Measurement of Sieverts' constant in lithium-lead alloys

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Motivations

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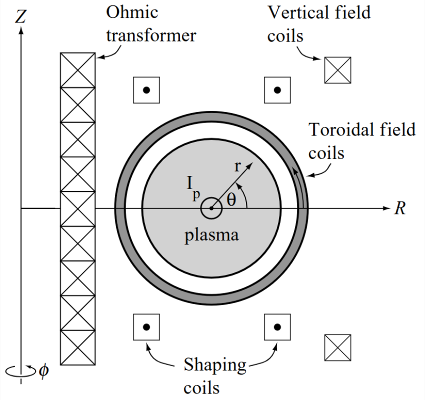
- Fusion energy: clean, safe, sustainable
- DEMO and ITER need tritium self-sufficiency
- Breeding blankets: key for tritium production, heat extraction, neutron shielding
- Reliable data on tritium solubility in PbLi is essential

Tokamak Basics

- Tokamak: magnetic confinement device
- Uses toroidal and poloidal magnetic fields to confine plasma
- ITER and DEMO are tokamak-based projects



Fusion Fuel Comparison

Why D–T is used:

- **Highest cross-section** at relatively low temperature (∼10–20 keV)
- **Moderate fuel availability**:
  - Deuterium abundant in water
  - Tritium bred from lithium in blankets
- **Energy yield**: 17.6 MeV per reaction
- D–D and T–T require **much higher temperatures**, with lower cross-sections
- D–D side reactions less favorable for reactor design

Main reactions:

$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He}\,(3.5\ \text{MeV}) + n\,(14.1\ \text{MeV})$$

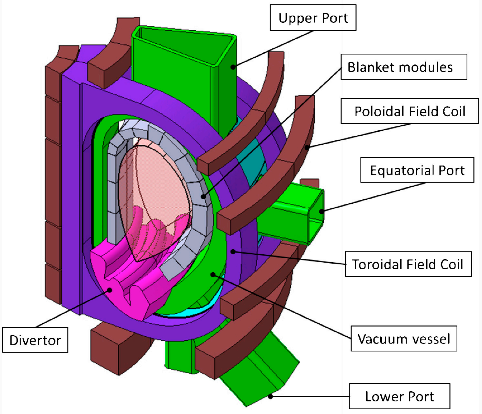
$$\mathrm{D} + \mathrm{D} \rightarrow {}^{3}\mathrm{He}\,(0.82\ \text{MeV}) + n\,(2.45\ \text{MeV})$$

$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T}\,(1.01\ \text{MeV}) + p\,(3.02\ \text{MeV})$$

$$\mathrm{T} + \mathrm{T} \rightarrow {}^{4}\mathrm{He} + 2n\ (+11.3\ \text{MeV})$$

Breeding Blankets

- Extract heat and breed tritium
- Blanket concepts:
  - WCLL (Water-Cooled Lead-Lithium)
  - HCLL (Helium-Cooled Lead-Lithium)
  - DCLL (Dual-Coolant Lead-Lithium)
  - Molten salts (FLiBe, FLiNaK)
  - Ceramic pebbles (HCPB, WCCB)



Tritium Breeding

- Lithium isotopes react with neutrons to produce tritium:

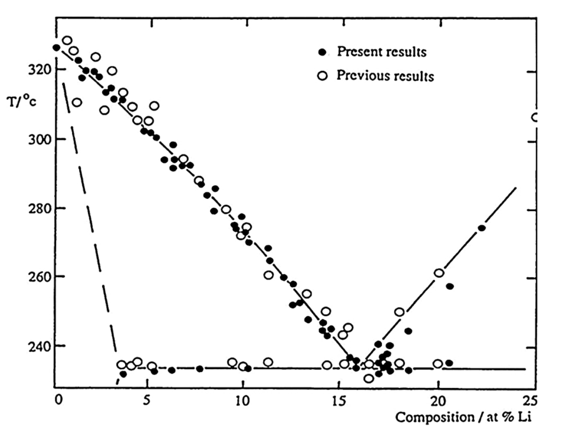
$$^{6}\mathrm{Li} + n \quad \rightarrow \quad ^{4}\mathrm{He} + T + 4.8\,\mathrm{MeV}$$

$$^{7}\mathrm{Li} + n \quad \rightarrow \quad ^{4}\mathrm{He} + T + n' - 2.5\,\mathrm{MeV}$$

- Issues:
  - Requires thermal neutrons (≈ 0.5 eV)
  - One to one correspondence between T produced and T consumed
  - Not accounting for losses during transport or tritium decay

PbLi as Breeding Material

- Neutron multiplier and tritium breeder
- Reduced chemical reactivity compared to pure Li
- Operates at eutectic composition (15.7 % At. Li)
- Efficient heat extraction medium
- Slows down neutrons and enhances multiplication



Sieverts' Constant

Tritium Solubility Challenge

T is radioactive $\rightarrow$ safety concerns

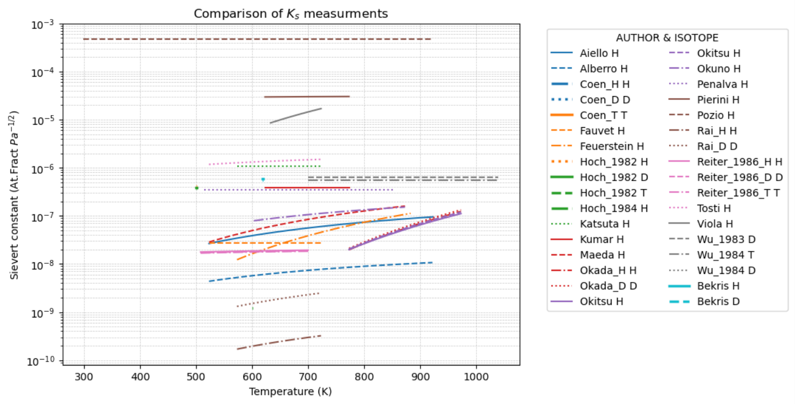
- Minimize permeation and accumulation
- The quantity of tritium in solution must be known
- Solubility follows Sieverts' law

Solubility needs to be known to design the auxiliary systems, in particular the extraction system

Sieverts' Law

$$C = K_S(T)\sqrt{P}$$

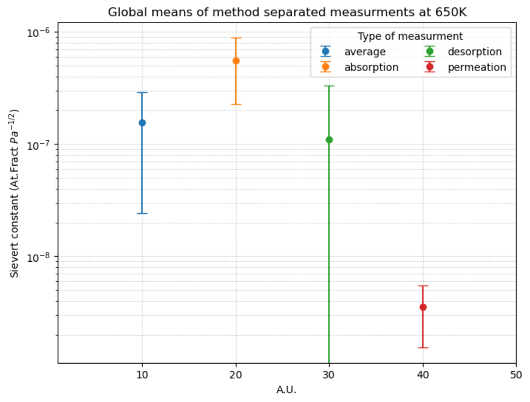
- C: concentration of dissolved gas
- P: partial pressure
- K_S: Sieverts' constant

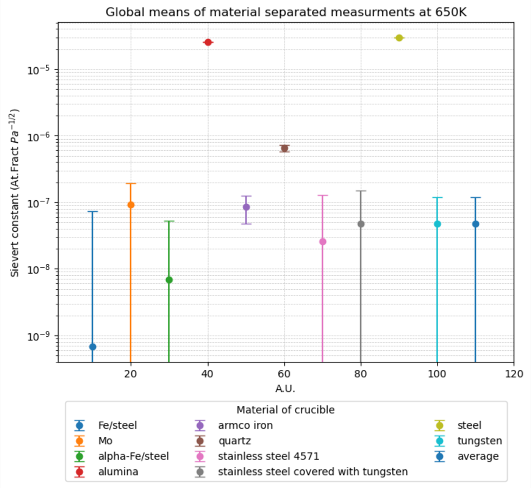


Average from literature data: $K_s = (1.71 \pm 1.39) \times 10^{-7}$ $At.Fract\ Pa^{-1/2}$

- Data spans over three orders of magnitude
- Inconsistencies between methods and materials

State of the Art





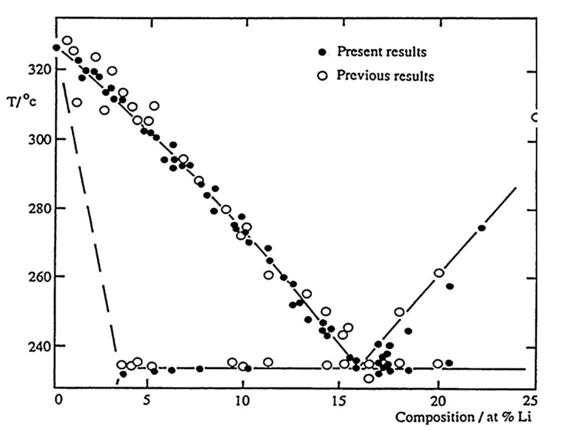
Objectives

- Refine experimental setup for PbLi measurements
- Reduce uncertainty in K_S
- Compare absorption, desorption, permeation approaches

Materials and Methods

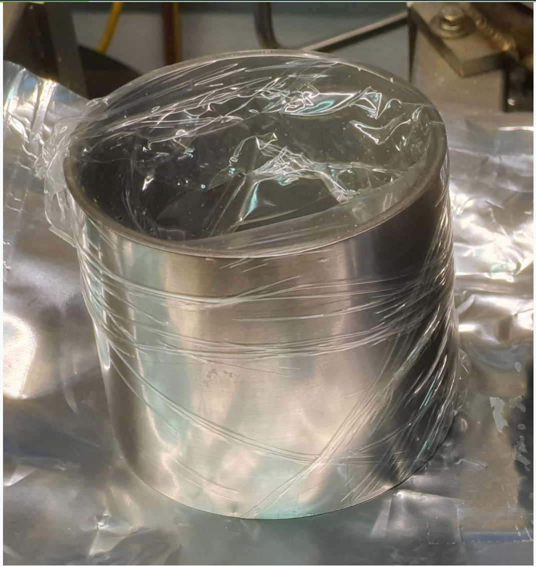
PbLi Alloy

- True eutectic composition in literature went through an evolution
- Pb–17Li commonly used; true eutectic closer to 15.7 at.% Li
- Composition affects solubility and Sieverts' constant (K_S)



Crucible Choice

- Steel: hydrogen absorption increases uncertainty
- Tungsten: very low permeability, lower influence on experimental results

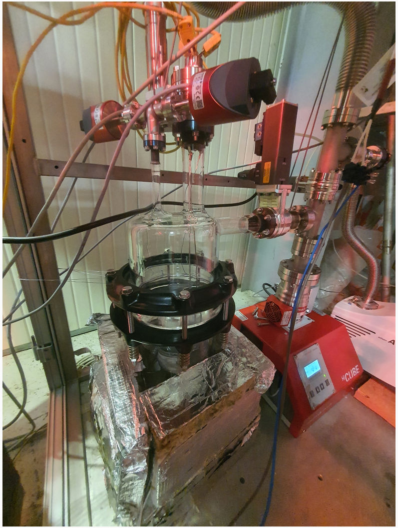


Chamber Design

- Quartz chamber: resistance to permeation and low absorption
- Reduced volume to improve measurement accuracy

Experimental Setup

- HyperQuarch II system overview
- Crucible and chamber arrangement
- Measurement of Hydrogen and Deuterium solubility
- Minimized volume for accuracy



Measurement Procedure

- Step 1: Deoxidation with H purge
- Step 2: Absorption until equilibrium
- Step 3: Desorption by vacuum
- K_S calculated from pressure differences

Absorption

$$K_S = \frac{n_{abs}/V_{PbLi}}{\sqrt{P_f}} = \frac{(P_i - P_f) \cdot V_g}{R \cdot T \cdot V_{PbLi} \cdot \sqrt{P_f}}$$

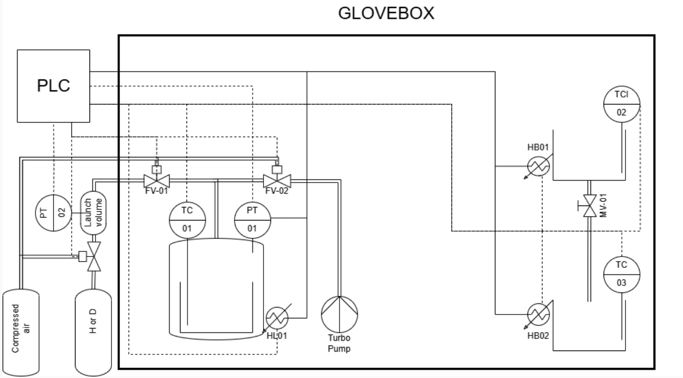
Desorption

$$K_S = \frac{P_f \cdot V_g}{R \cdot T \cdot V_{PbLi} \cdot (\sqrt{P_i} - \sqrt{P_f})}$$

Improved Procedure (HyperQuarch III)

To address contamination and oxidation issues found during HyperQuarch II campaign:

- Inert argon environment (glovebox)
- New crucible loading system
- Improved chamber assembly procedure

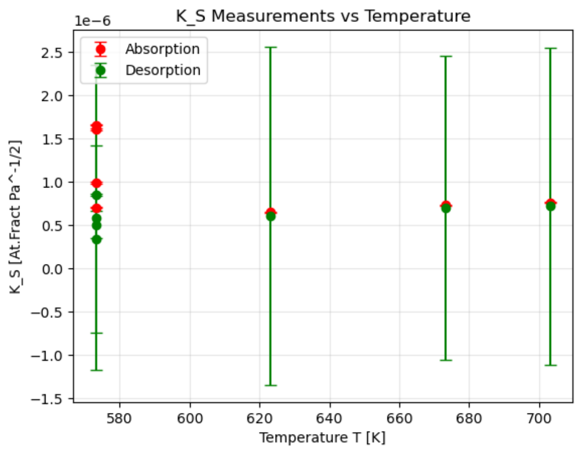


Results

Results

Results obtained for H:

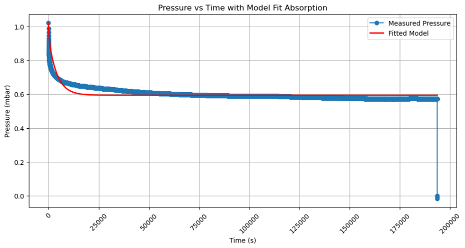
- No dependence on temperature found after statistical analysis
- Good agreement between absorption and desorption data

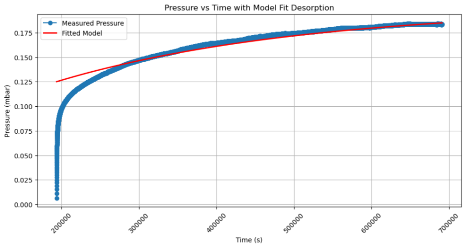


Analysis

Two methods used:

- Classical analysis with pressure difference
- Diffusion-limited model (proposed by Malo et al.)
- Different results obtained between the two approaches





Final Results

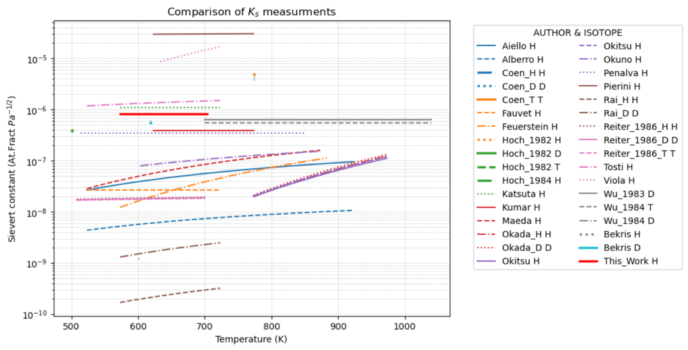
$$K_H^S = (8.16 \pm 5.89) \times 10^{-7} \text{ At.Fract Pa}^{-1/2}$$

$$K_{S_{Malo}}^H = (8.16 \pm 0.23) \times 10^{-8} At.Fract\ Pa^{-1/2}$$

- Classical approach is compatible with literature averages
- Diffusion limited model produces non compatible results
- No clear temperature dependence observed

Comparison with Literature

- Data fits within literature scatter
- Confirms reliability of absorption/desorption methods



Conclusion

Conclusion & Outlook

- K_S measured with improved tungsten/quartz setup
- Results consistent with previous absorption-based studies (Bekris and Penalva)
- Confirmed compatibility between absorption and desorption methods results
- Still large uncertainty — need systematic, standardized campaigns
- Future work: HyperQuarch III procedure