



The Need for Codes and Standards in Eutectic Lead-Lithium Manufacturing for Breeder Blanket Applications

Technical Meeting on Experience in Codes and Standards for Fusion Technology
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Max Monange
Head of EX-Fusion America | Reactor Systems Lead
max_monange@ex-fusion.com

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(I) INTRODUCTION

1.1. About EX-Fusion



~50 people



Osaka, Headquarters



Kyoto, Laser Processing



United States,
Reactor systems



Tokyo, lead-lithium
synthesis



Hamamatsu, R&D



Australia

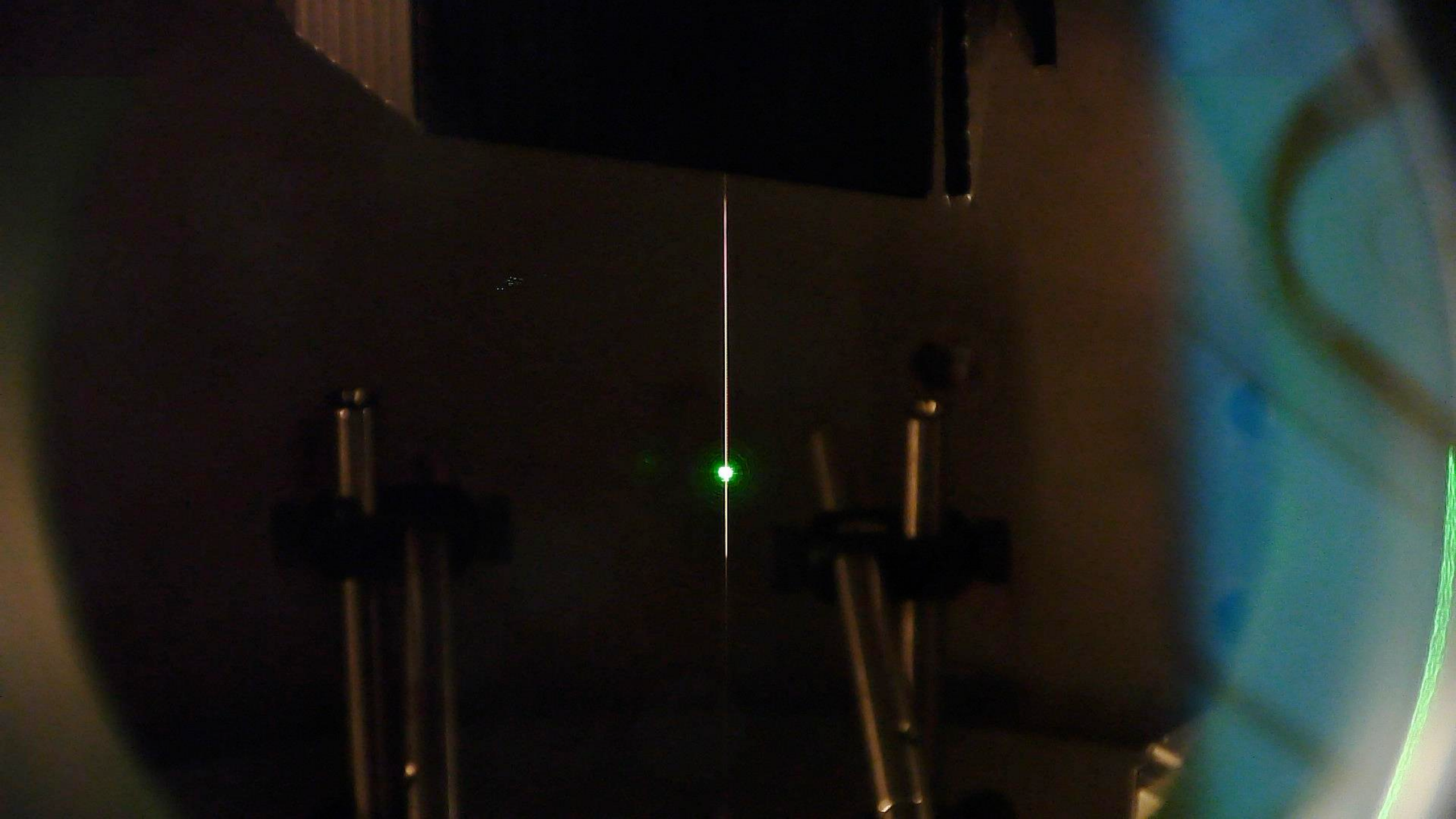


R&D Partners Japan



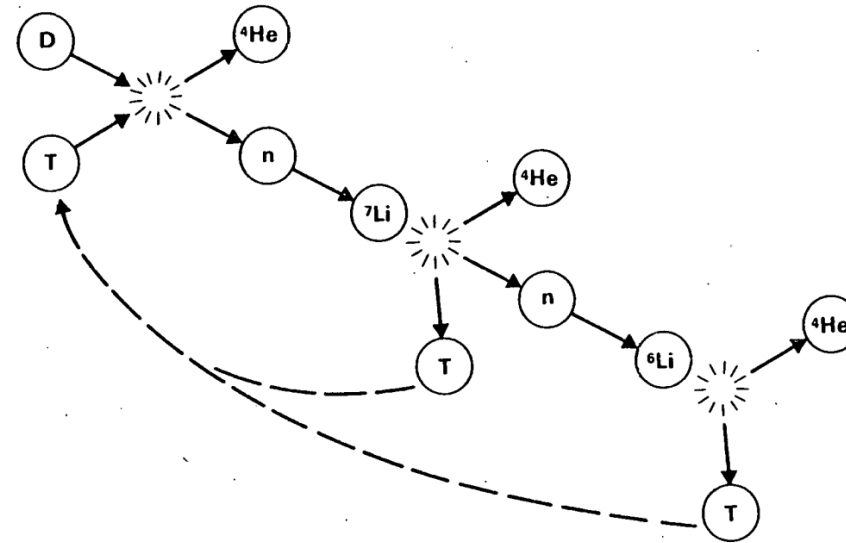
R&D Partners U.S.A





1.2. Tritium breeding

- Tritium is bred in a fusion reactor in the breeder blanket where neutrons interact with lithium to produce tritium.
- The liquid breeders of current interest include **Li**, **PbLi**, and **FLiBe**.



- It is estimated that a 3 GW fusion reactor will require around **168 kg** of tritium per year of operation [[T. Tanabe, 2017](#)].
- Current commercial world inventory is estimated to be around 20–40 kg.

1.3. Liquid coolant / breeders comparison

Breeder / Coolant	PbLi	Li	2LiF-BeF ₂
Melting point (eutectic) [°C]	235	180.5	459
Density [kg m ⁻³]	~9500	505	~2000
Thermal conductivity [W m ⁻¹ K ⁻¹]	15-35	40-60	0.57-1.1
Viscosity [mPa s]	0.7-0.9	0.3-0.6	9.5 -13.5
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, ^{235/8} U
Tritium extraction practicality	Proven, continuous (PAV, GLC)	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 and low viscosity.
- ⊗ However, it can suffer from severe **tritium permeation** issues in structural materials and low specific heat (leading to sharper temperature gradients).

(II) PROBLEM & IMPACT

2.1. The need for high purity PbLi

- Fusion industry requires industrial-scale supply of **high-purity PbLi** for breeder blanket systems across multiple reactor concepts.
- **Current suppliers** (e.g., Stackhow Metals, Camex Spol) produce **low-purity PbLi** unsuitable for fusion environments.
- Major inconsistencies in PbLi from commercial suppliers, with **metallic impurities ranging from dozens to hundreds of ppm** (up to ~400 ppm of Bi, Cu, Fe, Sn, Zn) [[B. Garcinuño, 2022](#)]



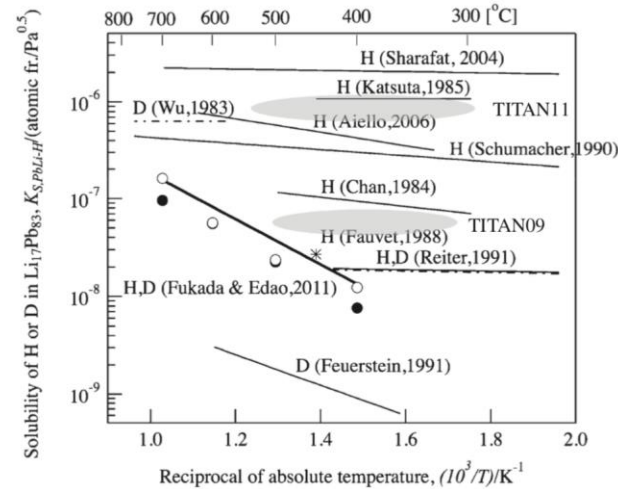
2.2. Impacts of impurities

Elevated impurity levels are linked to:

1. **Significantly altered tritium solubility** (including unexpectedly high hydrogen solubility even at lower lithium concentrations)
2. **Corrosion damage to structural materials**
3. **Production of long-lived radioactive isotopes** upon irradiation

- Many suppliers **do not provide full impurity analyses**, preventing suitability verification for fusion use.
- **Lack of quality control and standardization** in the commercial PbLi supply chain poses a **critical challenge** to fusion development.

2.2. Impacts of impurities: Background on Tritium solubility

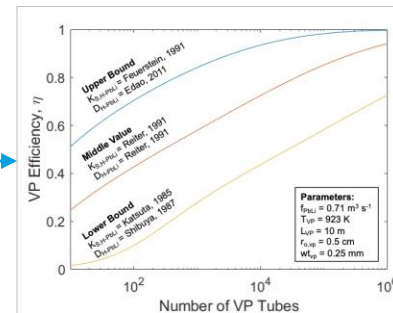


High versus low values for tritium solubility in PbLi affect how easily the tritium will precipitate out of the alloy.

Engineering

Using the ranging Sieverts' constants...

- Could cause the PAV to have **2-10× the tube length** required to extract tritium [C. Taylor, 2024]
- Would mean the extraction efficiency could range from 40-90% for a given number of vacuum permeator (VP) tubes



Safety & regulation

Tritium extraction efficiency governs safety margins...

E.g. in a 500 MW_{th} pilot reactor 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 [C. Taylor, 2024].

2.2. Impacts of impurities: (a) Tritium solubility

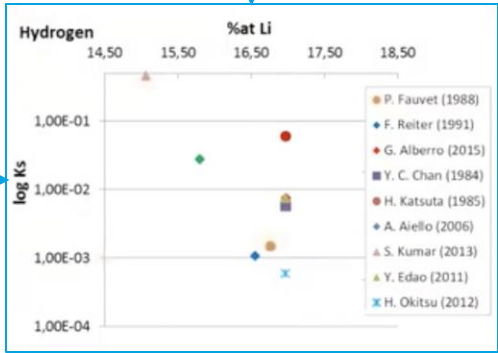
1. Impurities significantly altered tritium solubility

Impact of impurities on solubility

- Impurities tends to **increase** the solubility of tritium in PbLi
- [B. Garcinuño, 2022] compared data from all studies known to have performed hydrogen/deuterium solubility measurements in PbLi.
 - Only 5 of the 11 reports provided any information about the initial impurities in their starting PbLi sample.
 - None reported on the composition following the experiments.

Ref.	% at. Pb	% at. Li	Impurities
P. Fauvet	83.00	17.00	Not known
F. Reiter	82.97	16.46	<20 ppm (Fe, N, C)
G. Alberro	83.03	16.97	73 ppm (As, Fe, P, S)
C.H. Wu	83.00	17.00	Not known
Y.C. Chan	83.00	17.00	Not known
H. Katsuta	83.00	17.00	Not known
A. Aiello	84.20	15.80	<0.1 wt% (<1000 ppm)
S. Kumar	83.01	14.72	800 ppm (Fe, Na, Ni, Bi)
H. Feuerstein	83.24	16.76	64 ppm (Na, As, Ag, Zn, Fe, Cr, Ni, Mn, Sr, Mo, U, Sn, Se, Sb, Cd)
Y. Edao	83.00	17.00	Not known
H. Okitsu	83.03	16.97	Not known

[B. Garcinuño, 2022]'s data from all studies known to have performed hydrogen/deuterium solubility measurements in PbLi

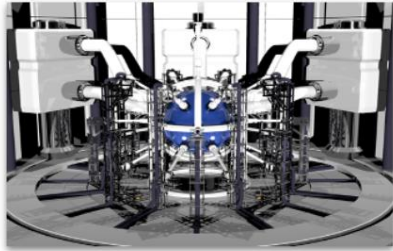


Solubility constant vs. %at Li for

Validation through DOE: INFUSE awarded for FY2025

INFUSE Technical Narrative

Title: Evaluating the impact of lead-lithium purity on tritium transport



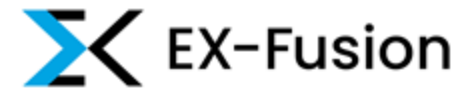
Company PI: Max Monange
Head of EX-Fusion America – EX-Fusion Inc.
max_monange@ex-fusion.com

INL co-PI: Thomas F Fuerst
Research Scientist – Idaho National Laboratory
thomas.fuerst@inl.gov

INL co-PI: Pierre Clement Simon
Computational Scientist – Idaho National Laboratory
pierreclement.simon@inl.gov

EX-Fusion America was awarded a U.S. Department of Energy (DOE) Grant ([INFUSE](#)) on “*Evaluating the impact of lead-lithium purity on tritium transport properties*” in partnership with Idaho National Laboratory.

U.S. DOE Fusion Energy Science (FES) recognizing our high purity fabrication method and the need for quality insurance standards when it comes to blanket coolant / breeder fabrication.

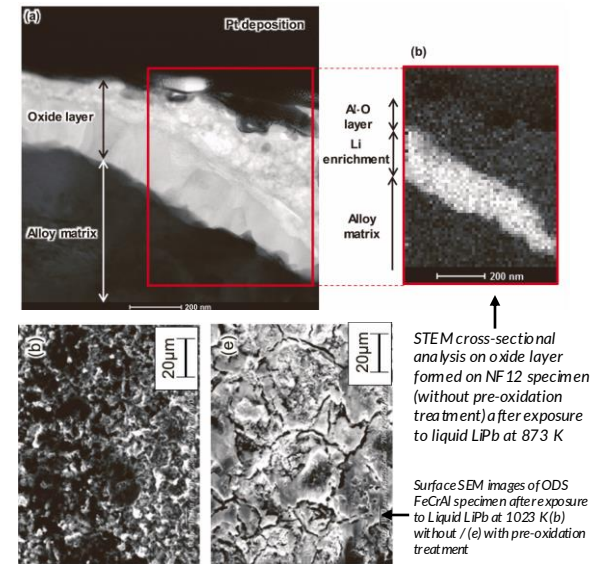


2.2. Impacts of impurities: (b) Corrosion damage

2. Impurities impact on corrosion to structural materials

Impact of PbLi corrosion

- PbLi is extremely corrosive at high temperatures ($>400^{\circ}\text{C}$).
- Liquid PbLi readily leaches Ni and Cr from stainless steels.
- Lithium preferentially binds with O (vs. Pb) which strips away the protective oxide (e.g., chromium oxide or aluminum oxide) that forms on steels.
- Leaching effects increase as temperature increases



Impact of PbLi impurities on corrosion



Though oxygen is known to attack metals

2.2. Impacts of impurities: (c) Irradiation

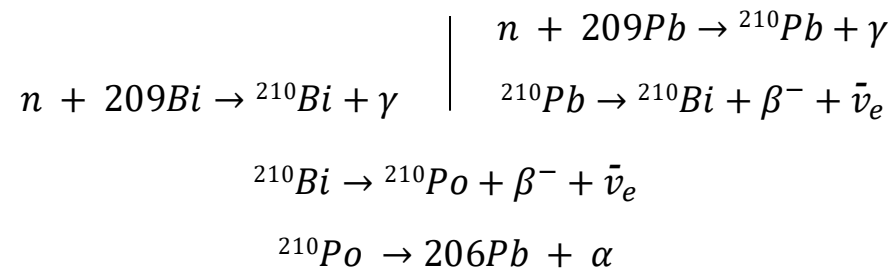
3. Impurities can lead to the production of long-lived radioactive isotopes upon irradiation

Impact on solubility

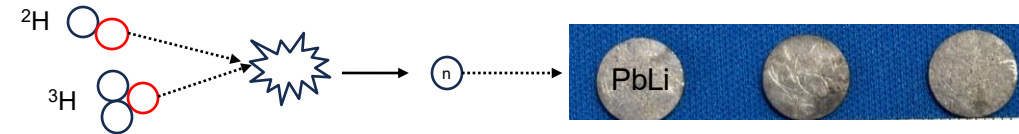
- Bismuth is a common impurity in commercial Pb, and the solubility of hydrogen in PbBi has been shown to be very low
- Effects of ^{210}Po 's impact on tritium solubility has never been investigated

Impact on safety

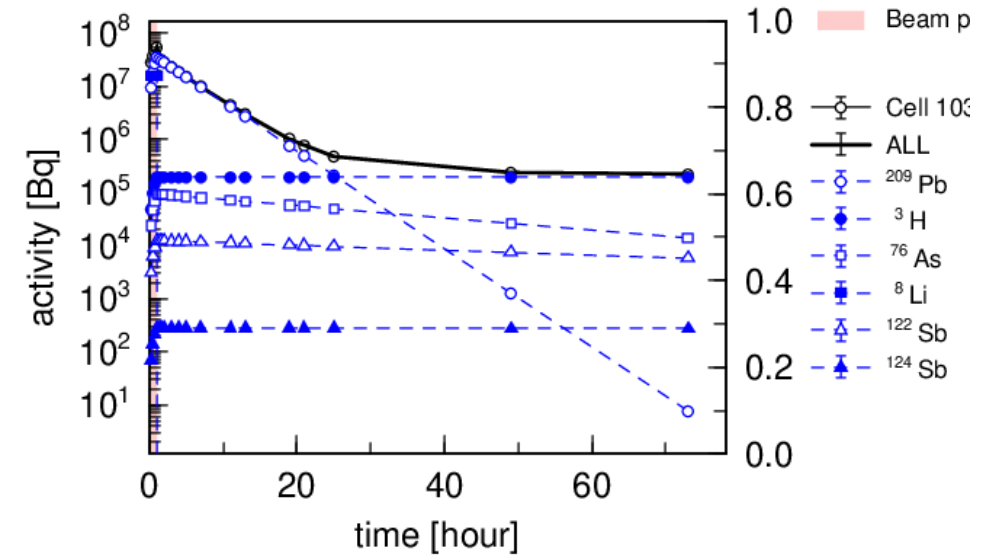
- In irradiation scenarios:



- Other Major Radioactive Nuclides : ^{209}Pb , ^3H , ^{76}As , ^8Li , ^{122}Sb , ^{124}Sb



- Li (Na, Ca, K Fe Si, N, Cl)
- Pb (Sn, Sb, Bi, Cu, Zn, Fe, As, Cd, Ag, Al)



DT irradiation of PbLi given impurity content measured in EXF-LL1 raw materials (Simulation ran in PHITS)

2.3. Impacts of chemical composition

4. Chemical composition affects Tritium solubility constant + thermophysical properties

- The eutectic value of PbLi recently changed: Pb-17Li → Pb-15.7Li (at%)
- A **lower lithium concentration** in PbLi **decreases** hydrogen solubility
- The solubility of deuterium in PbLi was shown to decrease by a factor of 10× as the atomic concentration of Li in PbLi decreases from 20 to 0 at.% [\[Wu et al., 1983\]](#) [\[C. Taylor, 2024\]](#)
- Tight control of the lithium concentration during the synthesis process is required

Breeder / Coolant	PbLi
Melting point (eutectic) [°C]	235
Density [kg m ⁻³]	~9500
Thermal conductivity [W m ⁻¹ K ⁻¹]	15-35
Viscosity [mPa s]	0.7-0.9
Specific heat [kJ kg ⁻¹ K ⁻¹]	0.19

(III) Synthesis Process

3.1. EXF synthesis program: Controlling impurities during synthesis

- Properties of PbLi are **highly dependent on purity**, and Li is easily oxidized during the alloying reaction with Pb
- PbLi must be synthesized under conditions that remove as much **non-metallic** and **metallic** impurities as possible.



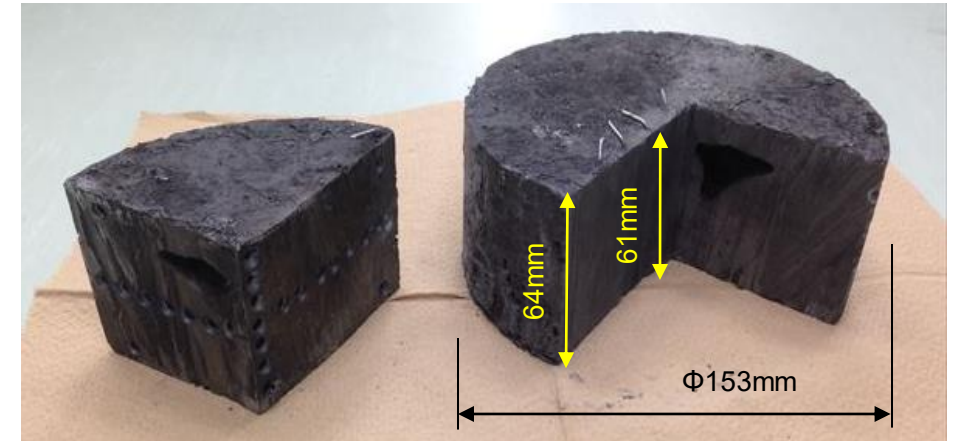
corrosion concern



Irradiation concern



EXF-IST Tokyo signing ceremony (October 2023)



High purity LiPb ingot (10 kg)

- EX-Fusion has synthesized PbLi alloys with commercial reactor grade purity.
- The first batch (EX-LLE-1) was a 10 kg (about 1 L) synthesis experiment conducted from **March 28, 2025** (start of synthesis) to **April 1, 2025** (extraction).

3.2. Two types of impurities found in commercial suppliers

Impurities can be introduced by:

1. Raw materials used for the production and nuclear processes.
2. Corrosion reactions with structural and auxiliary materials.
3. Contamination with atmospheric gases (during fabrications or operations).

Non-metallic impurities

Origins: **O, C, N, H**

- $\text{Li} + [\text{O, C, N, H}] \rightarrow \text{Salt}$
- $\text{PbLi} + [\text{CO, CO}_2, \text{O}_2, \text{H}_2\text{O}] \rightarrow [\text{Li}_2\text{O, PbO}]$

Metallic impurities

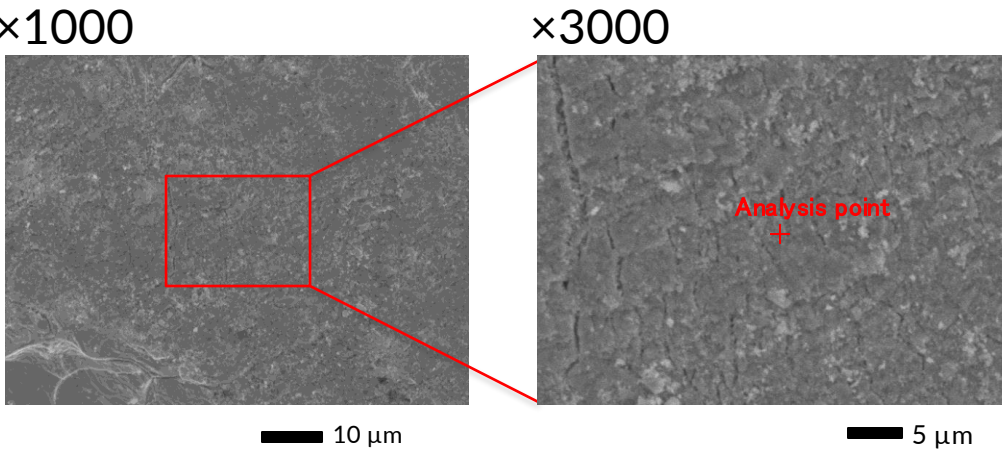
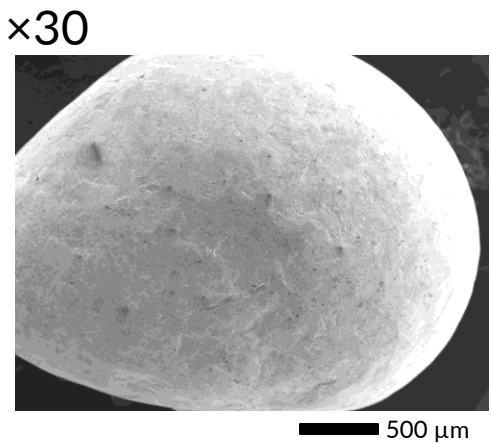
Origins: **Ag, Al, Au, As, Bi, Cd, Cu, Cr, Fe, Ga, Hg, Mn, Nb, Ni, P, Pd, Sb, Si, Sn, Ti, V, W, Zn**

3.3. Material Selection: Pb raw materials

- Pb (melting point: 327.5°C)
- High purity grain 99.99 wt% purity
- Provider: Sasaki Solder Industry

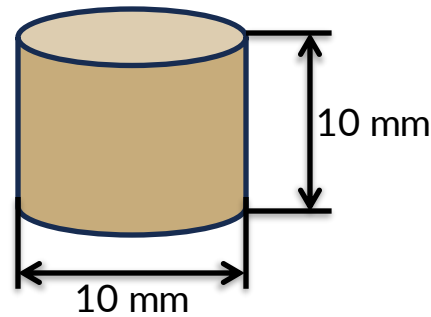
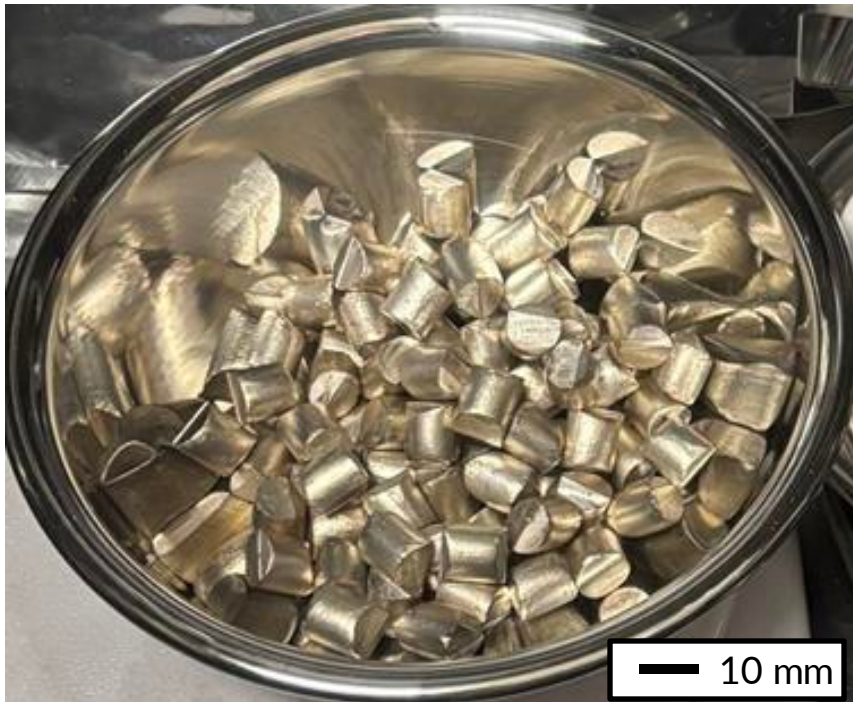


Element	Percentage [wt%].
Pb	remainder
Sn	<0.0001
Sb	<0.0001
Bi	<0.0001
Cu	<0.0001
Zn	<0.0001
Fe	0.0006
As	<0.0001
Cd.	<0.0001
Ag	<0.0001
Al	<0.0001



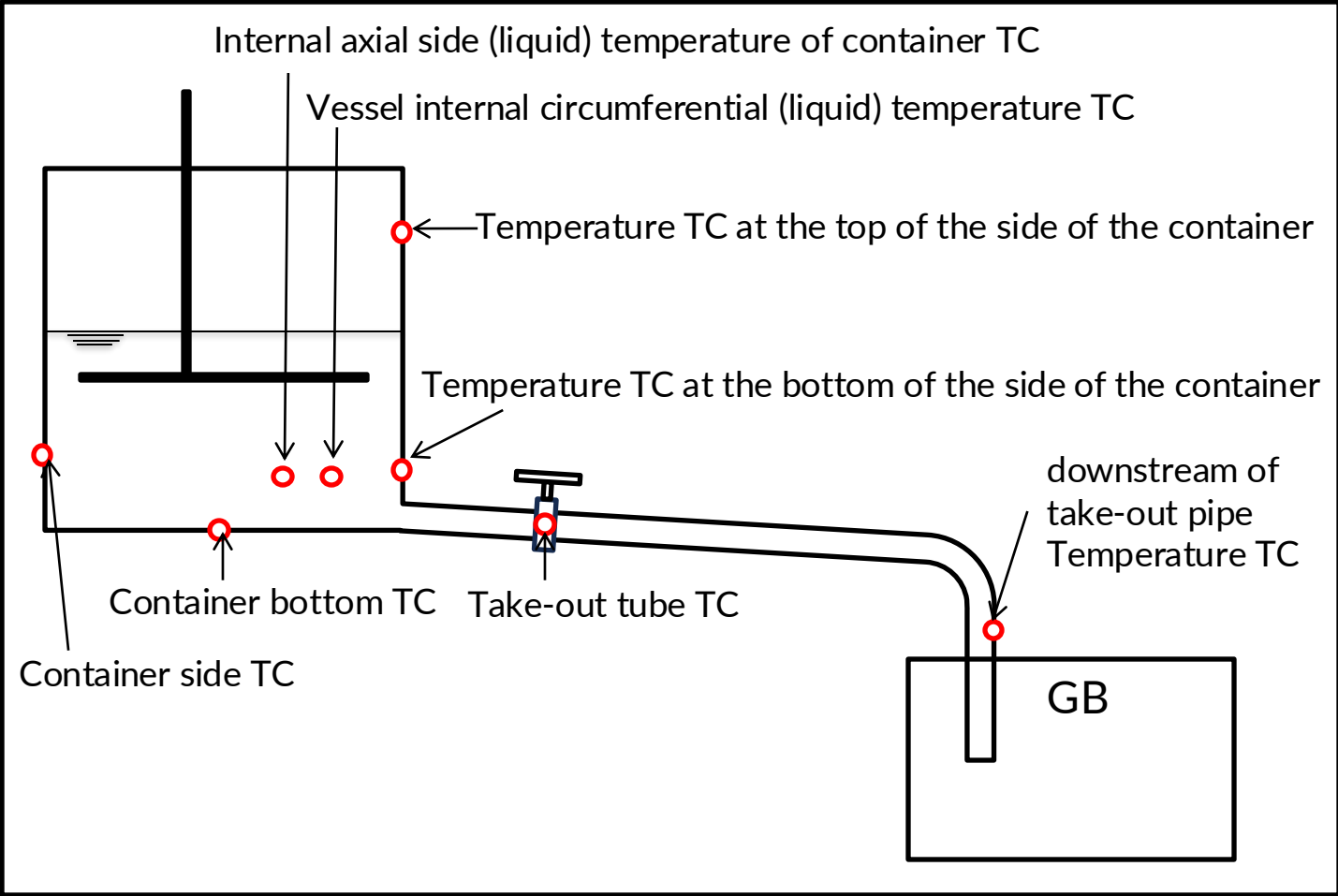
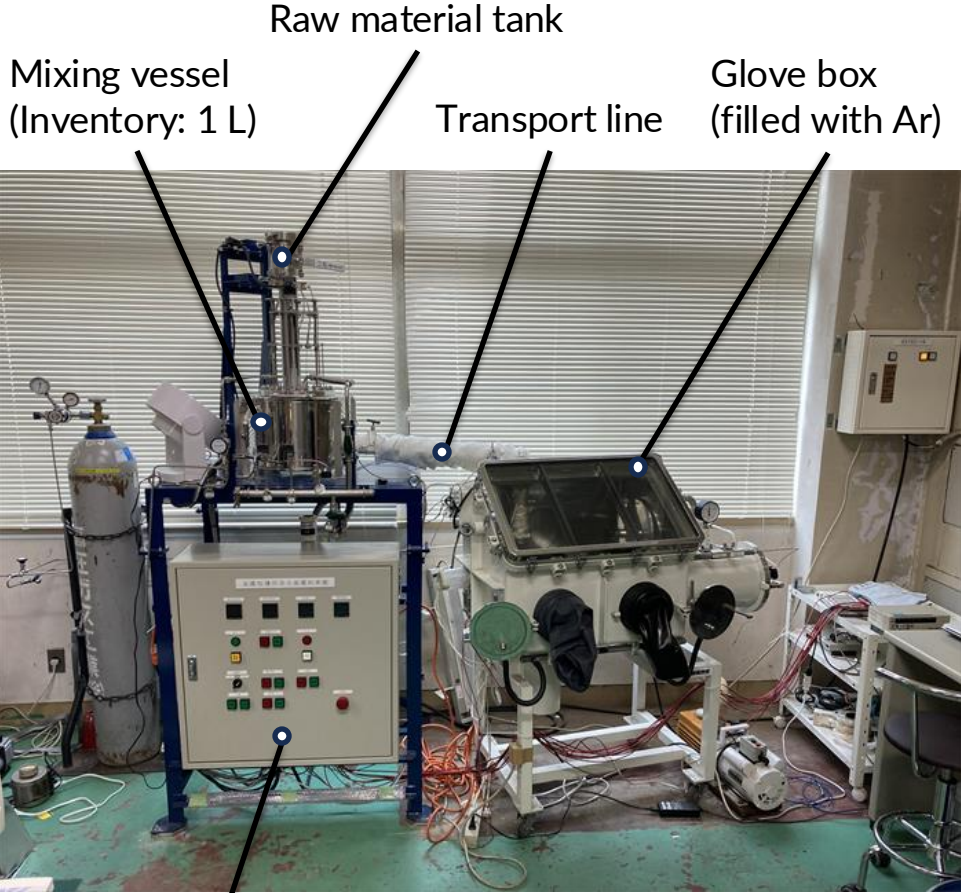
3.4. Material Selection: Li raw material

- Li (melting point: 180.5°C)
- High purity grain 99.98 wt% purity
- Provider: Honjo Chemical Co.



Chemical element	Percentage [wt%].
Li	99.980
Na	0.002
Ca	0.004
k	0.001
Fe	0.001
Si	0.001
N	0.009
Cl	0.001

3.5. Experimental device



Heater and temperature monitoring thermocouple position for agitator

3.6. Raw Materials – Pre-loading

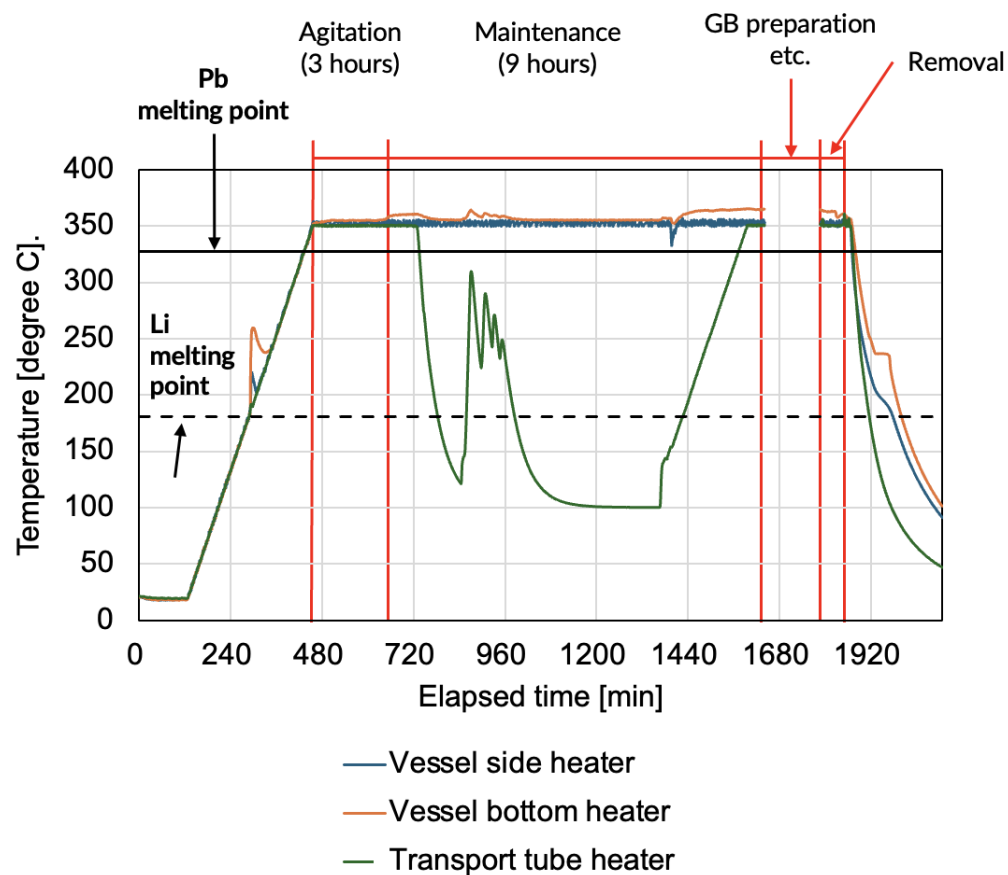


Mixed raw materials (100 cc)

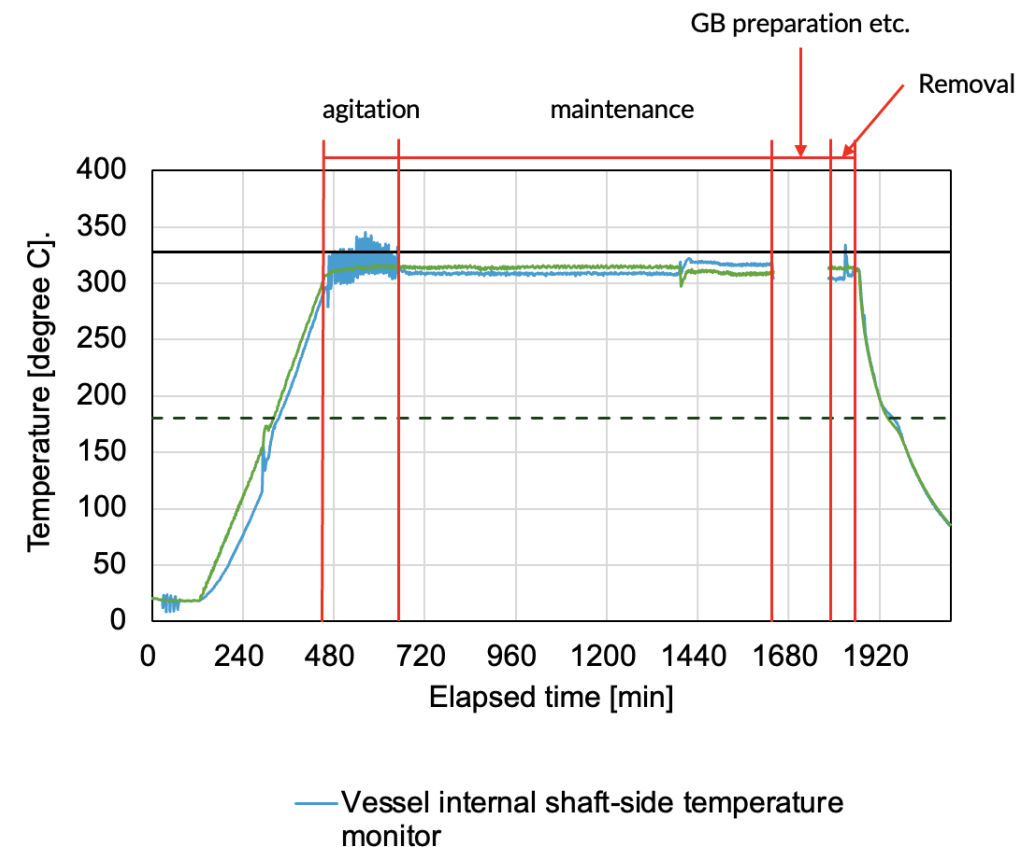


Condition after loading the crucible with raw materials (400 cc)

3.7. Temperature change during synthesis



Heater Temperature



Liquid temperature (in-vessel)

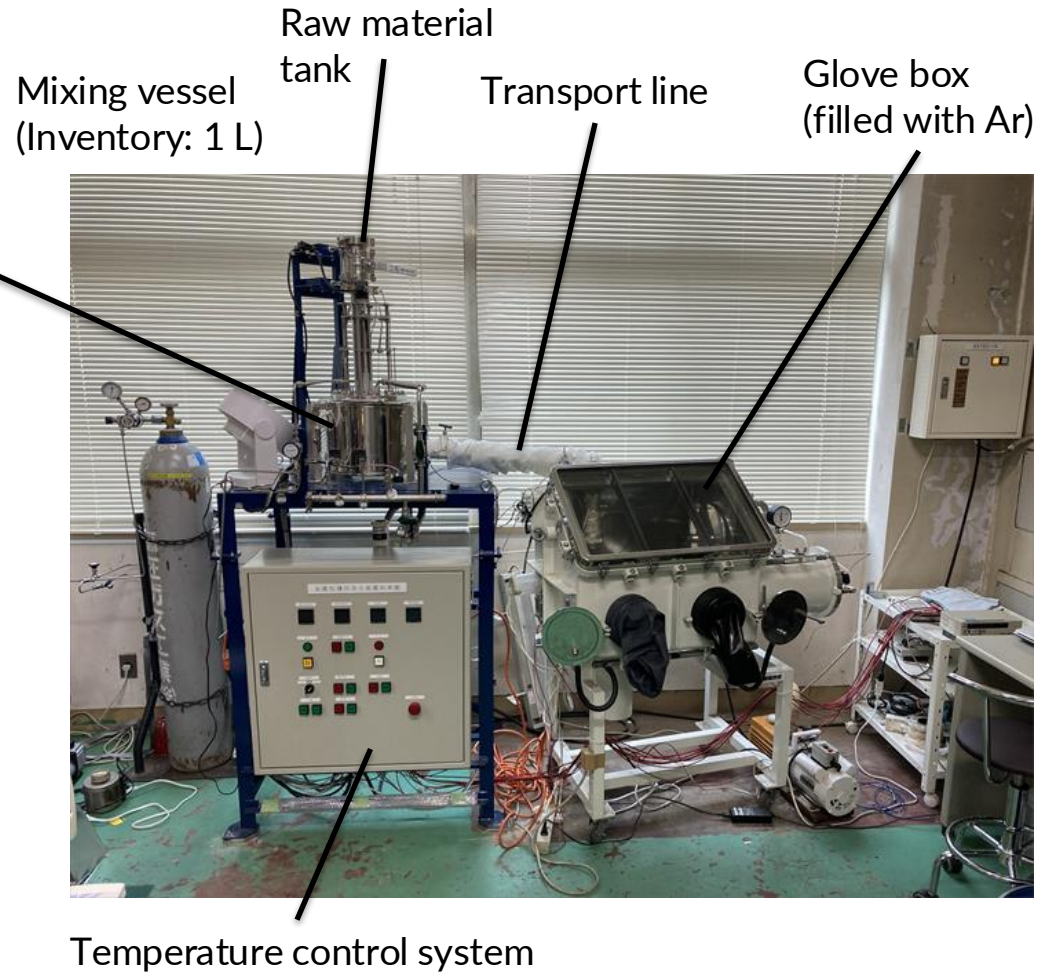
(IV) Synthesis Results

4.1. PbLi “coins”



Mixed raw materials (100 cc)

- Naturally enriched eutectic Pb-17Li
- Melting point @235°C
- Control of metallic, oxide, nitrogen impurities



4.2. Comparison of EXF-LLE-1 batch purity to industry

M. Kondo 08/2025 – measured via ICP-OES

[B. Garcinuño, 2022] on Stachow and Camex samples? – measured via ICP-MS

Batch #	EXF-1	EXF-2	EXF-3	EXF-4	EXF-5	EXF-6	S1-B1	S1-B2	S1-B3	S2	S3
Na	151	110	102	123	112	83	-	-	-	-	-
Bi	9	8	7	9	8	-	17.5	22.03	61.8	107	48
Fe	<3	<2	<1	<4	<1	<6	9.35	79.51	<14.00	<13.00	<14.00
Cr	<3	<2	<1	<4	<1	<3	0.27	14.25	<14.00	<13.00	<14.00
Ni	-	-	-	-	-	-	0.23	2.54	<14.00	<13.00	<14.00
Mn	-	-	-	-	-	-	1.9	0.3	<14.00	<13.00	<14.00
Ag	-	-	-	-	-	-	3.95	10.64	<14.00	16	<14.00
Cu	-	-	-	-	-	-	7.2	103.57	70	<13.00	<14.00
Sb	-	-	-	-	-	-	0.1	0.99	<14.00	<13.00	<14.00
Sn	-	-	-	-	-	-	5.95	86.53	152.6	<13.00	<14.00
Ti	-	-	-	-	-	-	0.1	5.2	<14.00	<13.00	<14.00
Zn	-	-	-	-	-	-	0.1	78.25	<14.00	<13.00	<14.00
Total (with Na)	166	122	111	140	122	92	46.65	403.81	396.4	240	188
Total (w/out Na)	15	12	9	17	10	9	46.65	403.81	396.4	240	188

Impurity specifications in PbLi eutectic (all concentrations in wppm)

4.3. Comments on synthesis results: (a) in Numbers

On average, our first batches contained **half** the metallic impurities compared to other suppliers

x2

If sodium contamination is removed, impurity levels would improve by **up to x21**

x21

Measured composition: **Pb–17Li (at.%)**, demonstrating precise control of lithium content.

17 at.%

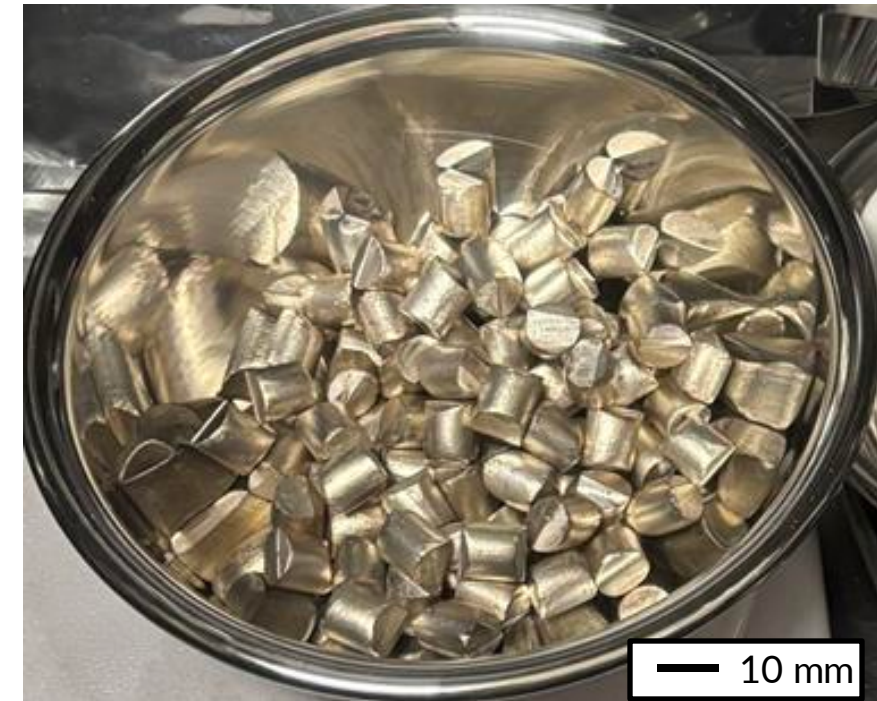
- Only one competitor's batch (S1-B1) outperformed EX-Fusion's first batch but other batches from same supplier (S1) did not maintain the same consistency.
- Additional factors to consider (not included in the table): Deviation from the eutectic composition (17 at.% Li), presence of non-metallic impurities, and the total number of different metals detected in each sample.

4.3. Comments on synthesis results: (b) Sodium impurities

EXF batches 1-6: Sodium impurity content currently under investigation

Candidates include:

1. Trace Na in the Li grain from the supplier
2. Contamination introduced during handling/cleaning or from consumables
3. Matrix/measurement effects in the ICP workflow



Lithium raw material

4.3. Comments on synthesis results: (c) Measurement

Different measurement methods

- [[B. Garcinuño, 2022](#)] measured metallic impurities using Inductively Coupled Plasma Mass Spectrometry (ICP-MS).
- Kondo used Inductively Coupled Plasma – Optical Emission Spectroscopy ICP-OES (also known as ICP-AES).



ICP-MS



ICP-AES

The key differences

- **ICP-MS** has a **lower detection limit** (down to ~0.01 ppb), allowing quantification of ultra-trace impurities, whereas **ICP-OES** typically detects at the low-ppb to ppm range.
- ICP-MS separates ions by **mass-to-charge ratio**, making it more sensitive for elements present at very low concentrations.
- Both methods require **acid digestion** of the PbLi sample before analysis, but Garcinuño note using a **simple nitric acid digestion** for small amounts of PbLi (~0.010 mg) prior to ICP-MS.

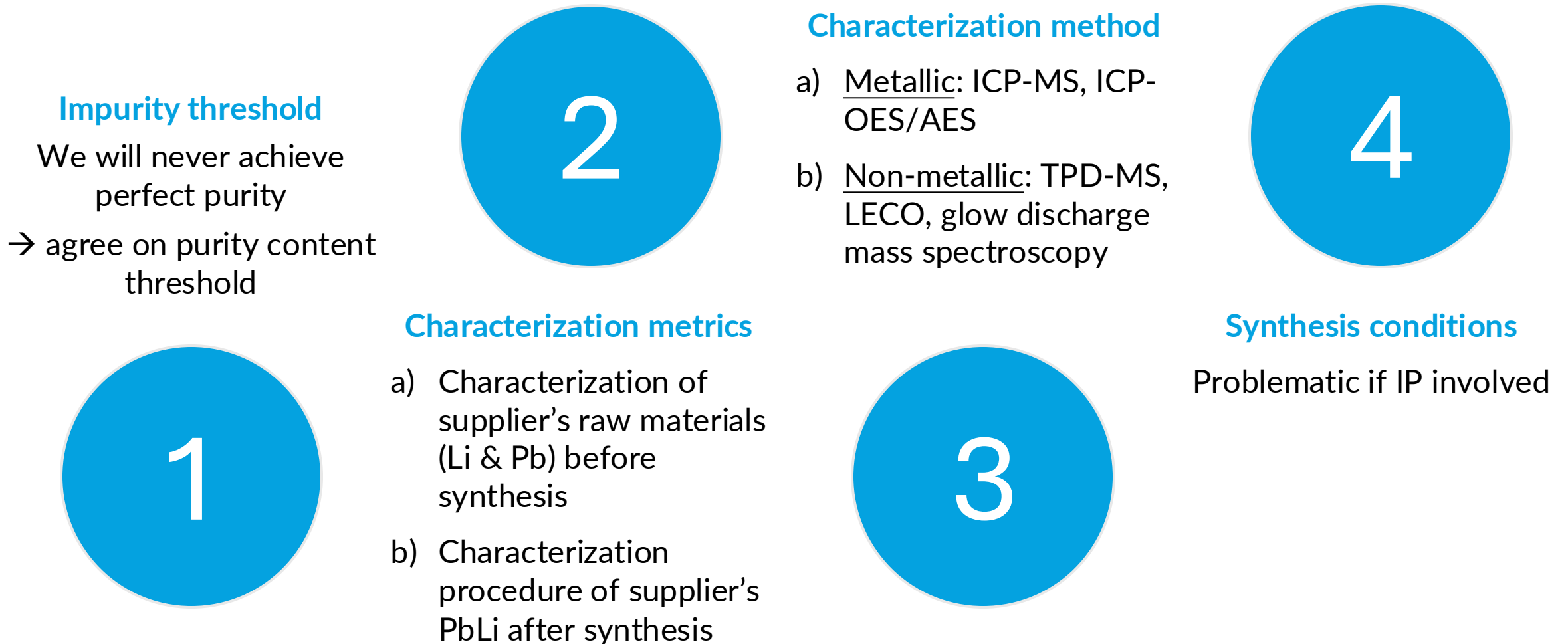
4.3. Comments on synthesis results: (c) Measurement

- Still awaiting on non-metallic impurity analysis: O, N, C content
- Problem: requires expensive diagnostics equipment
- Can be done via **TPD-MS** desorption analysis or **LECO**



(V) Codes and Standards Requirements

5.1. What do we need to standardize?



5.2. Conclusion

- The **~four-order-of-magnitude** spread in reported H/D solubility constants makes it impossible to **size a tritium extraction system** for an FPP with confidence, let alone select the most appropriate **extraction technology** for the true solubility regime.
- Hydrogen solubility in PbLi is highly sensitive to variations in **lithium concentration** and to the **presence of impurities**.
- Despite decades of laboratory studies, the link between PbLi chemistry and hydrogen solubility has largely been **neglected**.
- These effects will become even more pronounced in an operating tritium extraction loop, where the **chemistry evolves continuously**.
- In practice, any fusion power plant will need **real-time monitoring** of PbLi chemistry to account for lithium burnup, corrosion products, and transmutation effects.

References

- [1] [Thomas F. Fuerst](#), Foundational Research on Tritium Transport Phenomena in Liquid Breeder Blankets, Idaho National Laboratory
- [2] [Chase Taylor](#), ECRA proposal, PbLi impurities, Idaho National Laboratory
- [3] [B. Garcinuno et al.](#), Establishing technical specifications for PbLi eutectic alloy analysis and its relevance in fusion applications, CIEMAT, Laboratorio Nacional de Fusion



Max Monange
Head of EX-Fusion America | Reactor Systems Lead

max_monange@ex-fusion.com