully integrated test facilities.
    - What uncertainty within breeder materials can be tolerated before designing an FPP? What data is absolutely mission critical?
        - What data are available and usable?
        - What new data are needed?
        - How are those new data generated?

Multiplier materials

- Need to assess current datasets to determine gaps.
    - Thermophysical, corrosion, chemical data under irradiation
    - Fusion relevant environment behavior
    - Lack of covariance data for reliability analysis
        - Is the current neutronics modeling capability sufficient?
- Develop standardized database of material properties.

MHD effects

- What level of accuracy and understanding of MHD effects is needed to design an efficient blanket for an FPP?
- Need framework for generating quality data and metadata
    - Open-source database
    - Repeatability of experiments
    - Ability to meaningfully combine data from multiple experiments
- What is the highest priority experimental data needed?
    - What can be attained with existing facilities?
    - What new facilities are needed?
    - Facilities and experiments should be integrated with the data framework/database needs from the beginning.

3.3 Multipliers

- The key multipliers are beryllium and lead (Pb). They may be integrated into the plant on their own or used as inherent multipliers in the breeder compound (e.g., FLiBe, PbLi). Beryllium may also be present in the form of beryllides.
- Multiplier form, design, and requirements is dependent on FPP design.
- Need awareness of potential regulatory issues, as both Be and Pb multipliers mean large volumes of hazardous materials at the plant.

- There is a tradeoff between Li-6 enrichment and the need for multipliers.
- Beryllium poses major safety hazards that have to be accounted for.
  - Additional requirements for remote handling are needed.
  - There is a lack of experience with handling Be.
  - Designing facilities to handle Be have higher costs.
- There is a need to be thoughtful about the long-term beryllium supply chain. However, if first-generation plants are successful at tritium breeding, it might not be necessary to have the higher TBR enabled by beryllium in subsequent plants.
- What impurities are likely to be created? How to remove them?
- Lead poses activation issues
  - Need to model/study which transmutants are likely to appear in pure lead or PbLi
  - What is the waste cycle like?
    - Byproducts include bismuth (Bi) and mercury (Hg)
    - Process impurities out at the end?
  - Can lead be purified online?
  - Does lead need to be purified?
  - Lead is also toxic, but this is easier to deal with than beryllium.
  - Need to model nuclear heating effects.
- What purity of beryllium and lead is required?
  - How can beryllium be purified?
    - Pure form of Be vs in FLiBe form
    - Uranium removal

4 STRUCTURAL MATERIALS

Structural materials in the blanket are exposed to a high neutron flux, high head loads, potentially corrosive fluids, very high temperatures, and thermomechanical stresses. There is some overlap with fission technology, although the neutron energies and fluences (particularly those close to the first wall) are much higher, making radiation damage and activation concerns more challenging. The neutronics of the overall system are less constraining: it is beneficial to avoid neutron absorbers in the blanket structural materials because it is desirable to maximize absorption in the breeder (and thus TBR).

In general, the following must be assessed:

1. The minimum dataset needed to develop a given blanket concept to the point where it can be deployed in an FPP
2. Determine gaps in the dataset
3. Make a strategic plan to fill those gaps
4. Ensure data is collected in a user-friendly database with good metadata

Disconnected, one-off experiments collecting small subsets of compatibility data will delay R&D progress. Targeted, strategic campaigns which directly support commercial blanket development in a definitive manner can serve to accelerate blanket R&D.

The workshop's structural material breakout session had four tracks: materials compatibility, data and modeling needs/validation/qualification, activation and waste considerations, and fundamental properties and fabrication. Insights from participant discussion in each breakout session track are described below.

4.1 Materials Compatibility

In this breakout room, key challenges associated with structural materials for the four main breeder concepts were brainstormed.

- Common challenges for liquid breeders/structural materials
  - Galvanic and intergranular corrosion
  - Corrosion product transport
  - Impurity driven transport
  - Corrosion models/corrosion prediction
  - Need more quantified design targets for a given blanket concept in order to understand structural material performance targets
    - Temperature
    - Breeder flow rate
    - Geometry of structural materials

    - Note: design targets do not have to be perfect. Reasonable, directionally correct targets can provide sufficient value.
  - Low-activation, high-temperature silicon carbide (SiC): prone to swelling, limited development of SiC/SiC component-scale fabrication with advanced composites
  - Need to optimize cooling channels (poses a fabrication challenge), including the materials compatibility with the blanket medium
  - MHD compatible coatings needed in some cases
  - Novel materials (e.g., high entropy alloys optimized for fusion applications) require development of:
    - Supply chains
    - Purity standards
    - Fabrication techniques
    - Welding/joining techniques
  - Tritium control compatibility
    - Test compatibility with tritium permeation barriers
    - Test compatibility with tritium permeation membranes
    - Structural and functional material in liquid may lead to galvanic corrosion or other effects.
  - Need more testing facilities
  - Need a corrosion database with reliable datasets
    - Avoid having to unnecessarily repeat identical tests
- FLiBe
  - Hydrofluoric acid presents:
    - Corrosion risk
    - Safety hazard
  - Tritiated HF (TF)
    - Some of the bred tritium reacts with fluorine present in the salt
    - TF is hazardous and corrosive
  - Beryllium
    - Safety and handling hazard
    - It is difficult for most research teams to find Be-capable facilities.
  - Redox control
    - Multiple methods proposed
    - Adding beryllium is an option
  - F(n,alpha)N→ O reaction
    - Transmutation in the salt generally

  - Need to develop good reference electrode for FLiBe
    - Limited corrosion data set (only ~20 data points available for pure FLiBe)
    - FLiBe purification
    - Very constrained supply chain
    - Need to carefully quantify FLiBe composition before each experiment
    - Determine necessary purity of FLiBe for a blanket
    - Determine purification strategy
- Solids
  - Solid breeder pebbles prone to radiation damage
    - Aging and erosion of pebbles
    - Swelling
  - Novel ceramics with porous structures can lead to better tritium diffusion out, but these are at low TRL.
  - There is more structural material in a solid breeder blanket compared to other concepts (however, self-cooled designs are less complex), leading to challenges:
    - Steel-ceramic solid-state reaction
    - Li sublimation corrosion
    - Coefficient of thermal expansion (CTE) mismatch
    - High temperature creep
    - Coating degradation
    - Maintenance cost
  - Sublimation of Li in operating conditions
    - Observed in fission environments
    - Opportunity to learn from fission community
  - Good compatibility with ferrochrome (FeCr) and V alloys
    - Need oxygen control for V alloy systems
    - V alloy supply chain is under-developed
    - Need more corrosion data for FeCr and V alloy systems exposed to the coolant used in solid breed (e.g., He)
- PbLi
  - Lead is heavy; increases mechanical stress on structural materials
  - Coatings required at high temperatures; may have poor performance in radiation environment; difficult to fabricate parts
  - Need a forced flow loop (>500 °C, >2 Tesla)
  - MHD challenges

- Lithium
  - MHD challenges
  - Chemically reactive (safety)

4.2 Data and Modeling Needs, Validation, and Qualification

For each breeder material, and candidate structural materials, the following data needs must be considered, noting that many of these effects are coupled to each other:

- Chemical effects
  - High temperature testing
  - Corrosion behavior
  - Cracking in solids
  - Tritium permeability
- Neutron/radiation effects
  - Helium effects
  - Embrittlement
  - Ductile-brittle transition temperature (DBTT) changes
  - Neutron damage
  - Swelling
  - Microstructural evolution
  - Activation, transmutation
  - Enhanced corrosion
- Electromagnetic effects
  - Eddy currents, Lorentz forces
  - Effects on liquid coolants
- Need to be able to model joints and welds

Solution pathways for addressing data gaps

- Assess minimum dataset needed for effective lifetime analysis
  - Note that an incomplete data or some risk in materials selection may be acceptable for the first phase of FPP deployment and operation.
- Survey existing data and determine gaps
- Fill gaps where possible with existing data
  - Can the fusion industry access useful information on these topics developed for defense applications?
  - What can be learned from lead reactors and molten salt reactors?

- Plan to fill remaining gaps with experimental data
  - Collect new data where needed; data is frequently missing at high temperature and dpa
    - Match data needs to existing facilities that can be adapted/scaled
    - Build new facilities where absolutely necessary to fill gap
  - What gaps will have to simply be accepted for now? (e.g., 14 MeV/high dpa neutron data)
    - Clever “second-best” strategies, like isotope doping, can help mimic 14 MeV neutron effects
  - Figure out the right balance of single effects tests (easier, cheaper, faster - but less representative of how material will actually evolve in an FPP) and integrated tests

4.3 Activation and Waste Considerations

- Neutron activation should be a key consideration in structural material selection for the blankets.
  - Blanket structural materials are exposed to very high energy, high fluence neutrons, especially near the first wall.
  - For a given FPP concept, need a reasonable assessment of power output, followed by simulations of neutronics (TBR) and inventory analysis (e.g., FISPACT; determine long-lived activation)
  - Low-activation options optimized for DEMO pathway (e.g., EUROFER) are not necessarily deployable (at least not without undue challenges in design) in compact pilot plants designs, which have a much higher neutron fluence.
  - The activation of materials in an FPP will be quite significant: hundreds of sieverts (Sv) per hour on a decadal timescale is very likely in some cases.
    - This is comparable to the radiation levels associated with spent nuclear fuel from a fission plant.
    - Activation makes handling and waste disposal more complicated and raises concerns for public acceptance. The fusion industry should be careful about communications to the public that insinuate fusion is nuclear-waste-free.
    - Thousands to tens of thousands of Sv/h are possible in the short term (hours-weeks), which is the timescale relevant to maintenance and remote handling
  - Likely will need to select for low-activation materials and a maintenance scheme that involves frequent component replacement
- Specific materials of interest
  - Reduced activation ferritic-martensitic (RAFM) steels are an option for low activation material that can used on a decadal timeline
    - 350-550 °C
    - May not be useful for blanket operating at higher temperatures

  - Vanadium alloys
  - Silicon carbide and SiC/SiC
    - SiC/SiC is low TRL for large components that need to sustain durability for long periods of time in harsh fusion blanket environment
  - Isotope tailoring
    - High cost, but could be an option for components in the highest-fluence locations in the blanket
- How to define constraints on blanket material activation?
  - What decay heat is acceptable during maintenance?
  - What radiation levels are acceptable during maintenance?
  - What long-lived activation limit is acceptable for disposal?
  - How to define constraints on blanket material activation?
  - Maintain "as low as reasonably achievable" (ALARA) principles
- Large amounts of activated waste requires scaleup of waste disposal system
  - What are technical limitations of waste management technologies for metallic and mixed waste that are likely needed in an FPP?
  - For a given FPP concept, what volume, chemical form, and composition of waste is generated over a given amount of time?
  - Who owns the waste? Who regulates it?
    - How much will regulations need to change?
    - What is the likelihood of new regulations?
    - How much will regulations vary between countries?
  - How does beryllium affect the waste?
  - When is a decommissioning plan or strategy needed?
    - How much new strategy needs to be invented?
    - Unknown design may mean an undefined waste stream.

4.4 Fundamental Properties and Fabrication

There is no one material or set of materials that works for all blanket concepts or design. There are multiple blanket designs in development, and diffuse efforts aimed at R&D of novel materials. A targeted strategy is needed to prepare any one blanket concept for readiness in a fusion pilot plant.

It should be ensured that plant designers, regulatory bodies, nuclear materials researchers, and component vendors are keeping each other informed.

There is a lack of irradiation data at relevant dpa and neutron energy. A fusion prototypic neutron source (FPNS) is still an important need and has been regularly re-confirmed by the U.S. fusion community as a priority. However, it is not likely to be useful to the bold decadal vision or the first pilot plant on the current timeline. By the time the FPNS is funded, designed, built, and used, it may be past the point of structural material down selection for an FPP. Some appropriate risk will need to be accepted into FPP design (risk of economic consequences can be tolerated, risk of health safety cannot be tolerated). FPNS development and plans for its initial test runs should still progress in parallel.

Multiscale computational models to predict materials behavior are needed. Radiation damage happens on the atomic level, conglomerates on the mesoscale, creates microstructural evolution and results in global property changes. Ideally, the models would be the able to predict dpa, microstructural damage, temperature, helium formation, tritium retention, corrosion damage, and engineering property changes (e.g., Young's modulus, thermal conductivity) as a function of position inside a component.

5 BLANKET ENABLING TECHNOLOGIES

The concept of a fusion blanket has historically been considered to be the material which surrounds the fusion plasma to capture neutron energy for power production, generate tritium through lithium transmutation, and shield sensitive components from the neutron irradiation. There are several enabling technologies which do not neatly fit into this historical definition of a fusion blanket, but are still required to enable the functional operations of a blanket. This can include the engineering components required to operate the liquid immersion blanket concepts (such as pumps and heat exchangers), the equipment required to operate secondary coolants which flow through the blanket, as well as critical supply chain technology for key blanket materials. The workshop's blanket enabling breakout session had four tracks: thermal management, purification and corrosion protection, Li enrichment and supply chain, and dual coolant system needs. Insights from participant discussion in each breakout session track are described below.

5.1 Thermal Management (HX, Pumps)

- Need to model holistic fuel cycle to understand efficiency requirements
  - An FPP design is currently not defined, but useful fuel cycle models can still be made using existing tools for a given concept. This model can explore sensitivities including, but not limited to:
    - Presence of direct internal recycling (DIR)
    - Tritium processing time
    - Tritium residence time in different components
    - Leak rates in different components
    - Target doubling time
- Thermal management technology choice depends on inputs like coolant choice and temperature regime, which is difficult to define today.
  - In advance of determining specific blanket concepts for an FPP, meaningful work can be done using multiple high-level concept designs, in advance of detailed designs.
- There is interest in accelerating R&D for heat exchangers (HX).
  - Aggressive, high temperature fluids
  - Need tritium barriers to prevent tritium leaking into secondary fluid.
  - Need materials compatible with the primary and secondary fluids, resistant to some low level of radiation damage, resistant to creep at high temperatures.
  - HX research will benefit from compatibility research elsewhere (database/national-lab-supported materials compatibility data collection program).
  - To what extent can the HX be breeder agnostic (other than material compatibility issues)?

- There is interest in accelerating R&D for pumps
  - Long-term operability of advanced pumps
  - Tritium compatibility
  - Scale-up of pumps proposed for D-T operation in research devices like SPARC or ITER to handle commercially relevant throughput levels.
  - Engage vendors early. Work with private fusion companies to develop reasonable specification ranges for pumps so that the targets for development are understood. Good opportunities exist for project partnerships involving commercial pump vendors, academic/national lab research groups, and private fusion companies in the milestone program.
- For pumps and HX: consider what kind of maintenance will be needed during their lifetime. Are they accessible? What will maintenance challenges look like (e.g., tritium uptake, activation)?
- Turbomachinery for Brayton cycle does not work at fusion scale
  - High power levels, high gas temperatures
  - Private industry has not been able to bridge this gap yet
    - Risk of standing up a Brayton cycle for fusion is high. Who is responsible for industrialization?
    - Private sector: challenge to invest heavily in R&D now in the hopes of a market later, but likely will need public sector funding to motivate it.
- Leverage adjacent sectors with challenging heat management needs. What can be learned from them? Are there opportunities for collaboration?
  - Fission
  - Solar thermal industry (molten salt)
  - Oil and gas industry
  - Industrial process heat
  - Advanced thermal energy storage

As mentioned above, HX and pump design are areas where commercial vendors can be engaged with, rather than having scientists build bespoke one-off systems in a laboratory setting. Some items to consider:

- Federal funding can play an important role in supporting private industry development of high-risk projects that may not have strong market signals for in the near term.
- Opportunities for securing target funding for pump/HX development should be developed with industry engagement. Vendor-relevant research should be a goal such that vendors can use the data the projects produce. In some contexts, scientific researchers may not always be well positioned to assess prioritizes for commercial relevance.
- Purchase agreements between private fusion companies and vendors can also help.

- There is a need for nimble IP strategies when working across government, academia, vendors, and companies. Bespoke IP solutions negotiated on a project-by-project basis may delay technical progress.

5.2 Purification, Corrosion Protection

Purification considerations discussed in this breakout group are summarized below. For more insights from discussions on material compatibility for functional and structural materials, see sections 3.1 and 4.3.

An important note for all liquid breeders: in the near-term, understanding as-received breeder purity is a major consideration for the purposes of corrosion and breeding experiments.[4] The ability to build common databases of breeder/tritium properties would be beneficial, but in order to do this effectively, a baseline standard is needed for the purity of the liquid breeder. Two research programs could run identical corrosion tests but get different results if the as-received FLiBe or PbLi had different concentrations of impurities to begin with.

- General
  - What corrosion products are present? How do they affect chemistry?
  - What precision is needed for online impurity measurements?
- PbLi
  - How will Po-210 and Hg-203 activation products affect chemistry?
  - What is the purification procedure for PbLi for lab-scale experiments? Can these procedures be standardized?
  - Will MHD effects change how corrosion products move through the PbLi?
  - Need electrical insulator coatings that are compatible with PbLi.
- FLiBe
  - Need online salt purification/chemistry control technologies.
    - What technologies exist?
    - Can the technologies be scaled?
    - Redox control of salt
  - Specific to inertial fusion energy (IFE): need to test compatibility of target materials in salt.
  - How will high-temperature FLiBe degrade diagnostics?
  - FLiBe-specific transmutation (N, O)
- Solids:
  - O activation

[4] Massachusetts Institute of Technology Plasma Science and Fusion Center (MIT PSFC) is working on this for FLiBe in conjunction with CFS, for example.

- Liquid Li:
  - Need electrical insulator coatings that are compatible with Li (e.g., for self-cooled Li design, though Li-compatible insulator coatings may not be necessary for a dual cooled design as the lithium can have much lower flow velocity).

5.3 Li Enrichment and Supply Chain

A key challenge for Li enrichment and supply chain is first identifying the level of enrichment needed for a given FPP and breeder blanket design. It is important to note that Li enrichment is not a required need for all plants, as is commonly assumed. In self-cooled designs, and in particular, designs where the neutron source (plasma) is completely surrounded by breeder material, breeding contributions from Li-7 (the most abundant form of natural lithium) are effectively equivalent to contributions from Li-6 near the first wall. The vast majority of tritium breeding occurs near the first wall due to simple geometry (neutron fluence decays as $1/\text{radius}^3$), and a sufficient tritium breeding ratio (TBR) can be achieved without introducing enriched lithium. Further out into the blanket, where neutrons are more moderated, the Li-7 tritium breeding cross-section drops to 0. As blanket designs are advanced and more structural/functional components are added, the volume of breeder material is decreased and the boost from Li enrichment becomes more important. The steps for determining the level of enrichment needed for a prospective FPP design are:

1. Model the fuel cycle of the plant and account for the operator's target doubling time and target tritium reserve inventory. Calculate the required TBR. The fuel cycle model should account for tritium losses, uptake, and extraction efficiencies which are bundled into the required TBR.
2. Perform a neutronics analysis of the plant. Determine if the achievable TBR is greater than the required TBR.
3. Iterate the neutronics analysis at different levels of lithium enrichment until the level of lithium enrichment that enables tritium self-sufficiency as defined by the fuel cycle model is determined.

By understanding the required level of enrichment for each concept, better constrained discussions can be held on topics of lithium enrichment and defining effective research and development initiatives.[5] Minimizing the required enrichment level may also be a useful design goal as the various blanket concepts are advanced.

Additional challenges and research projects to consider:

- Need to survey which processes exist for lithium enrichment.
  - What is currently used?

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[5]An additional point of interest: lithium refueling is often considered as an required need, but this is not necessarily true. For example, current ARC models at the PSFC do not require "fresh lithium" during the blanket lifetime in order to attain tritium self-sufficiency.

  - What is currently under development?
  - How energy intensive are the processes?
  - For a given pilot plant design, is there a strategy that works to obtain enough enriched lithium?
  - Can collaborations with fission stakeholders be undertaken?
    - The fission industry seeks to reduce tritium production in molten salt coolants. Thus, fission developers and stakeholders favor Li-7 and want to eliminate Li-6 (nonzero tritium breeding cross section at moderated neutron energies). If the fission industry does isotopic tailoring, can Li-6 castoffs be used for fusion blankets?
    - Battery companies may have useful contributions
  - What are existing stockpiles of Li-6? (e.g., Y-12 at ORNL produced hundreds of tons of Li-6 in the 1950s).
- Li-6 enrichment and associations with weapons development
  - Public perception/community engagement needs
  - Regulatory framework
  - Proliferation risks
- Need to understand possible export control challenges surrounding enriched Li-6. Export control considerations may be less of a challenge for a pilot plant built in the U.S.

5.4 Dual Coolant System Needs

Technology development is ongoing with the dual coolant lead lithium (DCLL) blanket concept, and of significant interest to many researchers in the U.S. national lab system, although it is not clear whether it is of interest to private fusion developer companies. In this breakout session, challenges associated with DCLL development and scale up were discussed.

- Helium stream challenges:
  - Low heat transfer
  - Tritium contamination
  - Supply chain challenges for helium
  - Associated pumping power
  - Low heat transfer leads to high flow velocities, which leads to the need for high pumping power.
  - Likely needs intermediate HX
  - Need to test at >10 pascal (Pa) to improve uncertainty in helium properties
- Water/steam stream challenges:
  - Corrosion
  - Tritium permeation/detritiation of stream
  - Phase changes

- Activation
- Reactivity
- High pressure needed

- Carbon dioxide (CO_2) stream challenges:
  - Potential corrosion issue
  - How to extract T from CO_2
  - Neutron absorption
  - Carbon activation
  - Materials compatibility
  - Utilize knowledge from advanced fission
  - Investigate neutron flux on CO_2
- Leverage information from other research groups:
  - Lots of DCLL work for ITER
  - Fission: knowledge of CO_2 in a neutron spectrum

6 MAINTENANCE AND INTEGRATION

Reliability, availability, maintenance, inspectability (RAMI) is often overlooked as a leading design constraint for a fusion power plant. Particularly for the first generations of plants, fusion power plants will need frequent maintenance and component replacement as improvements are made in the understanding of delivering and operating fusion power plants. It is critical that plants are designed for maintenance from the outset of design activities, so that maintenance can be done efficiently when a design is finalized and a system is built and in operation. A situation where plants require substantial shut down periods should be avoided. Public fusion programs and private fusion developers must be mindful of historical examples of some research-scale devices which have required long periods of maintenances.

The workshop's maintenance and integration breakout session had four tracks: design for safety, design for integration, design for maintenance, and design for reliability. Insights from participant discussion in each breakout session track are described below.

6.1 Design for Safety

The liquid breeder concepts have the following safety challenges associated with them:

- Lithium
  - Reactive with water/moisture, oxygen gas, nitrogen gas, carbon dioxide
  - Flammability issues
  - Need fire extinguishing system for plant
- FLiBe
  - Beryllium is very toxic to humans; breathing in beryllium dust over time can lead to severe lung complications (berylliosis)
  - Health surveillance required for personnel (e.g., annual blood testing)
  - Fluorine is an HF/TF risk. Safety standards for working with HF need to be integrated into any FLiBe experiment/FPP.
- PbLi
  - Lead is toxic

In general, having very high temperature fluids also present safety hazards for personnel. However, this is a challenge that is common to many industries, so strategies already exist for managing the associated risk.

Before any given blanket concept can be operated in a pilot plant, and potentially even before a blanket concept can be operated in integrated blanket tests, plans should be developed to address the following:

- The standard safety plan for managing and accounting for tritium, and minimizing environmental release
- A plan for what happens in accident/fire scenarios: how will environmental release be minimized in this case? What needs to be communicated to the public about potential risk when a new facility is built?
- Activated structural materials: What are the decay heat removal needs for waste disposal? How will the waste be safely handled to minimize radiation exposure?
- What are risks due to coolant phase change or overheat? (e.g., sudden flash to steam)
- What is the probability that a loss of coolant accident (LOCA) occurs? What are the consequences of LOCA?
- What cryogenic hazards exist?
- What magnetic hazards exist?
- What electrical hazards exist?
- What laser hazards exist?

Note that for many of these hazards, standard procedures for dealing with them exist, and these risks have successfully been managed in other experiments for a long time.

A standard set of design basis accidents (DBA) that developers can use to analyze the safety of their concept should be built.

The fusion industry continues to work with regulators to develop a standard set of codes for minimizing/mitigating hazards.

6.2 Design for Integration

The blanket must integrate into the rest of a pilot plant. To maintain an aggressive timeline for pilot plant construction, developers should determine early in the selection and design process how a particular blanket concept will be adapted to the constraints imposed by the radial build, support systems, and diagnostics of the plant. Examples include integration with:

- The vacuum vessel and first wall
- How the blanket will be mounted in the structure
- Piping and manifolds
- Diagnostics

Design decisions for one point of the overall plant, or within the blanket, will affect design decisions elsewhere in the fusion plant. Many interfaces are coupled to each other, creating interdependencies. For example, it must understand how a given blanket design affects thermal management of a pilot plant and how it impacts neutronics/radiation fields throughout the plant (e.g., some blankets will shield magnets more efficiently than others).

Any blanket scheme must be compatible with maintenance needs of the plant. Liquid breeders may have an advantage for maintenance because they can be pumped out of the blanket. Self-cooled designs may have even more of an advantage because the liquid and/or coolants can similarly be pumped out to a holding tank, leaving a minimum number of solid structures behind that could otherwise impede access to other components.

The blanket design for a pilot plant will need to have some amount of flexibility in its final specifications throughout most of the development stage. This flexibility is needed because activities on blanket design must be started before final specifications for a full fusion pilot plant are knowns. A pilot plant blanket will need to generate useful data about performance in a 14 megaelectron volts (MeV) fusion neutron spectrum and demonstrate scaled up tritium breeding/extraction, but it does not need to perform at the same level as required for a commercial plant. An integrated, low fidelity software tool is needed for blanket design so that multiple design concepts can be explored quickly. Reduced order models are also needed that enable prediction of the whole system's behavior.

In short, waiting until the end of a blanket's R&D process to begin determining how it will be installed and how it will perform in the overall pilot plant is insufficient.

6.3 Design for Maintenance

The 2021 National Academies of Science, Engineering, and Medicine report, "Bringing Fusion to the U.S. Grid,"[6] indicates that a pilot plant should operate for ≥3 hours at a time, have a high availability (targeting >85%), and have technologies that should scale to commercial plants. Maintenance technologies and procedures used for a pilot plant should also be able to scale to commercial plants, such that a pilot plant is used as a testbed for maintenance and operations procedures. In designing a pilot plant, relevance to a commercial plant is often more important than pilot plant availability. A lower availability is likely acceptable if it means systems scalable to a commercial plant can be implemented. An operational pilot plant that that has maintenance schemes and component systems that are not relevant to a commercial plant, would not be an effective use of resources.

[6] 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.

The public fusion research community (i.e., national laboratory and university researchers) should engage with private fusion companies to gain an idea of:

- Maintenance needs
- How to plan efficient, flexible maintenance strategies
- What a pilot plant needs to demonstrate regarding maintenance strategies so that there is confidence in implementing these strategies in the first generation of commercial fusion plants.

Adjacent industries (e.g., high temperature chemical processing) should be reviewed for relevant methods of handling coolant flow into HX and how maintenance is done on cooling systems. Maintenance strategies should be planned at the beginning of the design, not forced onto a design once it is finalized.

In planning a maintenance scheme, interfaces between systems will be a key challenge. Tritium cross-contamination between subsystems needs to be mitigated. Making interfaces modular/standardized where possible will help simplify maintenance. This will be especially important for plasma facing components and subsequent components attached to them.

Seals, joints, and welds are a general challenge for plant construction due to complex geometry, materials compatibility issues, and the broad issue of joint durability in an extreme environment. It needs to be understood where interfaces need to be separable: for example, it would not be practical to have to saw through a welded interface to do maintenance and then need to reattach the interface.

Furthermore, if a section, module, or component is removed for maintenance, a strategy is needed for sealing off the vacant space from the rest of the system.

A pilot plant will also need to have associated tritium-compatible laboratory/factory spaces where components can be brought for maintenance. Tritium off-gassing is a particular concern.

Activation will present a challenge, especially near the first wall and for compact plants with a high neutron flux. Remote handling strategies currently implemented for fission systems might not be suitable for fusion, as components activated in fusion systems will likely become more heavily activated and will likely emit even higher radiation fields. Activation challenges might require frequent swap-out of electronics, or the development of better radiation-hardened systems. Fully mechanical, high-precision manipulators may provide a solution if electronics are unsuitable.

An important point that was strongly raised during this breakout session was the challenge of misalignment. Misalignment may occur for a variety of reasons, including:

- Thermal creep, radiation creep
- Radiation-induced swelling
- Corrosion degradation of surfaces
- Thermal expansion leading to mechanical stresses that exceed elastic limits

- Movement during maintenance leads to misalignment

A key issue is that misalignment may either (a) make components difficult to move during maintenance or (b) make components difficult to reinstall following maintenance. The following is needed:

- Assess the allowable margin that each component has for dimensional change. This is also influenced by what remote handling strategies can tolerate.
- Determine what *in-situ* metrology strategies are needed to detect out-of-bounds dimensional change before it happens.
- Develop remote handling procedures and maintenance strategies that can tolerate some level of dimensional change.

Another issue discussed in this breakout session was that when liquid metals or molten salts are removed from a system, there will be some amount of wetting of the solid components. Breakout room participants questioned if wetting matters.

Additional recommendations for research programs:

- Develop a probabilistic risk assessment (PRA) framework for assessing component reliability.
  - Key metric: (frequency of damage) *x* (severity of consequence to plant operation)
  - PRA enables assessment of the most critical risks to plant reliability, and then to prioritize the durability of those subsystems/components.
  - Often, the highest-risk "pathways" (e.g., a combination of component failures) are not immediately obvious without the PRA analysis.
- Build scaled mockups of blanket modules for practice maintenance. This can be done first in non-nuclear, non-tritium, surrogate-fluid environments.

6.4 Design for Reliability

In this breakout room, a variety of challenges were brainstormed that would impact the reliability of a pilot plant. These include:

- Power extraction capabilities
- Neutron shielding (ensure magnet longevity)
- Robust TESs that do not break or need frequent maintenance
- Maintain integrity of vacuum (for blankets that are inside the vacuum envelope)
- Evaluate likelihood of LOCA
- Planning for which components will be replaced, and how frequently
- Making sure that a given component can meet its lifetime service goal under
- Neutron degradation of materials

- Need qualified maintenance personnel
- Robust pump trains in fuel cycle
- Understand likelihood and magnitude of heat load transients
- Good corrosion mitigation schemes to minimize long-term damage to materials
- Reliability of pump systems

7 CONCLUSION

Prompted by rapid fusion power plant deployment timelines and significant existing technology gaps, the May 2023 Fusion Blankets workshop convened over 180 researchers to identify challenges, research gaps, and potential solution pathways for fusion blankets development. Throughout the workshop, extensive discussion was had in breakout rooms regarding pertinent topics for fusion blanket technology: tritium control, functional materials, structural materials, blanket enabling technologies, and maintenance and integration. 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 blanket systems. This report provided a full synthesized summary of breakout room discussions, and its companion report "Fusion Blankets Research Objectives: Results from the 2023 Fusion Fuel Cycle Workshop" (EPRI Report 3002029373) 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 blanket research programs.

A APPENDIX: PROJECT IDEAS

On the last day of the workshop, participants had the opportunity to fill out project idea templates aimed at addressing challenges identified earlier in 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 summary of these project ideas is presented in this appendix. Any mention of specific organizations or capabilities in this appendix do not imply endorsement.

A.1 General Materials Challenges

The most common theme when discussing general materials challenges was the need for a trustworthy database of important materials properties. Participants envisioned such a database to have the following attributes:

- Collects existing data from the literature
  - Easily available data (e.g., published papers)
  - Data from historic projects at national labs that may not be easily searchable online
- Easy to identify data gaps for a given system in order to define needed research projects
- Wide-ranging
  - Materials compatibility/corrosion as a function of temperature, irradiation conditions
  - Engineering properties of materials as a function of temperature, stress, dpa
  - Liquid metals and molten salts thermochemical/thermophysical properties, including under exposure to magnetic fields
- Careful curation of metadata
  - If the data is not from an obviously repeatable experiment, it needs to be recollected
  - Example: an experiment that measures tritium diffusivity in a molten salt as a function of temperature, but the purity of the molten salt was unknown or the experimental apparatus design was not described. Data produced in this manner cannot be used to design a blanket system.
- Open-source and easy to use
- Well-defined framework for data collection from new experiments
  - Requirements will need to be made clear to researchers from the beginning

There was also a great deal of interest in new test facilities (more projects are listed as they pertain to specific breeders below). Researchers in attendance at the workshop wanted to be able to test components, materials, and tritium management technologies in FPP-relevant conditions (e.g., high temperature, significant volume, high magnetic fields). More advanced facilities will be capable of testing with tritium and neutrons, but much can be learned from aneutronic facilities at today’s stage of facility development. The fusion community should carefully survey existing facilities to see what can be upgraded or adapted to suit the current needs, and where funding of new test loops is needed.

In general, researchers want to find clever ways to leverage existing facilities and capabilities. An example of this is determining a combination of existing fission reactors and fusion devices that can be used to gain neutron irradiation data on key materials. Related to the database commentary above, workshop participants were particularly interested in carefully curated, well-characterized irradiation experiments.

Specific points of interest include vanadium alloy development, low-activation material development, and durable, easy-to-fabricate coatings (either for corrosion mitigation or tritium control).

Finally, it was important to workshop participants that focused material research be continuously connected to broader development considerations in order for an FPP to be established on an accelerated timeline. Engaging with component vendors early on (e.g., pump suppliers) and working with them to create component specification sets that can be used to develop and improve their technologies is important. It is understood that it might not be feasible to deliver a definitive, down-to-the-decimal specification set today because the exact arrangement and requirements of an FPP are unknown. However, for a given concept, reasonable target points (e.g., mass flow rate required through a pump and likely temperature range) can be assessed. As materials are down selected, it is important to be mindful of the ability to make scaled-up components. Fabricability, joining, and weldability must be assessed and improved in parallel with other activities. The actual cost of building and operating various blanket concepts should be considered in an n^{th}-of-a-kind fusion plant, as the economics of a blanket technology are just as important as its technical performance when it comes to commercializing fusion.

High-level summaries of submitted project ideas relevant to the general materials challenges category are listed in Table 2.

Table 2. Summaries of project idea templates submitted at the Fusion Blankets Workshop related to general materials challenges.

What	Details	Implementation
Database		
Develop material property database at relevant conditions	● Temperature, dpa, stress ● Tritium transport ● High flux, high energy neutron environments: build test facility ● Interpret results with multiphysics models	● Data from facilities like High Flux Isotope Reactor (HFIR), CHIMERA, Joint European Torus (JET), Advanced Test Reactor (ATR), Molten Salt Reactor Experiment (MSRE): what can be implemented today? ● FPNS mission?
Materials database	● Obtain material properties vs neutron damage ● Develop simulation framework that can model property gradients due to various neutron energies ● There is currently virtually no high dpa data	● Need FPNS ● What other facilities are available? ● Fission, spallation sources
Fusion material property database	● Collect data from national labs on relevant material properties, assemble searchable database ● Identify gaps for research	● Survey fusion industry for missing data ● Create searchable database
Fusion Data Resource Library	● Do not lose data and redo experiments ● Maintain connections in the community	● Recover historical information ● Develop framework for gathering/organizing data ● Focus on data hygiene, data preservation
Materials compatibility for structural materials in nuclear fusion programs	● Understand compatibility issues associated with structural materials in FPPs	● Literature review, identify gaps ● Experimental work on LM breeders ● Development of coating

Table 2 (continued). Summaries of project idea templates submitted at the Fusion Blankets Workshop related to general materials challenges.

Facility		
Blanket material selection	• Need to know materials to model/characterize system	• Materials testing facility
Test facility for materials testing and systems	• Test materials in platform that includes many FPP systems	• Create database of experimental results •
Blanket component test facility	• Testbed for liquid metal (LM) in pilot-relevant environment • Investigate tritium transport and corrosion	• Pilot relevant heating, magnetic field, and materials in a new test facility • Tritium capability • Database (tritium transport, materials, MHD)
Experimental Campaign		
Material irradiation in FPP for NOAK material selection	• Forget about FPNS - can NOAK neutron spectrum at existing tokamaks be accessed?	• Use existing facilities like W-7X or DIII-D? • Work with private companies • Make public materials irradiation database
Irradiation program for tritium breeding structural and functional materials	• Irradiation experiments of functional materials • Lots of data gaps exist • Integrated designs hard to make without the data	• Develop quality assurance and quality control (QA/QC) data sets for microscale materials development • Machine learning (ML)/digital twin • Irradiation testing campaigns at DOE reactors

Table 2 (continued). Summaries of project idea templates submitted at the Fusion Blankets Workshop related to general materials challenges.

Specific Materials (Breeder Agnostic)		
Fabrication of vanadium breeder blanket module	● Build breeder blanket module with vanadium ● Manufacture, fabrication of V_4Cr_4Ti and other similar alloys ● Refine heat treatments to avoid embrittlement	● Focus on large-scale fabrication, not just test samples ● Has been done before but not optimized
Coatings for corrosion protection	● Develop tech to deposit coating on face centered cubic (FCC) materials ● Important for blanket integrity	● Evaluate present deposition technology ● Develop technology scalable to large surfaces in confined spaces ● Do adhesion testing, defect analysis
Low activation materials for FPPs	● Low activation materials that can withstand extreme conditions	● Determine gap ● Develop and test new materials
Manufacturing		
Development of liquid coolant loop and major component mini-specs	● Need tool to communicate with component developers from beginning ● Make sure component developers can deliver needed components on budget and time	● Develop template with important attributions such as process conditions, off-normal process conditions, thermal shock potential, thermal cycles, safety functions
Welding of fusion structural materials to conventional metals and hydrogen uptake	● Weldability of FeCrAl, Eurofer, V alloys to conventional pipe materials ● Explore joining techniques ● Test weld performance in high H environments	● Determine matrix of materials to test and weld methods to use ● Some data already exists - determine gaps first

Table 2 (continued). Summaries of project idea templates submitted at the Fusion Blankets Workshop related to general materials challenges.

Manufacturing (continued)		
Blanket structure manufacturing techniques	• Evaluate microstructures generated by manufacturing, forming, and joining • Establish suitability of welds and forgings	• Small scale test specimens that reflect scaled up microstructures • Develop database
Economic impact analysis of blanket concept	• Determine lifetime cost of different blanket costs - understand tradeoffs of each concept	

A.2 General Computational Challenges

Community members are very interested in a computational design tool that will allow them to study and optimize different blanket concepts. The ideal design tool will:

- Be open-source, well-documented, and easy to use
- Be capable of modeling steady-state and transient scenarios
- Have low-fidelity code for rapid iteration, high-fidelity code for optimization
- Have full CFD capabilities, including modeling MHD effects in liquid breeders (e.g., pressure losses, flow effects)
- Be validated with experimental data
- Incorporate tritium transport modeling

Surveys of what already exists should be undertaken, as there are already programs like FERMI at ORNL aimed at this sort of development for various specific breeder concepts. Researchers with simulation experience will also be able to characterize the specific challenges and limitations associated with creating computationally efficient, multiscale, multiphysics simulations.

High-level summaries of submitted project ideas relevant to the general computational challenges category are listed in Table 3.

Table 3. Summaries of project idea templates submitted at the Fusion Blankets Workshop related to general computational challenges.

What	Details	Implementation
Blanket Integrated Design Tool		
Development of modeling and simulation tool to inform design of breeder blanket	● Steady state, transient analysis for accident scenarios ● Modeling tool for blanket design ● Low fidelity system code ● High fidelity tool for design optimization ● MHD, pressure losses	● Need integral test data
Digital engineering platform for whole facility modeling	● Digital engineering capabilities for fusion plants ● Streamline design efforts	● Open-source tools ● Build validation database from existing and historic test facilities
Integrated breeder blanket/heat transfer	● Evidence-based breeder material/heat transfer ● CFD, simulation	● Develop common digital factory
Develop a capability/codes for multiphysics/ multiscale blanket modeling	● Solve structural stability/compatibility issues ● Couple different multiscale and multiphysics codes ● Gather materials data	● Create experimental data repository ● May require test facilities for validation
High fidelity multiphysics integrated computational framework	● Flexibility to assess multiple breeder and FPP design concepts ● Optimization, automation and uncertainty quantification	● Determine data gaps ● Develop tool that can predict dynamic behavior of integrated systems

Table 3 (continued) Summaries of project idea templates submitted at the Fusion Blankets Workshop related to general computational challenges.

What	Details	Implementation
Tritium Transport		
Material agnostic, multiscale modeling tool for tritium transport	• Develop validated numerical tool for tritium transport that can work for any blanket design • Flexible • Accelerate blanket design, fuel cycle studies, T life cycle	• *To what extent can FERMI do this?* • Validate with T experiments

A.3 Regulatory Challenges, Public Outreach

Many project ideas had a regulatory focus, especially as it pertains to issues around Li-6 enrichment. Key efforts and issues that participants would like to resolve include:

- Gain an understanding of current relevant export controls
- Work with regulators to understand if current export controls and regulations will be used for a fusion industry, or if they will be updated
- Develop more efficient processes for Li-6 enrichment
- Quantitatively assess, for different pilot plant and blanket concepts, what level of Li-6 enrichment is likely to be needed
- Determine a strategy to ensure that commercial fusion will have access to Li-6 as needed, and the ability to remain in compliance with regulations and export controls

There was large interest in understanding what the regulatory framework for a fusion power plant will be. Beyond Li-6 enrichment, this also includes factors like tritium accountancy requirements and disposal of activated material. Regular engagement across the industry, research community, and regulatory bodies is needed to all stakeholders informed of current technical and regulatory progress. Finally, the fusion community should mindfully engage the public, listening to their concerns, and ensuring public safety. An initial activity could include surveying the public (in general or near where projects are being built) to gain an understanding of their concerns around fusion technology, and what they would like to see from private fusion companies related to safety and trust building.

High-level summaries of submitted project ideas relevant to regulatory challenges and public outreach are listed in Table 4.

Table 4. Summaries of project idea templates submitted at the Fusion Blankets Workshop related to regulatory challenges and public outreach.

What	Details	Implementation
	Public Outreach	
Giving the public a voice in fusion	• Identify public concerns • Build trust	• Catalog public concerns and share with fusion industry
	Li-6 Enrichment	
Export control regulatory scoping and strategies for Li-6	• Understand current export controls. How will they work with fusion? • Strategies for compliance	• Engage with DOE and other regulatory bodies
Li-6 enrichment with less mercury	• Develop efficient, low-cost system that does not use Hg or hazardous materials	
Li-6 enrichment regulation and control assessment	• Understand current export control situations • Chart pathway to commercial supply chain	• Need clarity and framework before working on technology
Li-6 Supply Chain Development	• Confirmation on fusion industry use of Li-6 strategies that already exist • Get regulatory clarity on accountancy, non-proliferation • Identify Li-6 source for FPP and beyond	• Develop lab-scale validation of Li-6 technology • COLEX process no longer environmentally acceptable
Regulatory issues for fusion	• Get clarity on need to allow private generation of isotopes like Li-6 • Actual implementation may be stopped after if regulatory issues are not resolved first • Provide firm targets for developers	• Should be able to work on this now without knowing explicitly what an FPP will look like

Table 4 (continued). Summaries of project idea templates submitted at the Fusion Blankets Workshop related to regulatory challenges and public outreach.

What	Details	Implementation
Regulatory Framework		
Fusion Regulation, codes, and standards	• Clarify regulatory framework needs for blanket development	• European Union (EU) already working on this
Development of regulatory pathways for blankets and fuel cycle	• Develop consensus-based set of regulatory requirements, design and analysis methods, and regulatory methods supported by codes and standards • Consensus committee	• Consensus committee from multiple stakeholders • Work with professional societies • Work with regulators • Work with companies to get realistic standards • Kickstart public discussions on safety
Misc.		
Safety	• Develop detector relevant to nonproliferation • Build public trust	

A.4 FLiBe

FLiBe and molten salt blankets are of particular interest to multiple organizations targeting D-T fusion concepts. There is a great deal of interest in expanding programs to develop functional and structural materials that work in a FLiBe system and which resist corrosion in the fusion power plant environment. This will require facilities capable of handling Be and flowing FLiBe loops (some of which already exist and may be able to be leveraged for these purposes).

High-level summaries of submitted project ideas relevant to FLiBe are listed in Table 5.

Table 5. Summaries of project idea templates submitted at the Fusion Blankets Workshop related to FLiBe.

What	Details	Implementation
General		
Supply chain for FLiBE	• May need grants or guarantees from government to ensure that that Be is available for fusion and FLiBe production is scaled up	• Collaborate on FLiBe supply chain development with other stakeholders • Explore government support options to scale up commercial production
Tritium Management		
Molten salt compatible permeation barriers	• Develop corrosion-resistant TPBs that do not affect salt redox control	• Need more data for post-irradiation materials
Tritium extraction from FLiBe	• Optimization of extraction techniques	• Build suitable testing facilities • Leverage collaborations with universities, national labs, and private companies
R&D for environmental T mitigation suitable for FLiBe facility	• Modify old/design new concepts • Need to be able to work with FLiBe	

Table 5 (continued). Summaries of project idea templates submitted at the Fusion Blankets Workshop related to FLiBe.

Materials Compatibility/Corrosion Control		
Functional Material Compatibility with Liquid Breeder Materials	● Functional material compatibility with LM, FLiBe (e.g., extraction materials)	● Flowing experiments ● Study impurities and off-normal conditions ● Identify gaps and then partner industry/research institutions based on desired material/breeder pairs ● Focus on gaps and priority breeder/material combos. Tests are expensive.
Materials suitable for FLiBe FPP	● Downselect candidate materials	● Need FLiBe capable facilities
FLiBe loop for corrosion measurement and impurity removal	● Need to develop online corrosion management/impurity removal	● Build FLiBe loop ● inject/introduce impurities
Corrosion behavior in flowing molten salt loop	● Bridge gap between lab and FPP scale research ● Material interactions in integrated environment	● Design loop with modularity and flexibility ● Public and private input ● Monitor corrosion, analyze corrosion products online

A.5 PbLi

Lead-lithium is one of the more "popular" blanket concepts: it is well-established (including as part of the ITER-TBM program), it avoids beryllium, and is amenable to self-cooled concepts. Major challenges include MHD effects due to the interaction between the conductive PbLi and the plants' strong magnetic fields. A main theme of PbLi-related projects is the need for flowing test loops with strong magnetic field capabilities (>2 Tesla) and high temperatures that will enable researchers to study pressure drops, test components, and investigate materials compatibility. The **DCLL** is a relatively mature concept, and many participants were interested in expanding U.S. work on this blanket concept, in particular by optimizing channel design in the DCLL to improve heat transfer without sacrificing TBR.

High-level summaries of submitted project ideas relevant to FLiBe are listed in Table 6.

Table 6. Summaries of project idea templates submitted at the Fusion Blankets Workshop related to PbLi.

What	Details	Implementation
Tritium Control		
Tritium barrier for PbLi blanket	● Need reliable TPB to prevent permeation and T loading of structure	● TPB research and development to be undertaken
DCLL Design Optimization		
DCLL blanket flow channel inserts	● Fabricate and test flow channel inserts in complex geometries relevant to complete blanket flow path ● Baseline DCLL needs isolation of PbLi from steel, thermally and electrically	● Fabrication, flow channel inserts mechanical testing, mockup testing in blanket test facility needed
Dual coolant PbLi breeder blanket concept	● DCLL (He coolant, PbLi breeder) ● Optimize DCLL to achieve necessary TBR and heat removal capability ● Reduce MHD effects ● Mitigate effects on plasma	● High fidelity computational model for PbLi flow needs to be established ● Optimize cooling channel design ● Small scale test facility to validate ● Scale up ● Work with plasma physicists to mitigate plasma effects from PbLi flow

Table 6. (continued). Summaries of project idea templates submitted at the Fusion Blankets Workshop related to PbLi.

Test Facility		
PbLi blanket test facility	• Reduce risk/increase readiness of PbLi and DCLL for FPP • Address multi-effects issues	• Need magnetic field (5 Tesla or higher), flowing PbLi, corrosion monitoring, T permeation studies, pumping power monitoring, plasma transient effects • Need reference design to drive testing
PbLi lab-scale test loop	• Test tritium extraction and measurement • Test TPB • Develop safety procedures	• Lab-scale PbLi loop • Later phases - neutrons, tritium
Build PbLi flow loop with magnet (>2 Tesla)	• Build loop, study MHD effects and breeder/material compatibility	
DCLL / reduce PbLi flow from MHD pressure drop	• Improved blanket feeding geometry design, lower MHD pressure drop, produce uniform flow distribution	• PbLi facility under high magnetic field >2 Tesla and high temperature >500 °C • Validate MHD simulations with data on pressure drops • Explore compatibility
DCLL PbLi demonstration facility	• Increase TRL of PbLi blanket concept • Need testing under prototypic conditions • Confirm durable materials options exist for PbLi blanket	• Flowing PbLi facility >500 °C, >2 Tesla magnetic field
Blanket Component Test Facility for PbLi	• Corrosion testbed and dihydrogen isotopologues (Q_2) testbed needed • Develop flow diagnostics	• Prototypic PbLi testing facility

Table 6 (continued). Summaries of project idea templates submitted at the Fusion Blankets Workshop related to PbLi.

Materials Compatibility/Corrosion Control		
Functional Material Compatibility with Liquid Breeder Materials	● Functional material compatibility with LM, FLiBe (e.g., extraction materials)	● Flowing experiments ● Study impurities and off-normal conditions ● Identify gaps and then partner industry/research institutions based on desired material/breeder pairs ● Focus on gaps and priority breeder/material combos. Tests are expensive.
Corrosion testing of fusion structural materials in contact with PbLi blanket	● Test EUROFER, ODS, V alloy	
PbLi loop to study high flow rate corrosion nand Bi removal	● Understand corrosion in PbLi blanket	● Test facility with PbLi flow at high temperature

A.6 Liquid Li

Liquid lithium is an important breeder material for UK concepts and is being pursued by multiple organizations. Proposed lithium projects were interested in test loops to study MHD effects, material compatibility studies, and Li-specific coatings and flow inserts.

High-level summaries of submitted projects relevant to liquid lithium are listed in Table 7.

Table 7. Summaries of project idea templates submitted at the Fusion Blankets Workshop related to liquid Li.

What	Details	Implementation
Test Facility		
Lithium flow loop with hydrogen extraction system	• Better understanding of lithium with different impurities • Corrosion in flowing lithium • Purification • Li safety	• Need adequate Li loop • Develop property database • Collaborate with national labs, international labs, private industry
Facility for demonstrating MHD pressure drop mitigation solution for Li blanket	• Mitigate MHD pressure drop for an Li blanket at >500 °C, >2 Tesla magnetic field. This is a top issue for Li blankets	• Flowing Li facility with temperature gradient • Forced convection, >2 Tesla magnetic field

Table 7 (continued). Summaries of project idea templates submitted at the Fusion Blankets Workshop related to liquid Li.

What	Details	Implementation
Materials Compatibility/Corrosion Control		
Purification of lithium	• Develop and test Li purification technologies • Minimize material degradation in blanket	
High-performance structural materials for Li blanket	• Need low activation structural materials with high strength and gas immunity	• Neutron testing • He testing • Mechanical testing
Materials development for lithium breeder/TES components	• Fundamental behavior of materials and lithium • Materials downselection • Effect of impurities in lithium	• I: Model based calculation of corrosion rate • II: Lab-scale testing for long durations, static/flowing, validate model • III: Medium-scale forced convection testing
Material properties of Li	• Thermophysical, thermochemical transport • Define gaps, run experiments	• Is there data in the non-public domain that can be accessed?

Table 7 (continued). Summaries of project idea templates submitted at the Fusion Blankets Workshop related to liquid Li.

What	Details	Implementation
Li-Specific Technology Development		
Lithium breeder material - electrical insulators	• MHD coating or flow-insert concept to provide insulation to Li blanket • Minimize negative MHD effects	• Test in flowing Li loop in prototypical B field
Scaled Li pumps	• Develop pumps that work for Li in MHD conditions	
Li safety protection system testing	• Drainage and fire suppression system development	• Use argon (Ar) pressure systems as inert gas suppressant • Need Li facility for testing
Dual Cooled Liquid Lithium Design Optimization		
Purification of helium (DCLL relevance)	• Make and use pure helium • Test material impact • Test separation systems	

A.7 Solid Breeders

There were no project templates submitted aimed specifically at solid breeder development.

A.8 Agnostic: Tritium Permeation Barriers, Tritium Management

Many participants submitted project templates that were agnostic to breeder concept but were broadly concerned with tritium management. The discovery, development, and validation of tritium permeation barriers is a high priority for the community. Participants also wanted to better understand how tritium will behave in the overall blanket/fuel cycle (e.g., uptake in components) and generate more reliable data for tritium kinetic behavior in liquid breeders generally.

High-level summaries of submit project ideas agnostic to breeder concept are listed in Table 8.

Table 8. Summaries of project idea templates submitted at the Fusion Blankets Workshop agnostic of breeder concept.

What	Details	Implementation
Tritium Permeation Barriers		
Tritium permeation barrier characterization	• TPB TRL is quite low, need to raise to 5-6 • Simulation and experiment, use experimental data to improve models	• Need dedicated facility for flowing liquid metals and molten salts
Materials selection for TPB for PbLi blankets	• Determine data gaps for tritium-material permeation for PbLi blanket systems • Experiments to close gaps	
Tritium barrier for PbLi blanket	• Need reliable TPB to prevent permeation and T loading of structure	
Tritium production and permeation analysis	• Understand sensitivity of cross section data in tritium production modeling • Understand sensitivity of T permeation from structures and facilities • Evaluate various blanket concepts in terms of T inventory and release (a major liability)	• Combine neutronics studies and permeation experiments to create better systems models • Will need single effect T permeation testing
T diffusion barrier for V	• Identify coatings that work with V • Test and model	

Table 8 (continued). Summaries of project idea templates submitted at the Fusion Blankets Workshop agnostic of breeder concept.

What	Details	Implementation
Tritium Management/Extraction		
Tritium management in blanket loops	• Understand T permeation in all blanket streams, functional materials, and equipment • Minimize T retention	• Run T through HX, loops • Account for losses • Refine models • Structural material post-mortem
Prove out Tritium / He Skid Separation Systems	• Modularization of tritium separation systems	• Ongoing work exists on He^3+ separation skids
Tritium extraction development campaign	• Identify candidate TES technologies • May need to prioritize one breeder	• Can use some existing facilities?
Fundamental tritium properties	• Establish dataset of fundamental T properties for breeder design	
Material/T compatibility facility	• Identify best materials for tritium storage • Decommissioning process after test	
Tritium management in FPPs	• Develop tritium management technologies • Test under extreme conditions	• Leverage existing expertise in tritium (handling, waste management, materials qualification) • Adapt / scale technologies from CANDU reactors • Develop comprehensive dataset
Blanket component test facility	• Testbed for LM in pilot-relevant environment • Investigate tritium transport and corrosion	• Pilot relevant heating, magnetic field, and materials in a new test facility • Tritium capability • Database (tritium transport, materials, MHD)

A.9 First Wall

Several participants submitted templates focused on first wall technology. While this is not a direct concern of this workshop, in certain concepts (e.g., ARC) the first wall is heavily integrated with the self-cooled blanket.

High-level summaries of submitted projects relevant to first wall technology are listed in Table 9.

Table 9. Summaries of project idea templates submitted at the Fusion Blankets Workshop related to first wall technology.

What	Details	Implementation
Protect first wall with coolant/breeder	• Wetted first wall concept • Analyze for design life, heat transfer, T recovery	• Test scaled systems in fission spectra
Development of helium cooling capabilities in high heat flow environment	• Helium cooling for first wall	• Need test facility capable of testing high He flow at high temperature / heat flux
Plasma facing component (PFC) research	• High heat flux tests needed • Integrated component design needed • Will benefit other FPP systems • Need functional PFCs	• Manufacturing/joining/ advanced manufacturing (AM) studies
Design cooling channels for vacuum chamber	• Investigate cooling channel geometry and cooling of FW	

A.10 Maintenance

A useful FPP will need a robust maintenance strategy, and it should be thought about from initial design stages (versus trying to retrofit a strategy after designing the plant). Key challenges will include remote maintenance in harsh environments, handling of tritiated and activated materials, and managing dimensional changes of components during service (e.g., due to creep or swelling).

High-level summaries of submitted projects relevant to maintenance challenges are listed in Table 10.

Table 10. Summaries of project idea templates submitted at the Fusion Blankets Workshop related to maintenance challenges.

What	Details	Implementation
Mockup of partial scale remote handling	• Test modularity/alignment and remote maintenance • Plan for scaleup • Necessary for FPP	• ORNL has experience in this issue for the Spallation Neutron Source (SNS) and MSRE

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EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com