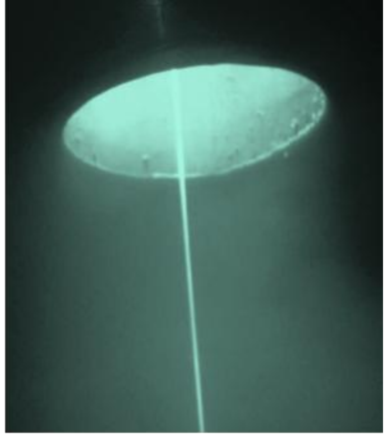
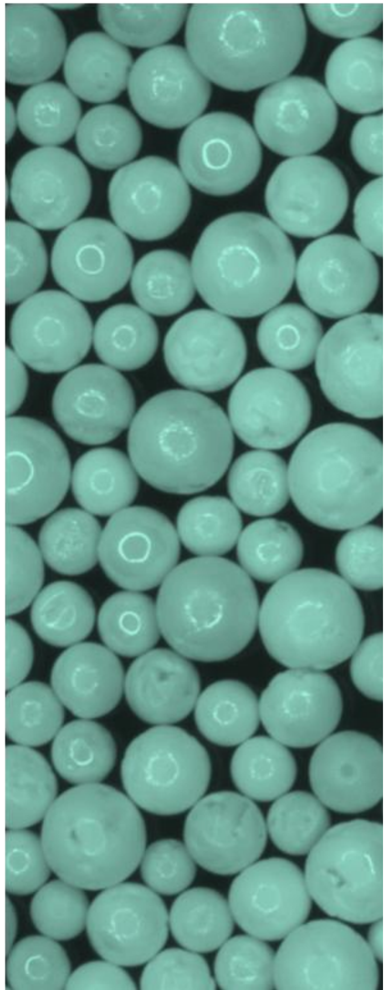
# Tritium Breeding Ceramics for Nuclear Fusion





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# 1. Introduction

- Tritium breeding for fusion using $^{6}Li$
- Material requirements and challenges

# 2. Advanced Ceramic Breeders

- R&D activities at KIT
- Production of ACB pebbles
- Material qualification
- Material recycling

# 3. Summary

# Tritium Breeding for Fusion

Plasma: $D + \boxed{T} \rightarrow {}^{4}He + n + 17.6\ \text{MeV}$

Blanket: ${}^{6}Li + n \rightarrow {}^{4}He + \boxed{T} + 4.8\ \text{MeV}$

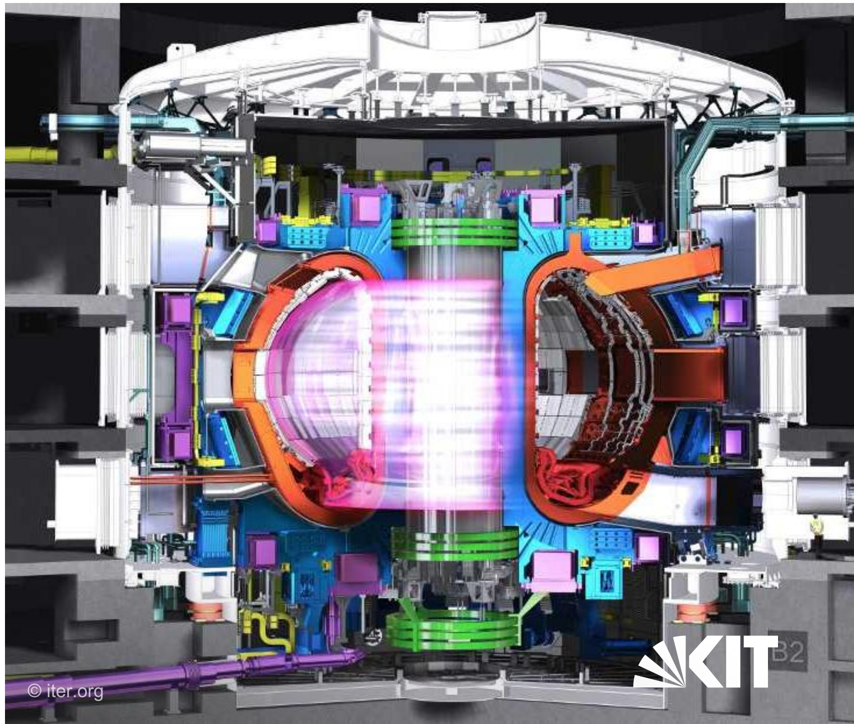
| | |
|---|---|
| **3** | **6.94** |
| 0.98 | [He]2s1 |
| | 181 |
| | 1347 |
| **Li** | |
| Lithium | |

## Lithium

- Melting point: 181 °C
- Very reactive
- Natural $^{6}Li$ abundance: 7.6 at%

## Neutron multiplier

- Pb, Be



# Tritium Breeding Materials – Requirements

| Operability | |
|---|---|
| ▪ Tritium generation | → High Li-density & low T-trapping |
| **Reliability** | |
| ▪ Neutron irradiation | → Phase equilibria upon Li-burn-up |
| | → Low activation of elements beside Li |
| ▪ High temperatures | → High melting point / thermal conductivity |
| ▪ Mechanical stress | → Reasonable resilience |
| **Safety** | |
| ▪ Structural material compatibility | → Little interdiffusion |
| **Cost efficiency** | |
| ▪ Fabrication & recycling | → As easy as possible |

# Tritium Breeding Materials

- Liquid breeder blanket concepts → e.g. Li-Pb alloys
- Solid breeder blanket concepts → Li-ceramics
  - Well investigated breeder materials: $Li_2O$, $Li_4SiO_4$, $Li_8PbO_6$, $Li_2TiO_3$, $Li_2ZrO_3$, $LiAlO_2$
  - At KIT: Advanced Ceramic Breeder (ACB) material
    → Biphasic material, combining $Li_4SiO_4$ + $Li_2TiO_3$

# Advanced Ceramic Breeders (ACB)

- Biphasic pebbles consisting of $Li_4SiO_4$ and $Li_2TiO_3$
- ACB pebbles represent the EU reference tritium breeding material *(→ ITER, EU-DEMO)*

- Activities at KIT are focused on the process development and the material qualification
  - The production facility was recently converted from a batch process to a continuous operation *(production rate of 2 kg/h)*
  - Standard quality control
  - Testing material under extreme conditions

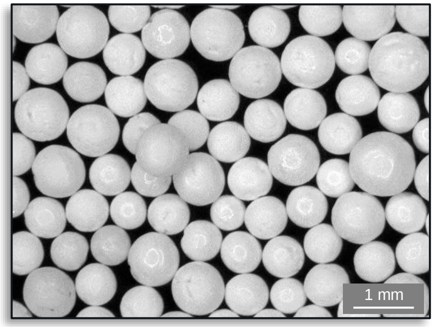
# ACB Pebble Production at KIT

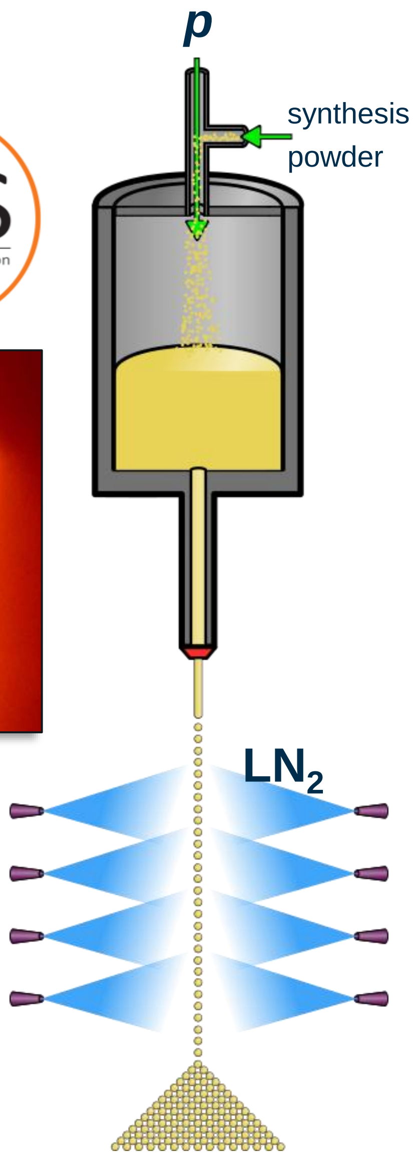
KALOS process *(KArlsruhe Lithium OrthoSilicate)*

- Raw materials: $LiOH \cdot H_2O$, $SiO_2$, $TiO_2$
  - Mixing, ~500 °C for 5 h, sieving
- Pretreated powder is melted at ~1400 °C
- Jet break-up with adjustable droplet size
- Solidification using liquid nitrogen

- Pebble size: 250–1250 µm
- Process yield: ~95 wt%

KALOS
Advanced Ceramic Breeder Production





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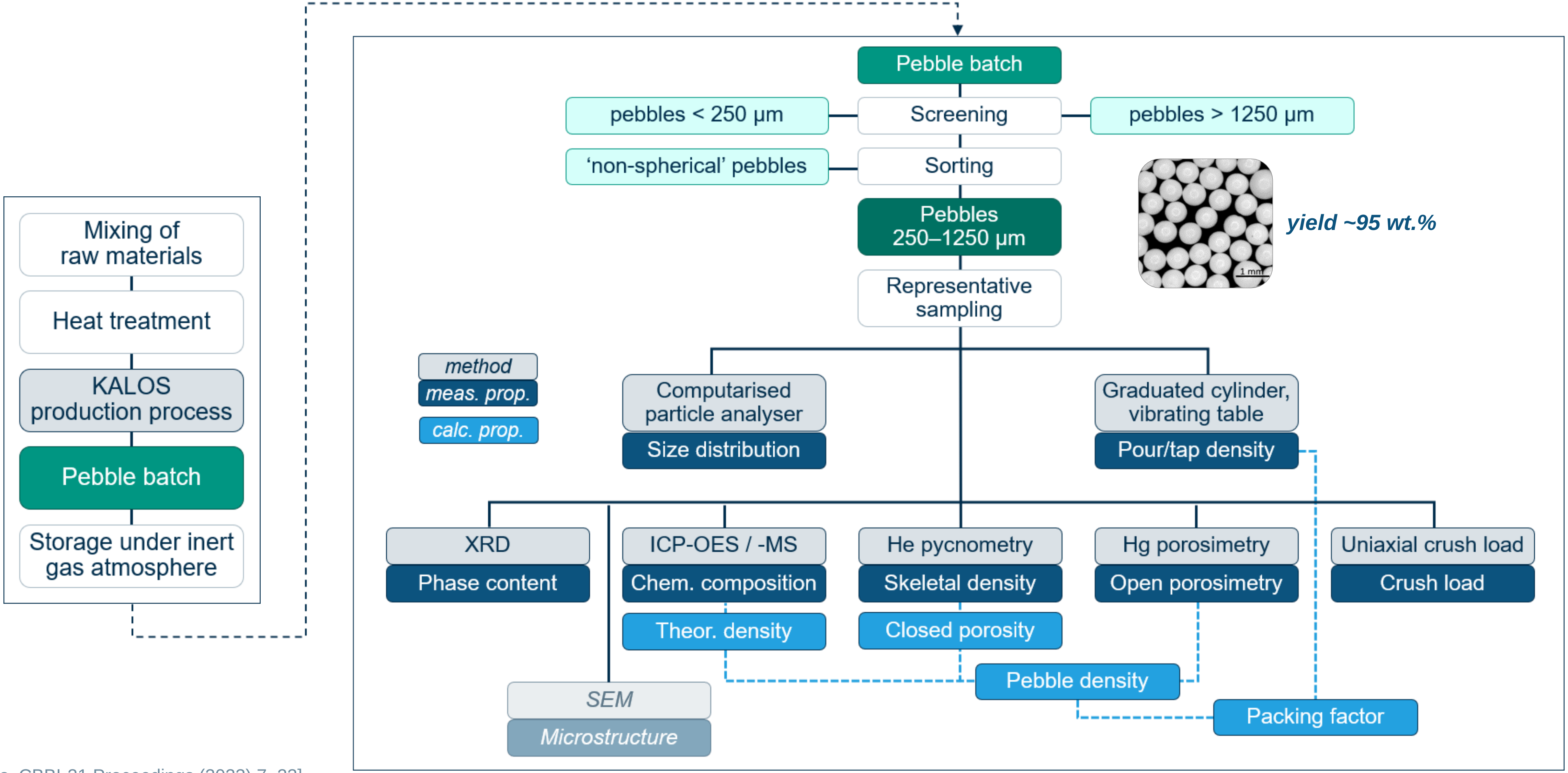
[O. Leys et al., FED 164 (2021) 112171]

# KALOS Production and QC Flow Chart

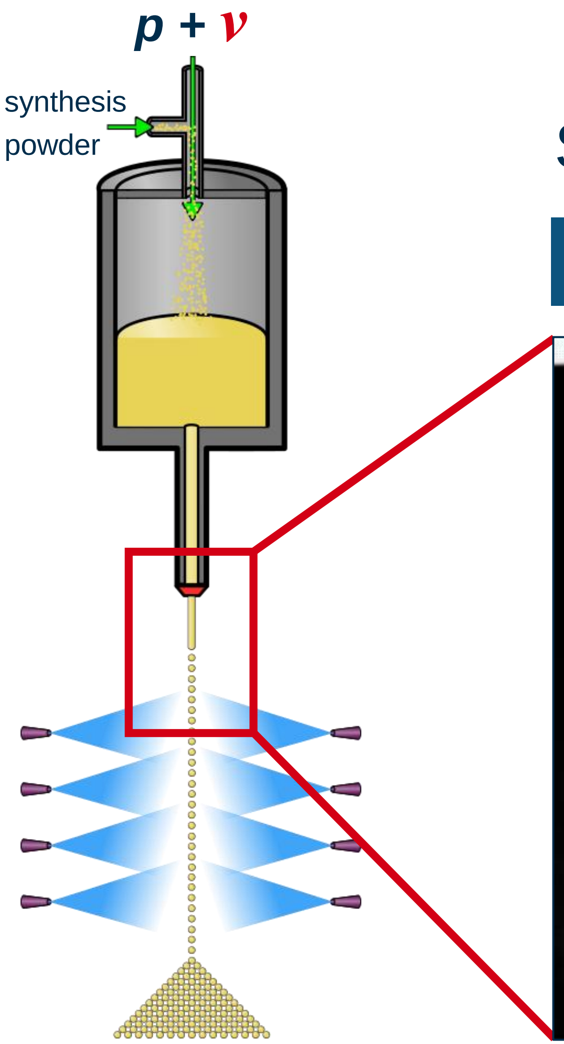
$LiOH \cdot H_2O$, $SiO_2$, $TiO_2$

– 44 wt.% $H_2O$



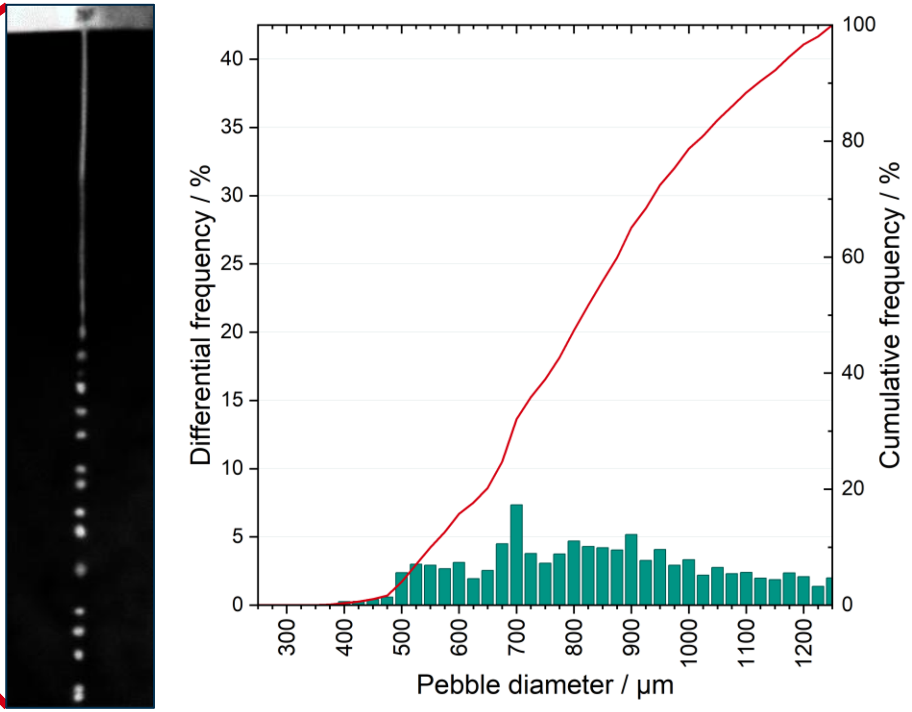

[Knitter & Zmitko, CBBI-21 Proceedings (2023) 7–23]

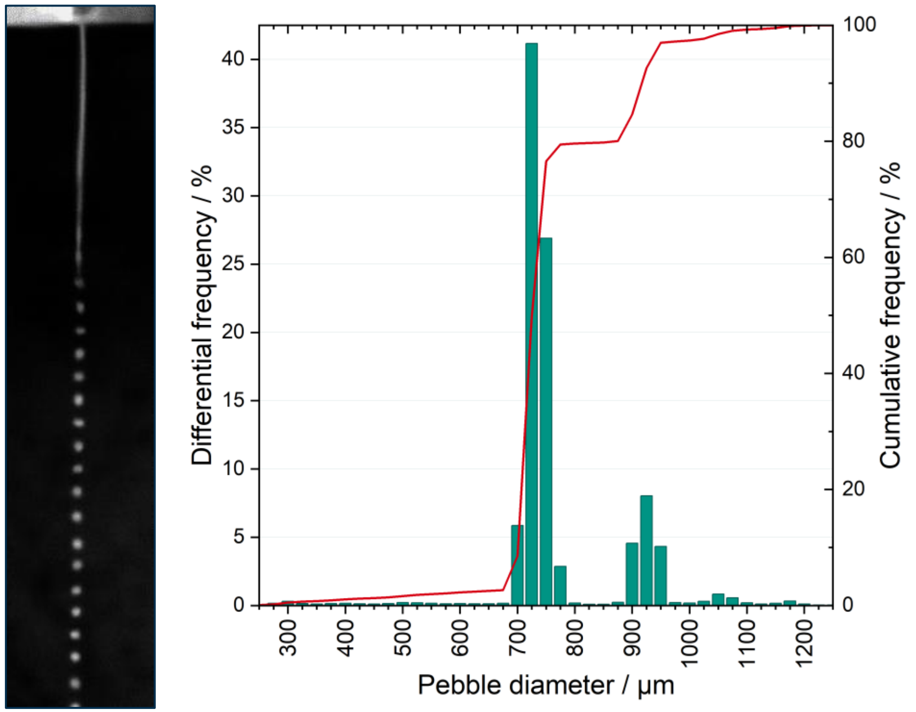
# ACB Pebbles – Size Distribution




Size distribution can be controlled by applying selected frequencies

| No frequency | Induced jet break-up |
|---|---|



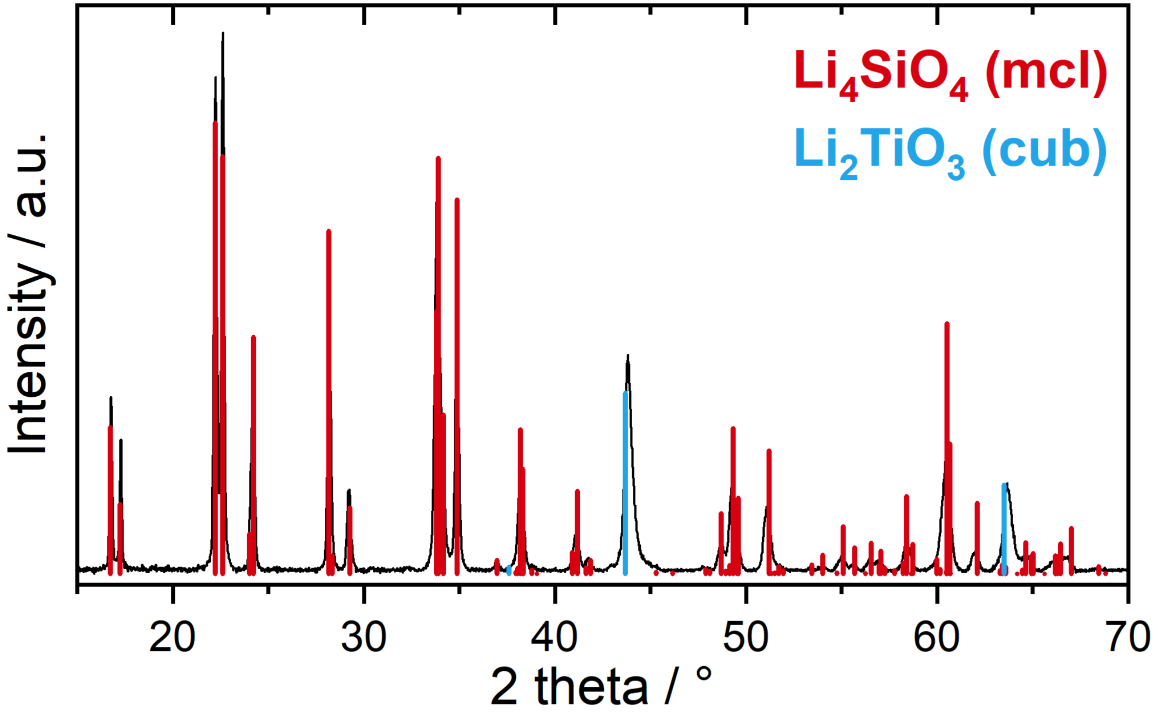




[O. Leys et al., IJAMT 98 (2018) 2311–2318; Zhang et al., IJAMT 136 (2025) 1253–1265]

# ACB Pebbles – Phase Composition & Microstructure

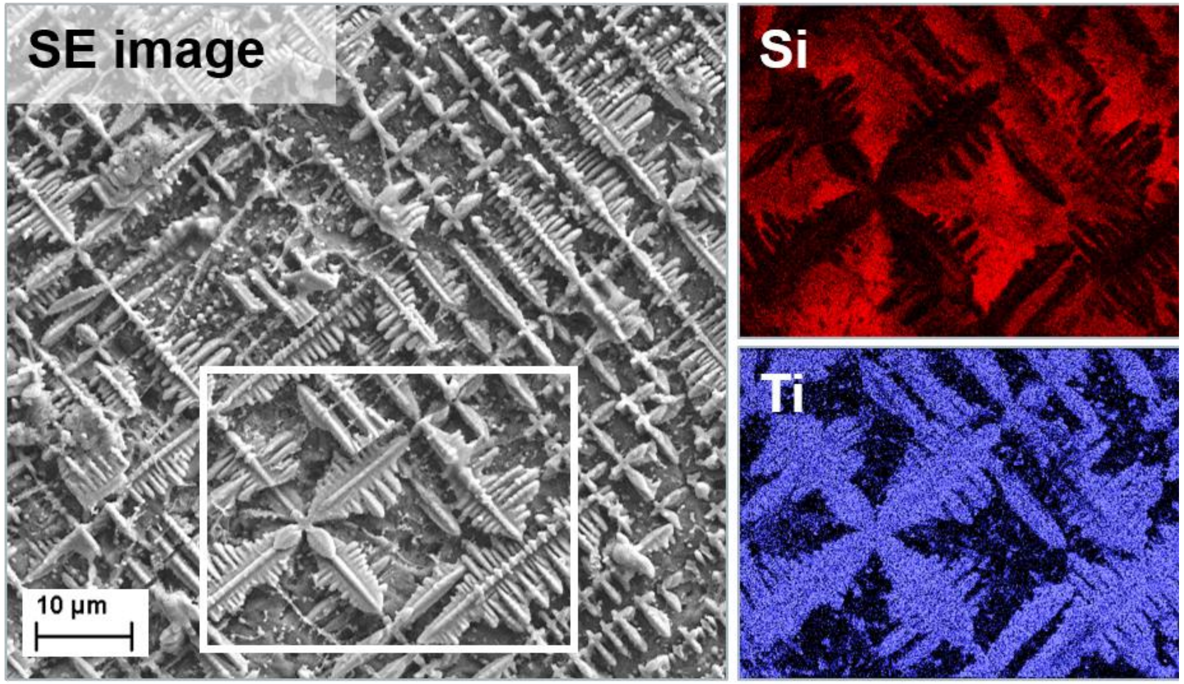
## Phase composition

Lithium orthosilicate + lithium metatitanate

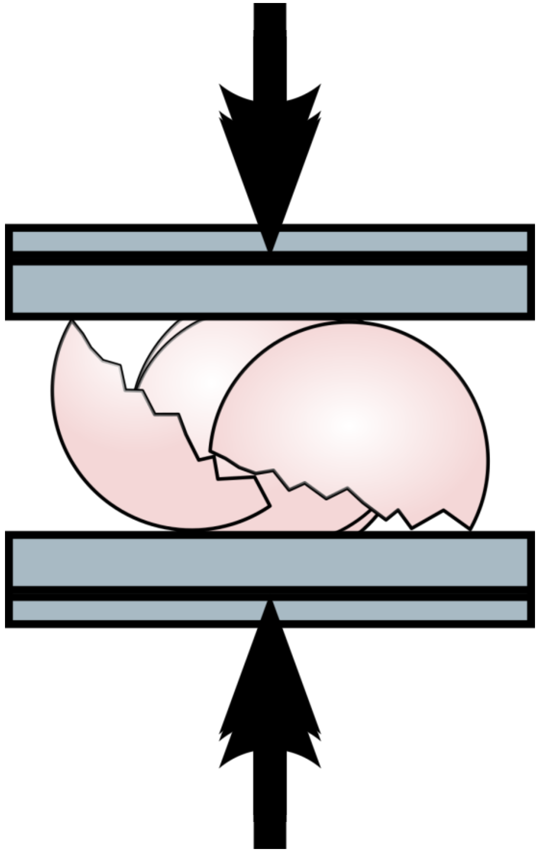



## Microstructure

$Li_2TiO_3$ dendrites & $Li_4SiO_4$ forming in between



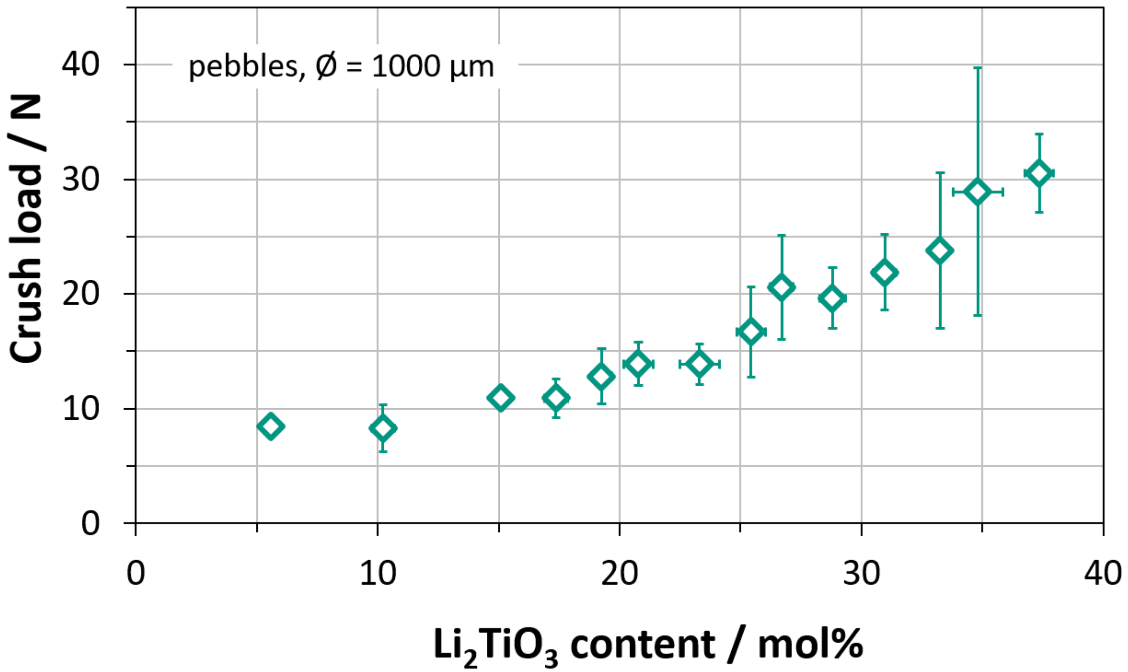
# ACB Pebbles – Mechanical Strength

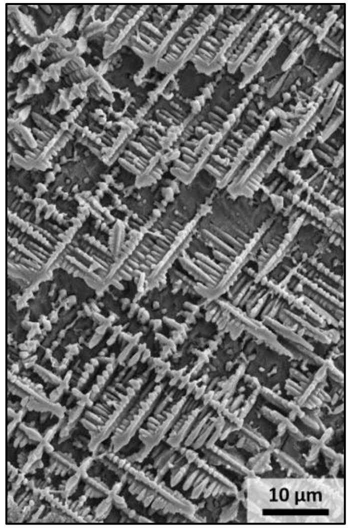


Uniaxial crush load tests

Main phase $Li_4SiO_4$ with additions of $Li_2TiO_3$

→ Higher mechanical strength with increasing $Li_2TiO_3$ content

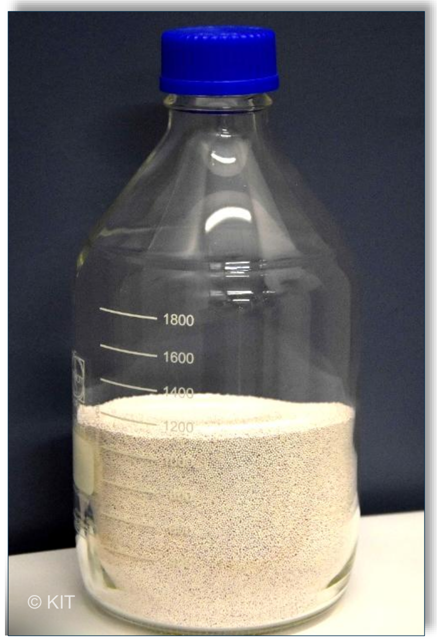



[O. Leys et al., FED 164 (2021) 112171]

# Characteristic Material Properties for ACB

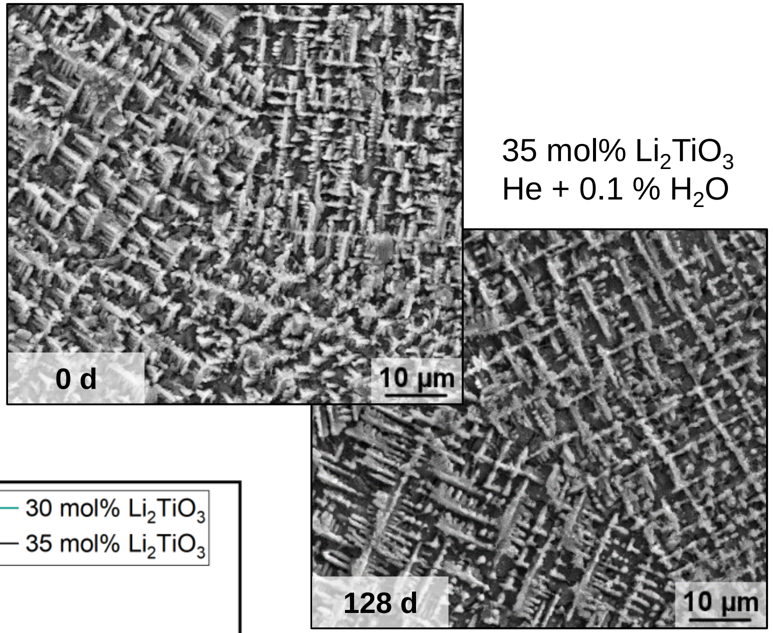
| | |
|---|---|
| **Phase composition** | $Li_4SiO_4 + Li_2TiO_3$ |
| **$Li_2TiO_3$ content** | 30–35 mol% $Li_2TiO_3$ (max. 40 mol%) |
| **Pebble size range** | 250–1250 µm (smaller range possible) |
| **Mean crush load** | ≥18 N … ≥22 N<br>(for 30 … 35 mol% LMT, Ø 1000 µm) |
| **Open porosity** | 3 ± 1 % |
| **Closed porosity** | 2 ± 1 % |
| **Relative pebble density** | 95 ± 1 % |
| **Pour density** | 58 ± 1 % |
| **Tap density** | 61 ± 1 % |
| **Packing factor** | ~ 64 % |

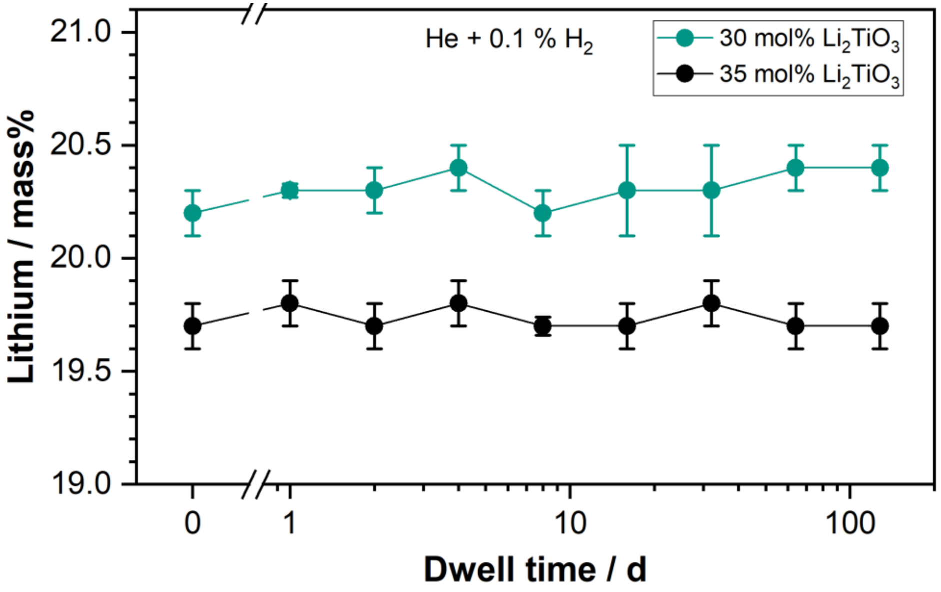


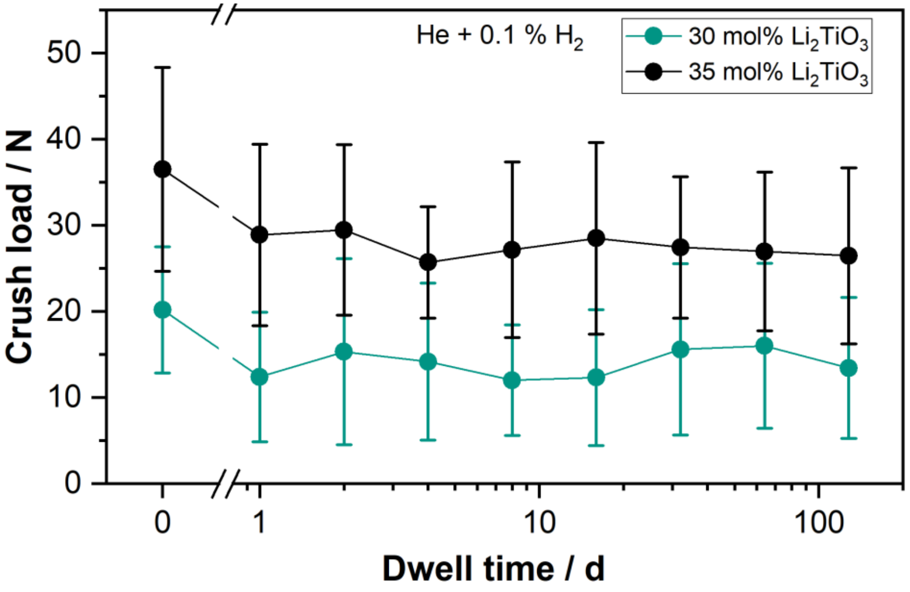

[O. Leys et al., FED 164 (2021) 112171;
Knitter & Zmitko, CBBI-21 Proceedings (2023) 7–23]

# Long-term Thermal Stability

- Thermal treatment at 900 °C for up to 128 days
- Gas atmosphere: He + 0.1 vol% $H_2$ / $H_2O$
  → High chemical and mechanical stability in both atmospheres
  → Stable microstructure with limited grain growth over time



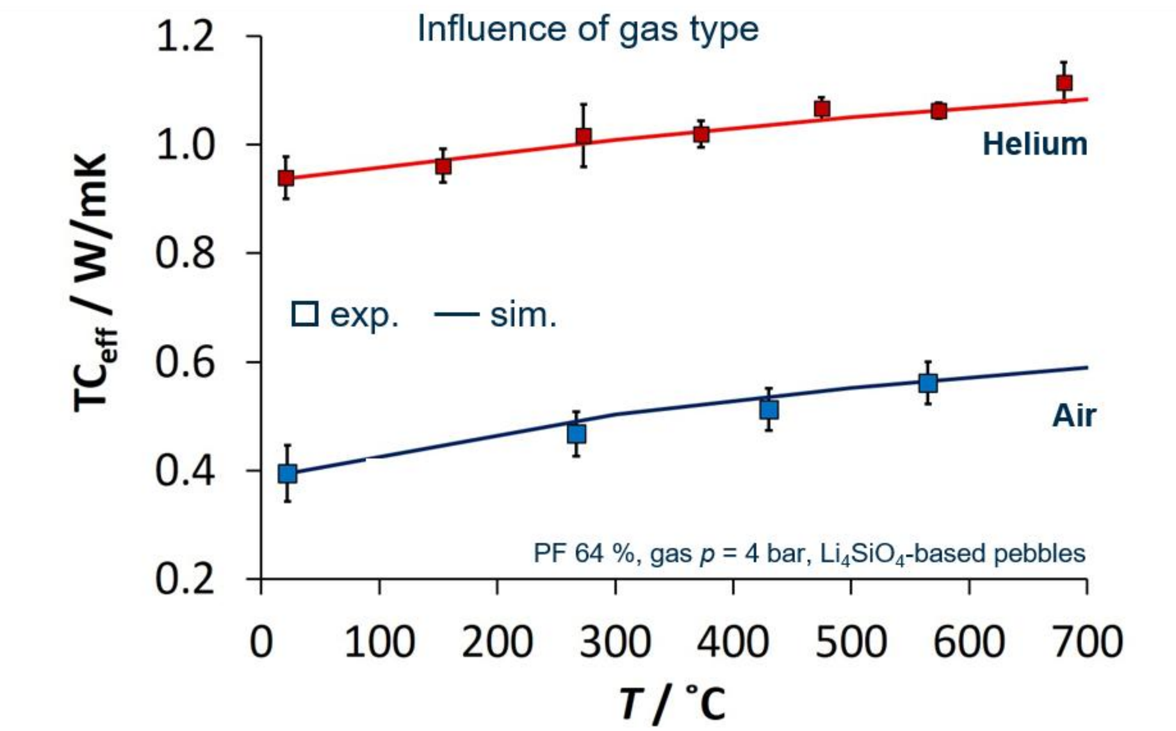



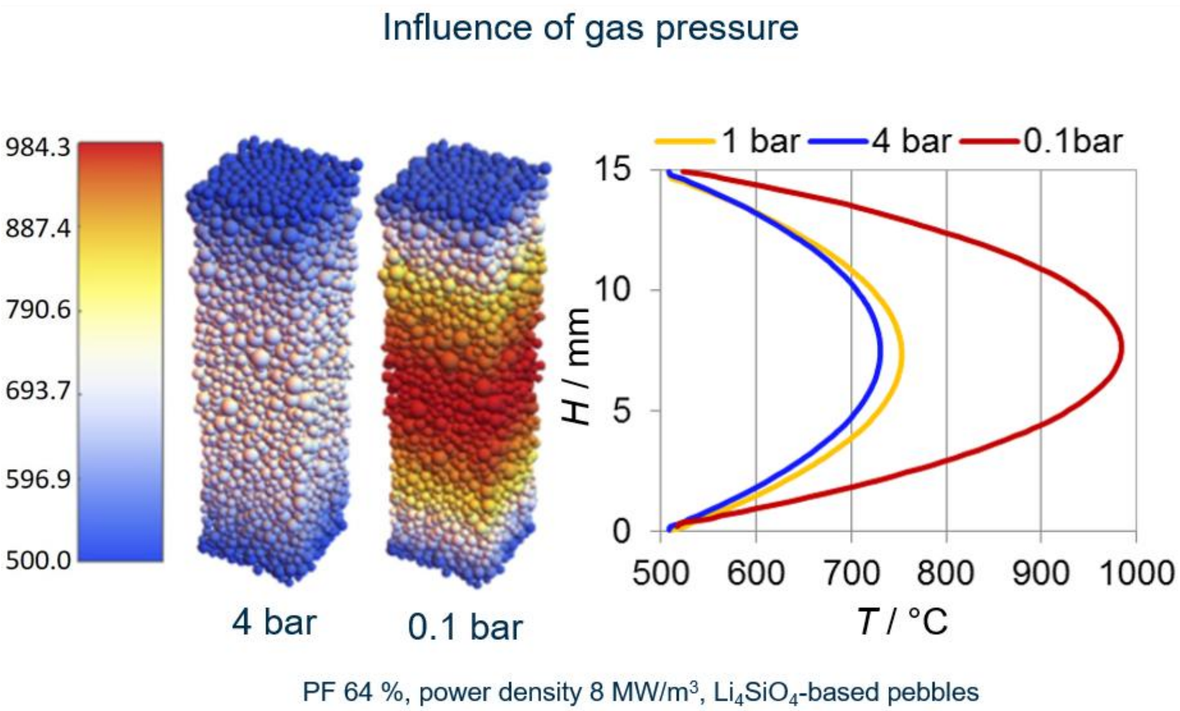

[Heuser et al., JNM 507 (2018) 396–402;
Leys et al., NME 43 (2025) 101932]

# Thermal Behaviour of Pebble Beds

Discrete Element Method to model the heat transfer in ceramic breeder pebble beds

| Effective thermal conductivity | Temperature profile |
|---|---|



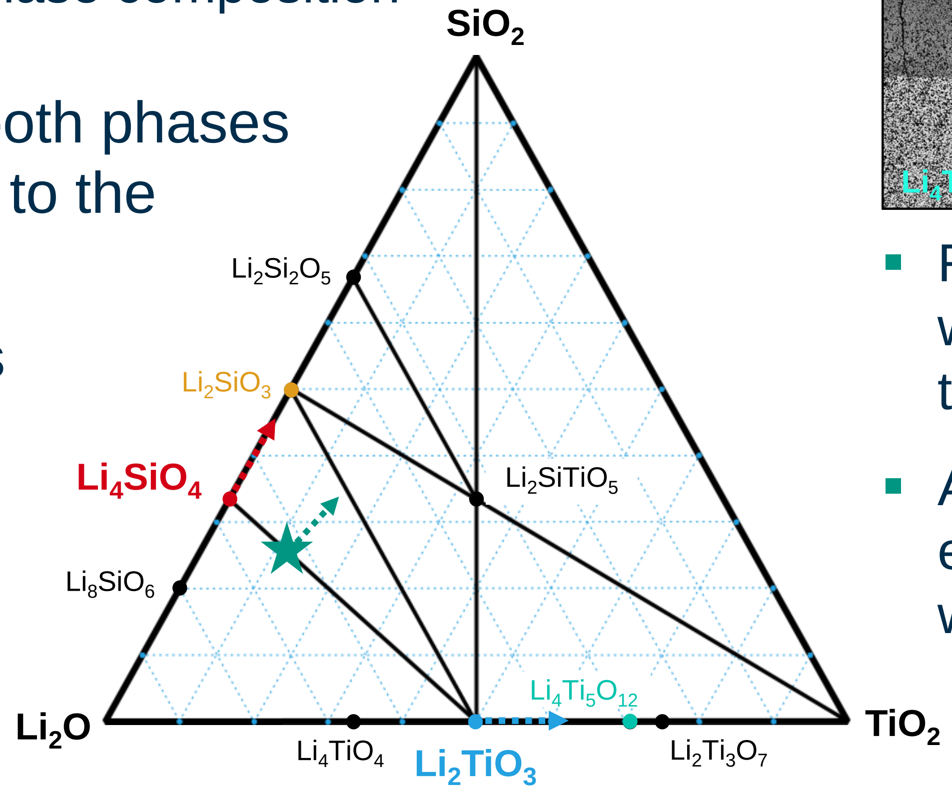



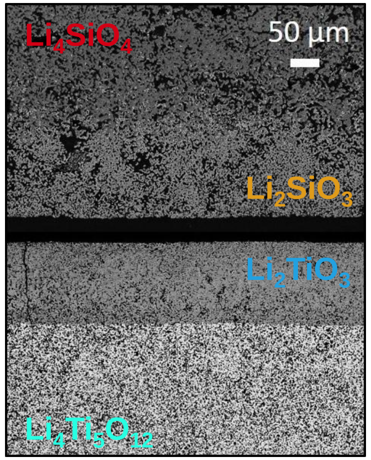

[Pupeschi et al., FED 116 (2017) 73–80; Moscardini et al., FED 127 (2018) 192–201; Moscardini et al., FST 75 (2019) 283–298]

# Phase Stability regarding Lithium Burn-up

★ Typical ACB composition

- Li burn-up due to $^{6}Li(n,\alpha)^{3}H$ reaction
  → Change in phase composition
- Assumption: both phases will burn-up Li to the same degree
- Only 3 phases will occur according to the phase diagram

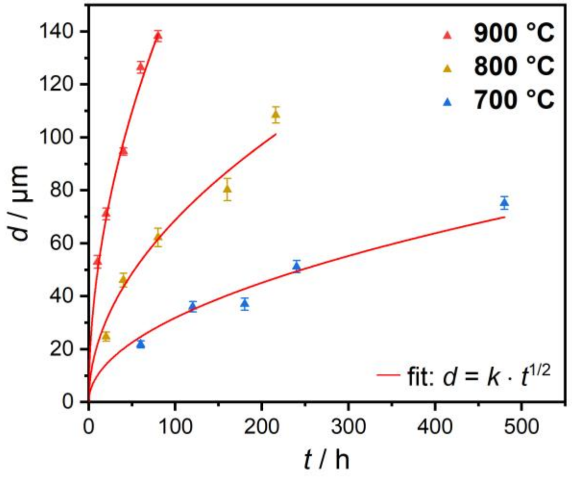



- $Li_4SiO_4$ and $Li_4Ti_5O_{12}$ pellets in contact show reaction zones:

$$3\ Li_4SiO_4 + Li_4Ti_5O_{12} \rightarrow 3\ Li_2SiO_3 + 5\ Li_2TiO_3$$

- Reaction constants were determined at three temperatures
- An activation energy of 0.78 eV was derived



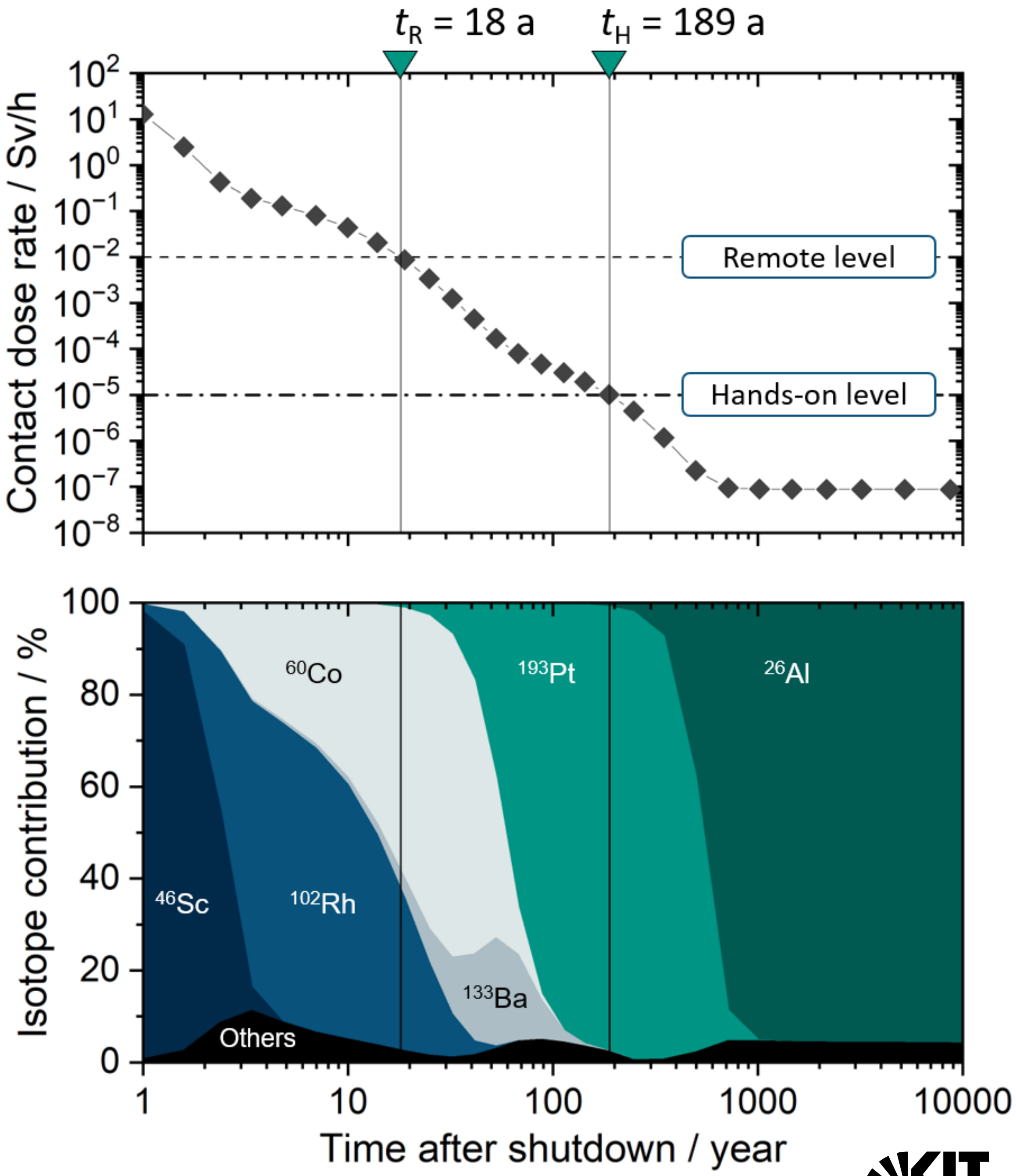

[Leys et al., NME 39 (2024) 101650]

# Behaviour under Neutron Irradiation – Activation

Neutronic calculations performed for ACB with 30 mol% $Li_2TiO_3$

- Remote level is reached after 18 years
- Hands-on level is reached after 189 years

- The activation is determined by critical isotopes resulting…
  - from the raw materials (e.g. $^{46}$Sc, $^{60}$Co, $^{133}$Ba, $^{26}$Al)
  - from the crucible of the fabrication process (i.e. $^{102}$Rh and $^{193}$Pt)

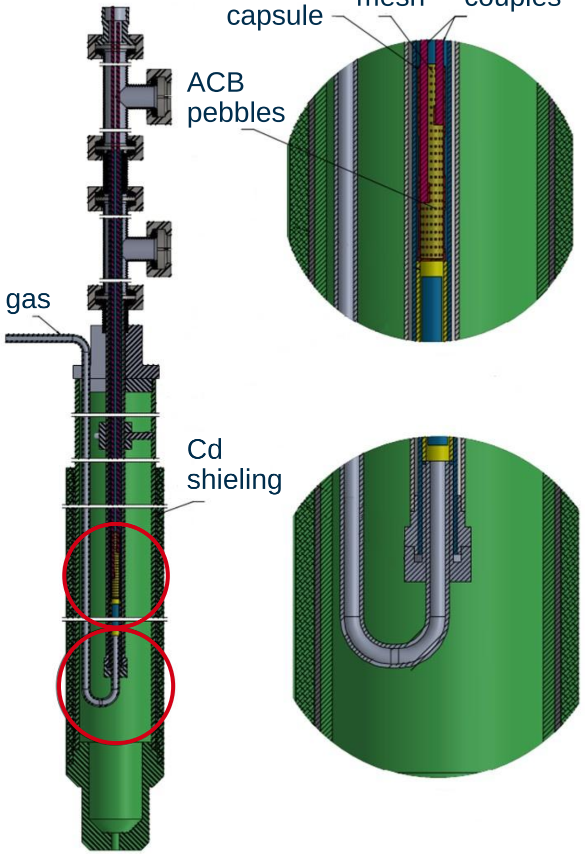


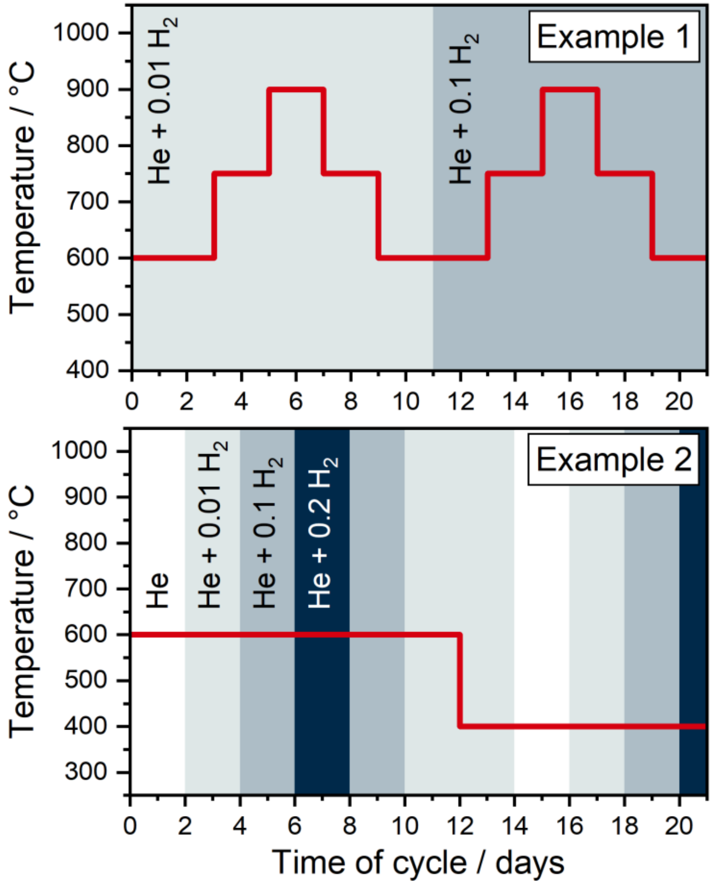

cf. [Mukai et al., FED 100 (2015) 565–570]

# Behaviour under Neutron Irradiation

## Neutron irradiation in Almaty  with in-situ measurements

→ Information on the tritium release behaviour
- Tritium inventory
- Tritium residence time
- Ratio of released species *(HTO + HT)*
- Influence of the temperature *(400–900 °C)*
- Influence of the purge gas *(He + x $H_2$ %)*




[Shaimerdenov et al., FED 212 (2025) 114851]

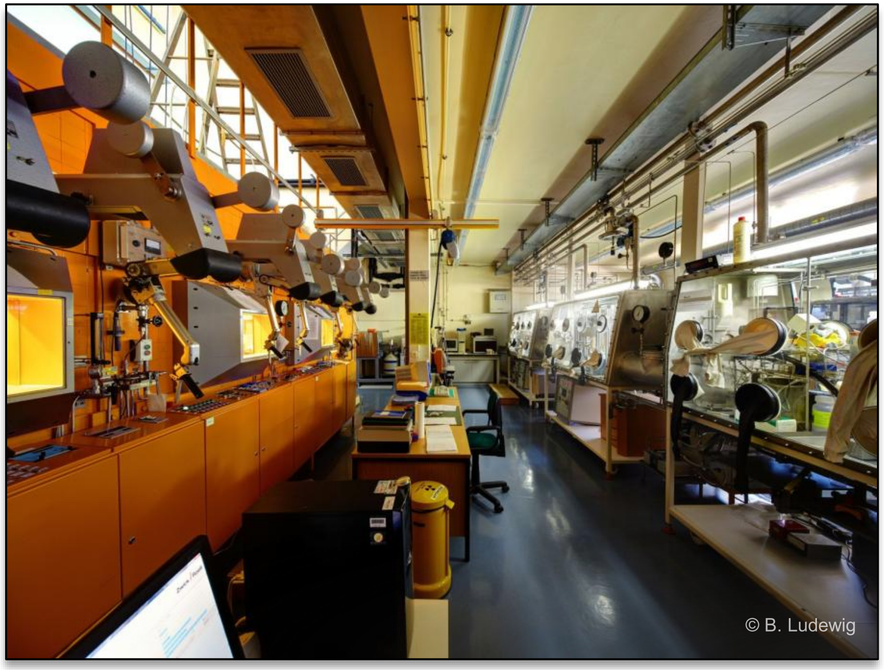
# Behaviour under Neutron Irradiation

Neutron irradiation in Mol

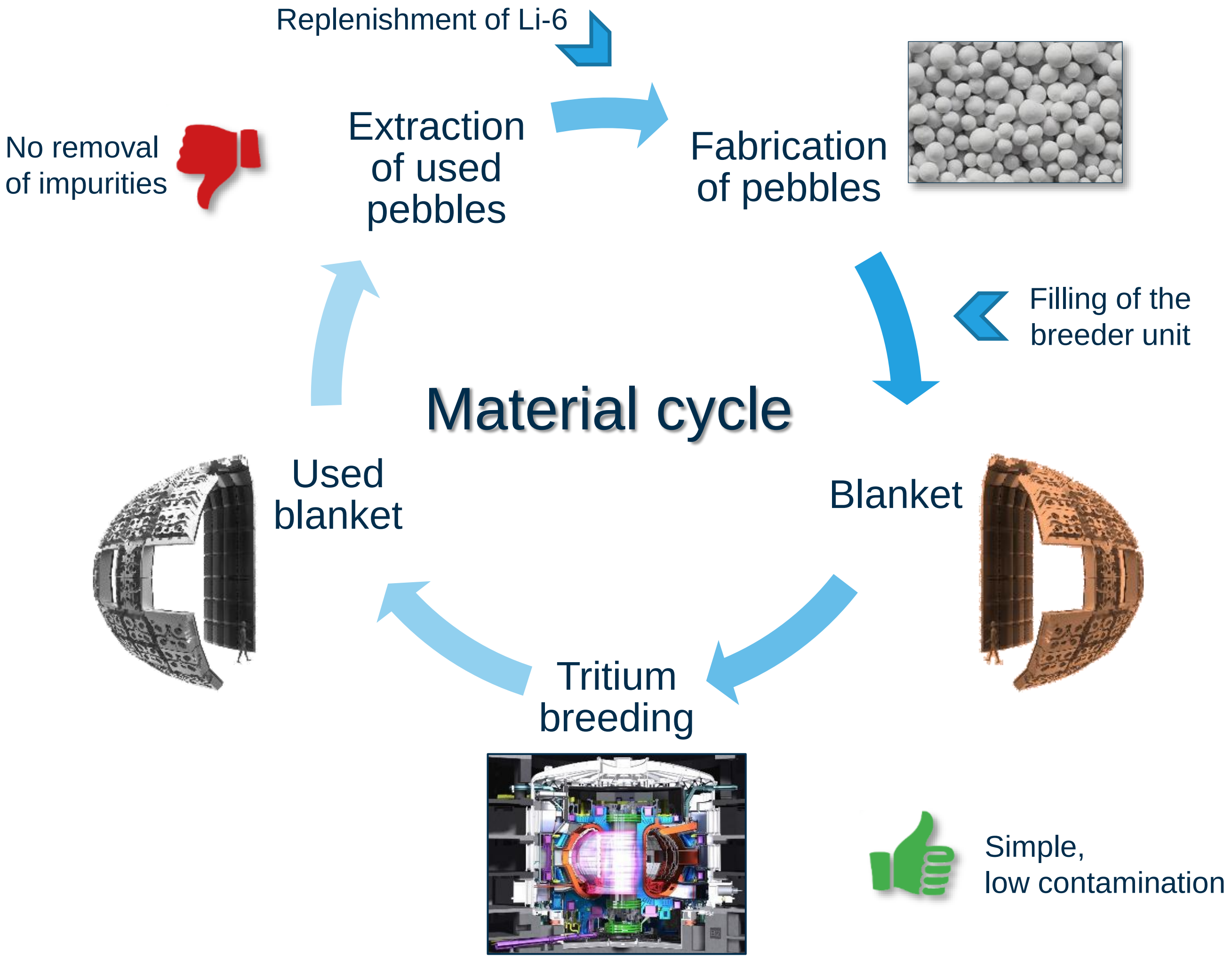
for Post-Irradiation Examination (PIE)

→ Information on the material properties affected by radiation-induced damages and the burn-up of lithium

- Comprehensive PIE at the *Fusion Materials Lab* at KIT
  - Out-of-pile tritium release / TPD; IC + QMS
  - Microstructure / light microscopy + SEM
  - Phase analysis / powder XRD
  - Mechanical stability / crush load tests
  - Density + porosity / pycnometry



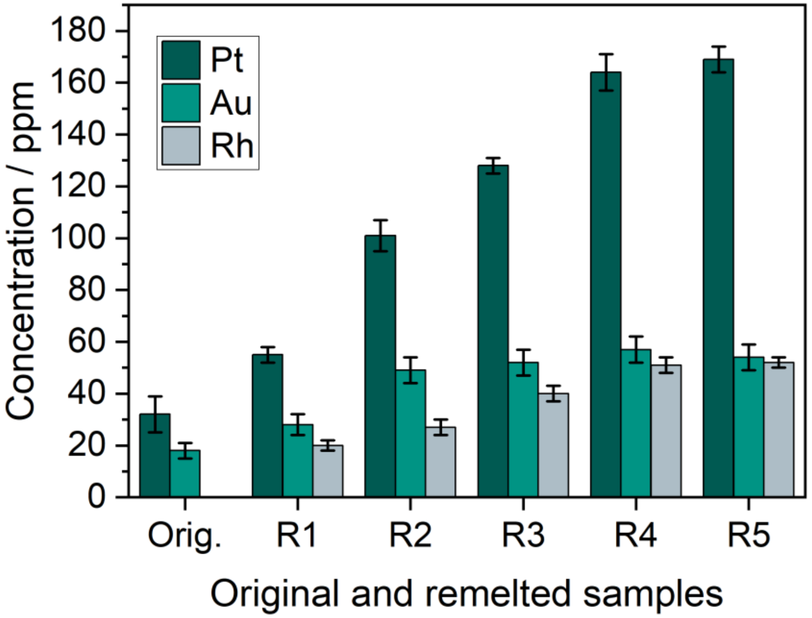
# Possibilities for Material Recycling




[Images: iter.org; KIT]

## Tests on the reprocessing of ACB pebbles

→ Accumulation of the crucible-related elements Pt, Au, Rh




[O. Leys et al., FED 107 (2016) 70–74]

Summary

# 1. Tritium Breeding for Fusion

- $^{6}Li + n \rightarrow {}^{4}He + {}^{3}H$
- Li-containing ceramics as solid breeder materials

# 2. Advanced Ceramic Breeder

- Biphasic material consisting of $Li_4SiO_4$ and $Li_2TiO_3$
- ACB pebble production using melt-based KALOS process
- Material qualification incl. e.g. long-term thermal stability, thermal behaviour of pebble beds, phase stability with regard to Li burn-up
- Material behaviour under neutron irradiation
- Material Recycling (→ incl. $^{6}Li$ replenishment)

EUROfusion

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# Thank you for your attention