# Evaluating the impact of lead-lithium purity on tritium transport

## for tritium extraction system design in fusion plants

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## 1. Problem

Tritium control is central to safe fusion operation. Lead–lithium (PbLi) eutectic, used as breeder and multiplier, remains poorly characterized for tritium transport, with reported Sieverts' constants spanning nearly **four orders of magnitude**. Tritium solubility in PbLi varies drastically due to: (1) Impurities (metallic & non-metallic) increasing solubility; (2) Lithium depletion from burnup or evaporation reducing solubility; (3) Corrosion products dynamically altering alloy composition. This uncertainty prevents accurate TES (Tritium Extraction System) sizing and regulatory assessment.

## 2. Why lead-lithium (PbLi)

| Breeder / Coolant | **PbLi** | **Li** | **LiF-BeF$_2$** |
|---|---|---|---|
| Density (kg m$^{-3}$) | ~9500 | 505 | ~2000 |
| Thermal conductivity (W m$^{-1}$ K$^{-1}$) | 15-35 | 40-60 | 0.57-1.1 |
| Chemical reactivity | Mild | Violent | Very low |
| Corrosion tendency | Moderate | Moderate | Moderate |
| Specific heat (kJ kg$^{-1}$ K$^{-1}$) | 0.19 | 4.26 | 2.4 |
| Multiplier built-in | Yes | No | Yes |
| Concerning activation products | $^{210}$Po | No | $^{10}$B, $^{18}$F, $^{20}$F |
| Tritium extraction practicality | Proven, continuous | Difficult / batchwise | Slow, chemistry-limited |
| Tritium permeation in struct. mat. | High | Intermediate (LiT) | Low (ionic TF, HF) |

✓ PbLi offers **greater tritium production** and energy capture per unit blanket thickness.

⊗ However, it can suffer from low specific heat (leading to sharper temperature gradients) and severe **tritium permeation** issues in structural materials.

## 3. Lead-lithium Fabrication

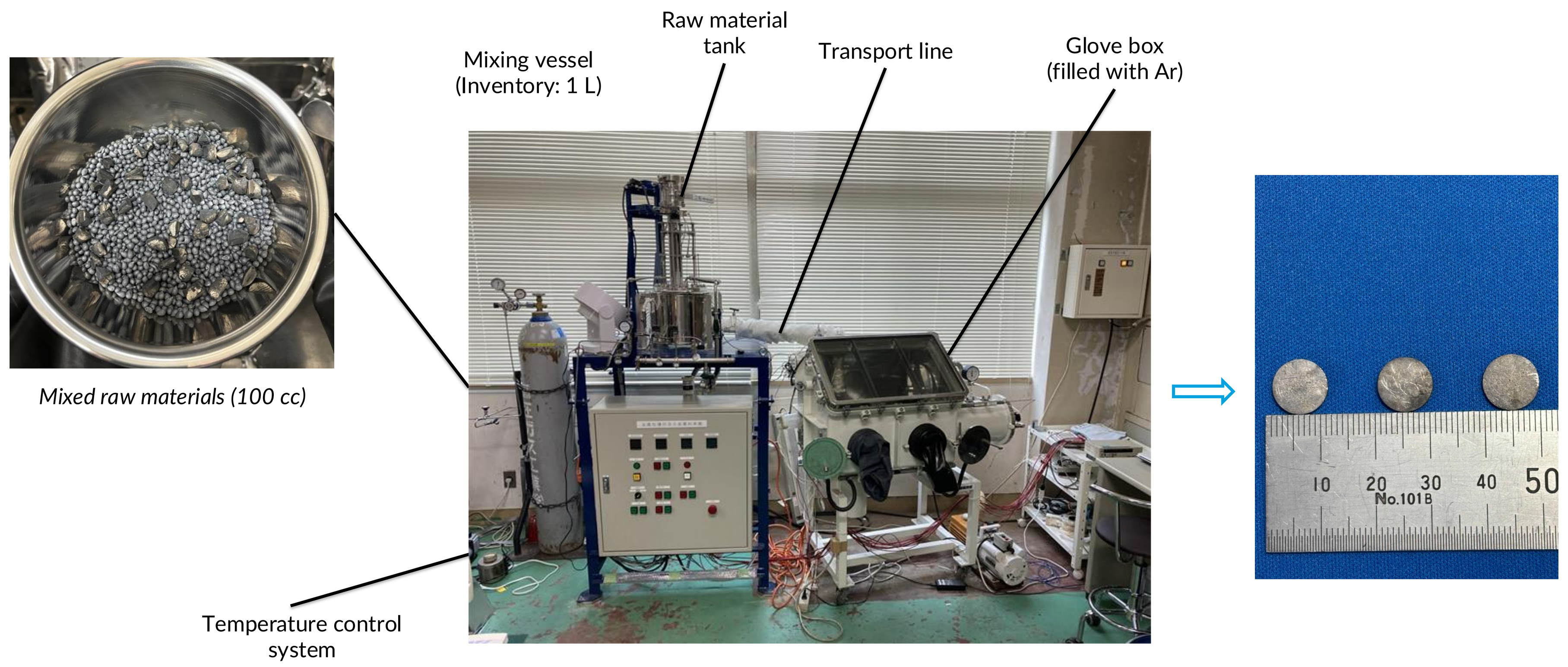


*Fig 1. EX-Fusion PbLi Lab (Tokyo)*

- EX-Fusion produces PbLi alloys with **commercial reactor grade purity** using low-temperature synthesis (300–340°C)
- Input metals: 99.99 wt% Pb, 99.98 wt% Li.
- Metallic impurity total < 20 ppm per batch up to **20× purer** than other commercial suppliers.

## 4. Solution: Experimental Set-up

INL will employ TGAP at the STAR facility to quantify tritium solubility and diffusivity in four PbLi chemistries:

(1) High-purity eutectic PbLi
(2) Li-depleted PbLi (Pb-5Li)
(3) PbLi with oxide impurities
(4) PbLi with metallic corrosion products (Fe, Cr, Mo)

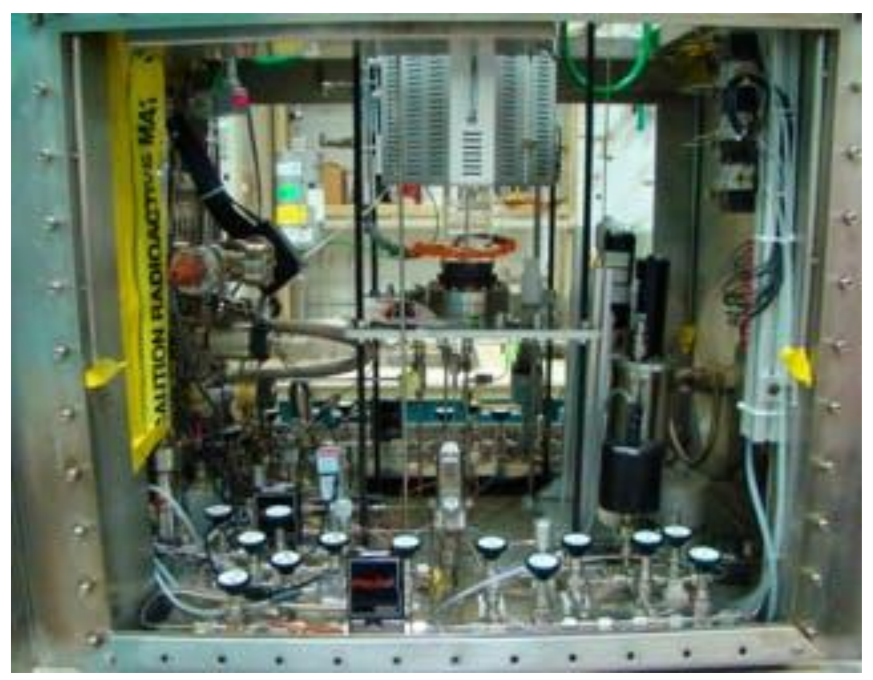

*Fig 2. Tritium Gas Absorption Permeation (TGAP) Experiment*

*Fig 3. The TGAP experiment enclosure*

These tests will determine how PbLi chemistry influences Sieverts' constants, using tritium gas absorption and permeation kinetics. Results with form a new validated database for use in **TES models** and **blanket simulations**.

## 5. Solution: Simulation Validation

Data is interpreted with **TMAP8** in the MOOSE framework, **coupling** diffusion, solubility, and surface kinetics. Simulations quantify how chemistry shifts extraction efficiency and feed directly into vacuum-permeator design (PAV) for blanket systems.

## 6. Extraction Systems

Tritium extraction efficiency governs safety margins. In a 500 MW$_{th}$ pilot reactor (FNSF-DCLL), extraction efficiency of **95%** corresponds to **6.2 g T/y** permeation loss, while **70%** efficiency raises losses to **38 g T/y**, potentially exceeding NRC dose limits. By quantifying how impurities and Li depletion alter tritium solubility, this project provides the data necessary to:

1. Optimize **vacuum-permeator sizing** and **membrane selection**
2. Define **impurity thresholds** for fuel-cycle safety analyses
3. Support **qualification** of EX-Fusion PbLi as a reference material for U.S. blanket R&D

## 7. Market Opportunity

| Type of Contract | Horizons | Quantities per deal | Anticipated revenue per deal | Anticipated number of deals |
|---|---|---|---|---|
| National Labs & Universities | 2025+ | 1 – 100 kg | $1k – $10k | ~100+ between 2025-2040 |
| Fusion Developers (experimental scale) | 2028+ | 10 – 200 kg | $5k – $100k | ~10+ between 2025-2040 |
| Fusion Developers (blanket scale) | 2030+ | 10,000 – 100,000 kg | $1M – $10M | 3-5 between 2030-2040 |

High-purity PbLi remains **unavailable** commercially. EX-Fusion's process establishes a scalable route for fusion-grade breeder and coolant supply while highlighting the need for **standardized** specifications (composition, impurity thresholds, and QA).

## 8. References

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