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Materials Challenges In Thermo-Nuclear Fusion Reactor Research

Liquid metal issues in WCLL blanket development

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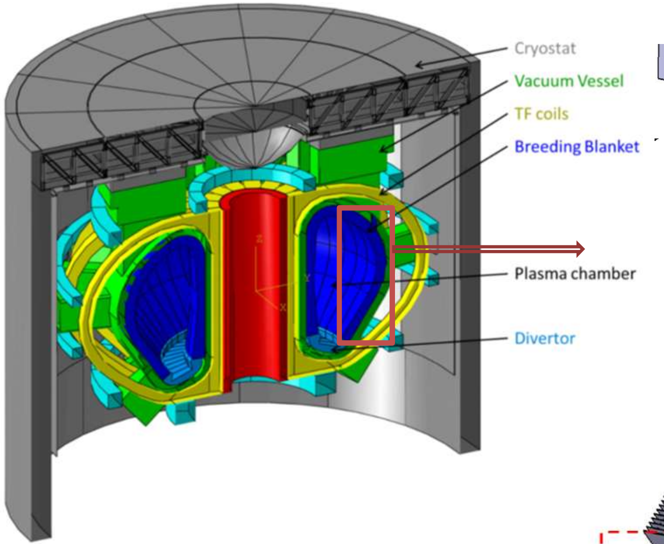
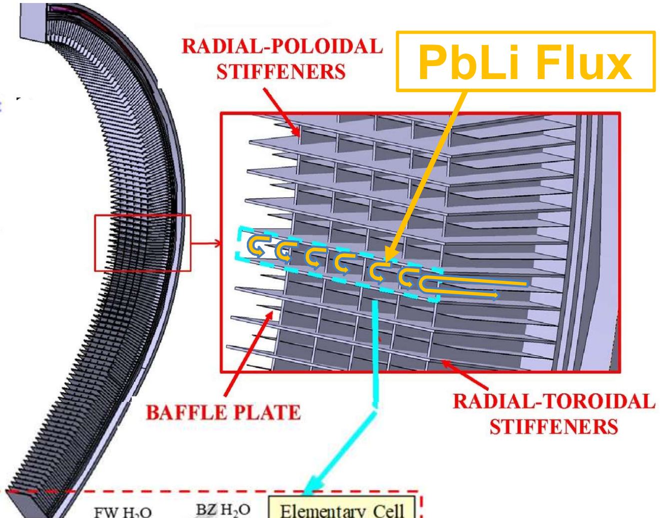
General description of the Water-Cooled Lithium-Lead (WCLL) breeding blanket concept



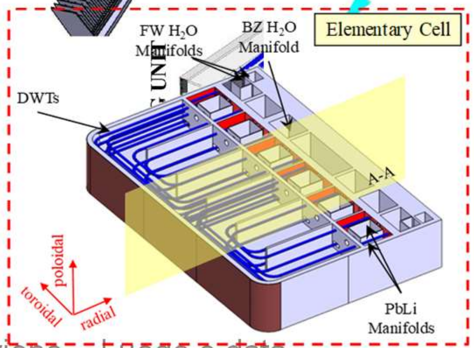


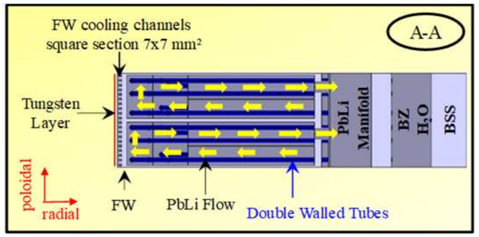
PbLi, 90% ^{6}Li enriched for breeding the tritium needed to feed the DT fusion reaction

$$^6Li + n \rightarrow \alpha + T + 4.78 MeV$$

- The heat produced is removed by the water coolant using double walled pipes
- Hot water is used to produce steam that feed the turbine to produce electricity.

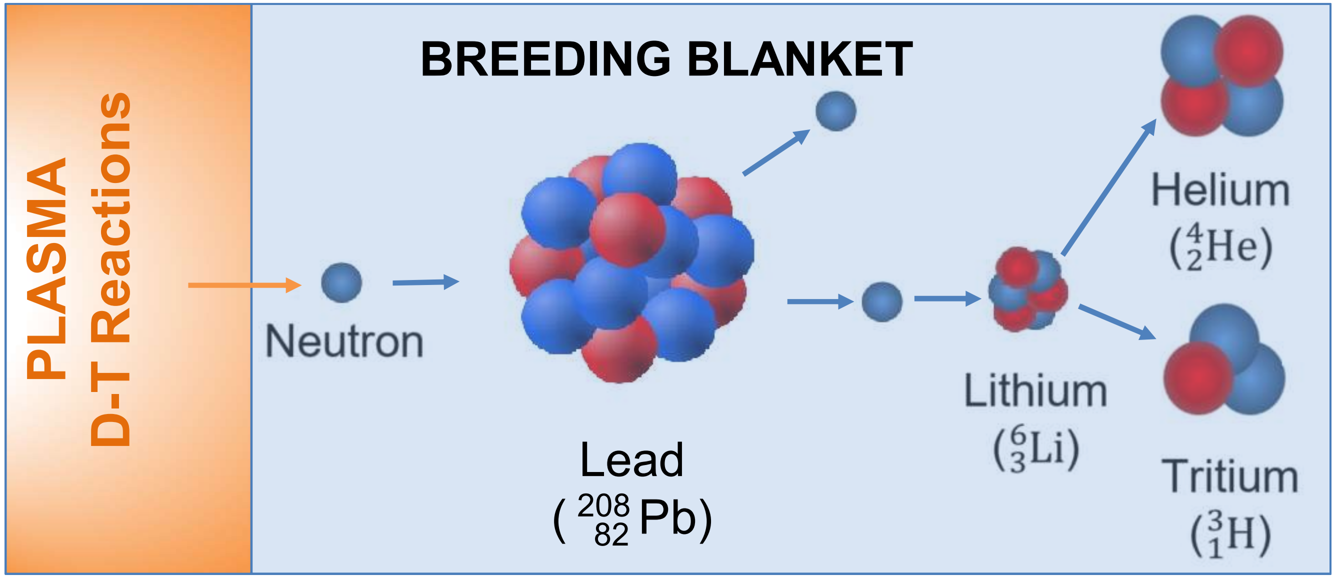
- EUROFER
- PbLi temperature
  300 °C - 330 °C
- Water pressure 15.5 MPa
- Water temperature
  295 °C - 328 °C





PbLi as neutron multiplier and T breeder and carreier

Lithium ⇨ **breeder**
Lead ⇨ **neutron multiplier**

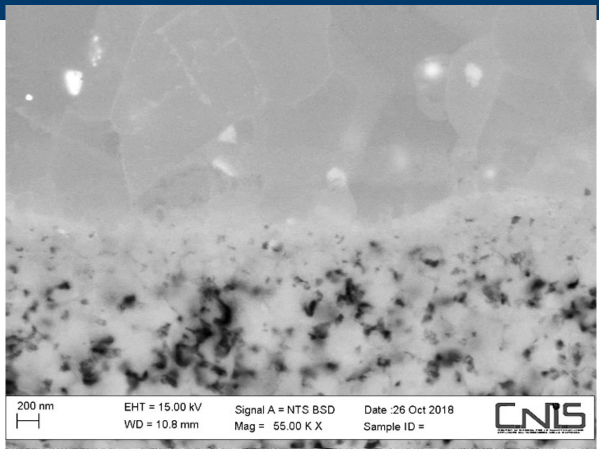


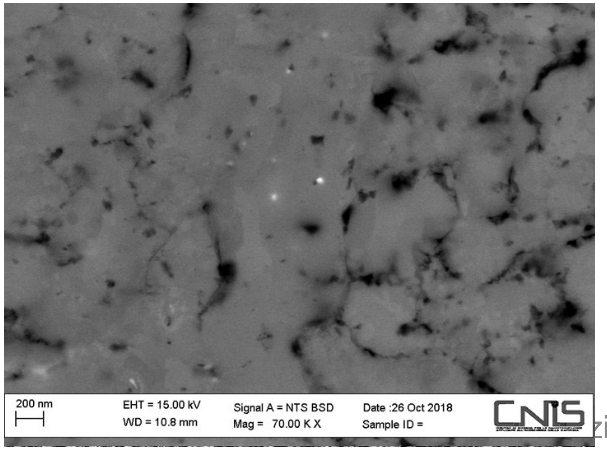
Tritium produced in the BB is recovered from the PbLi to feed the fusion reaction inside the chamber of the tokamak and make the process self sustaining

ISSUES (among many others…)

1. Liquid metal corrosion
   Li and Pb both corrode the structural steel
2. Liquid metal embrittlement (possible)
   Liquid metals may cause embrittlement
3. Tritium contamination of the water coolant
   Eurofer tubes are permeable to T2 – contamination of the water coolant – production of a large amount of waste

Liquid Metal Corrrosion





- **Liquid metal corrosion is associated to the failure of the passive oxide on the steel surface followed by dissolution**
- **The FeCr passive layer perform bad both in pure Pb and Li living the steel exposed to the molten metal**

Molten Pb

Fe dissolution from the FeCr oxide => porous structure permeable to oxygen

Molten Li

The Li has great affinity for oxygen and grab the oxygen atoms off of the FeCr oxide which is dissolved

Corrosion-dissolution of the steel in the melt. The solubility is enhanced/driven by the formation of compounds soluble in the melt

Mixed oxides - oxygen atoms with Fe and Cr atoms form metal oxide complexes in the melt. [Corrosion Science 118 (2017) 1–11]

Nitrides: Li_9CrN_5 formation

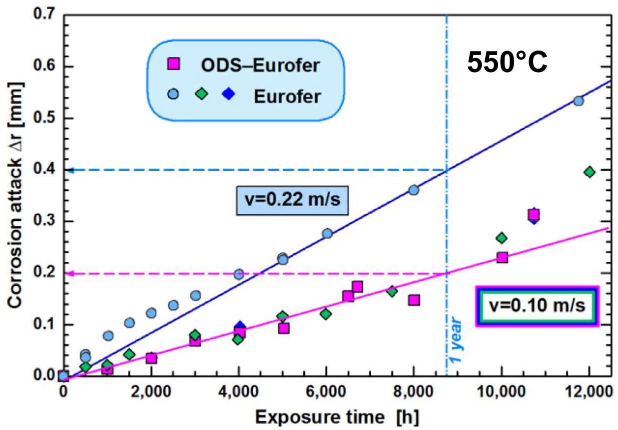
Eurofer 97:

Corrosion rate ~ 3.2 µm/y **Nitrogen concentration ~ 300 wppm**

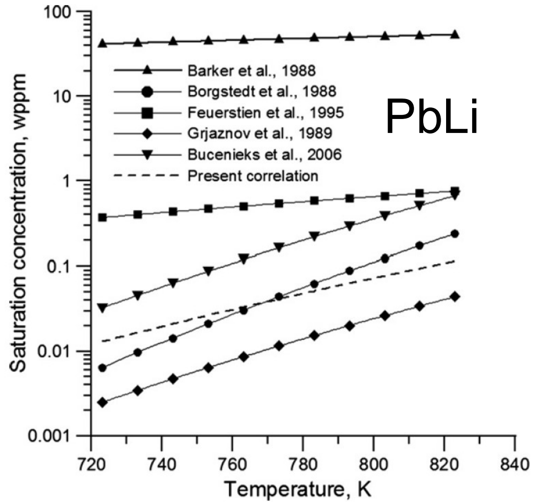
Max corrosion rate ~ 0.2 µm/y **After installation of a N trap (Ti Sponges)**

PbLi Liquid Metal Corrosion

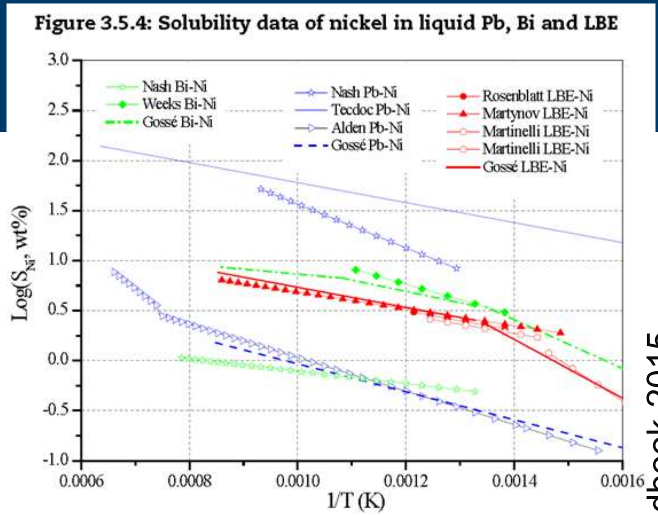
Corrosion rate reported in the range 20-900 μm/y depends on maximum temperature, temperature gradient, flow velocity, flow regime, shape of the loop, metallic impurities and application of a magnetic field

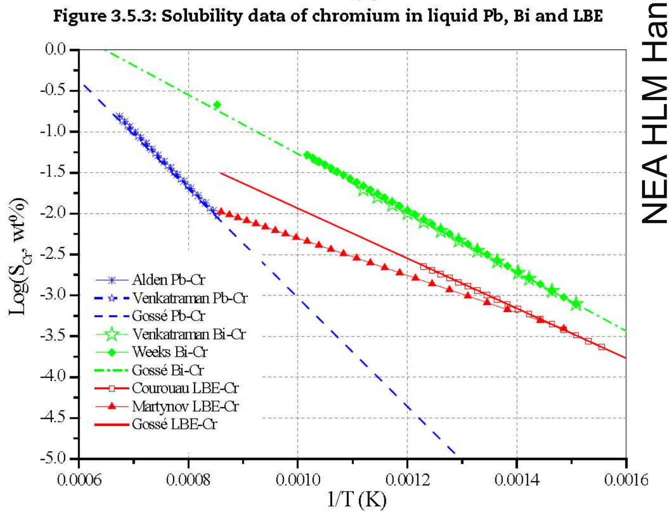


Nuclear Materials and Energy 9 (2016) 512-518



Smolentsev Journal of Nuclear Materials 432 (2013) 294–304



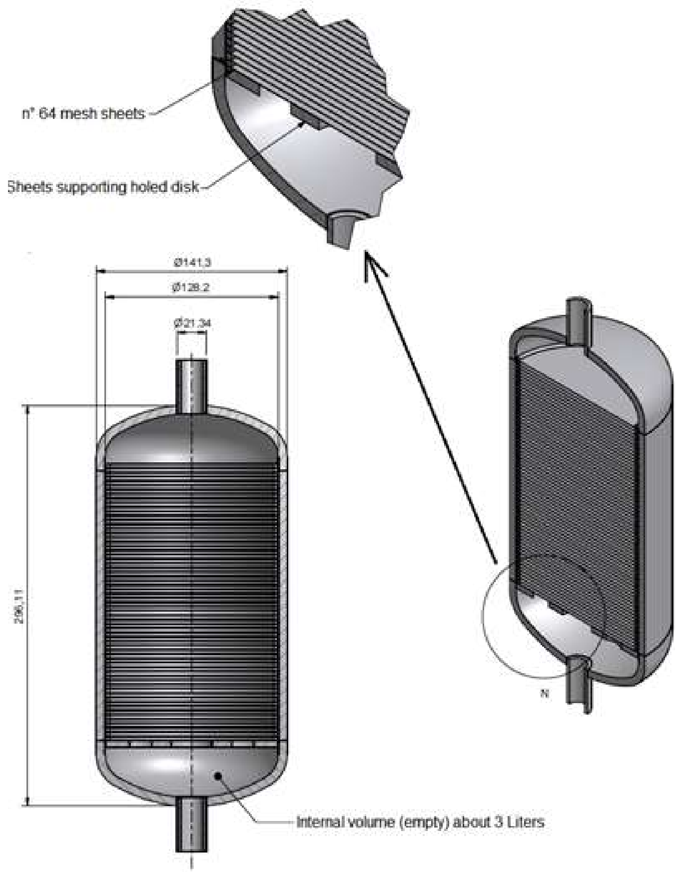


NEA HLM Handbook 2015

Measures against Liquid Metal Corrosion

- Purification systems – oxygen and nitrogen getters
- Monitor/control the dissolved gasses
- Coatings - physical barriers between the melt and the steels

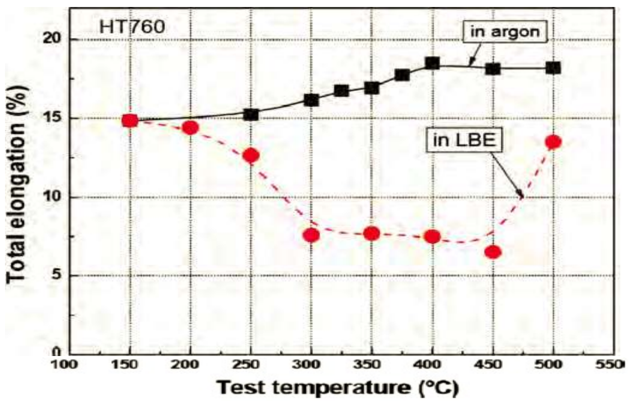
Material of construction	AISI 321
Purification Temperature	550-600°C
Total Inner Volume	~ 30 L
Filled Volume (by Li)	~ 19 L
Getter type	Ti sponge in chunks
Getter amount (in contact with Li)	~ 9 kg



Liquid metal embrittlement

Liquid metal embrittlement (LME) refers to various different phenomena that take place when a ductile metal in contact with a liquid metal, shows an unusual and unpredictable brittle behaviour when stressed in tension, compared with the tensile behaviour in air

The failure occurs by nucleation of a crack at the wetted surface with the propagation into the bulk of a brittle fracture



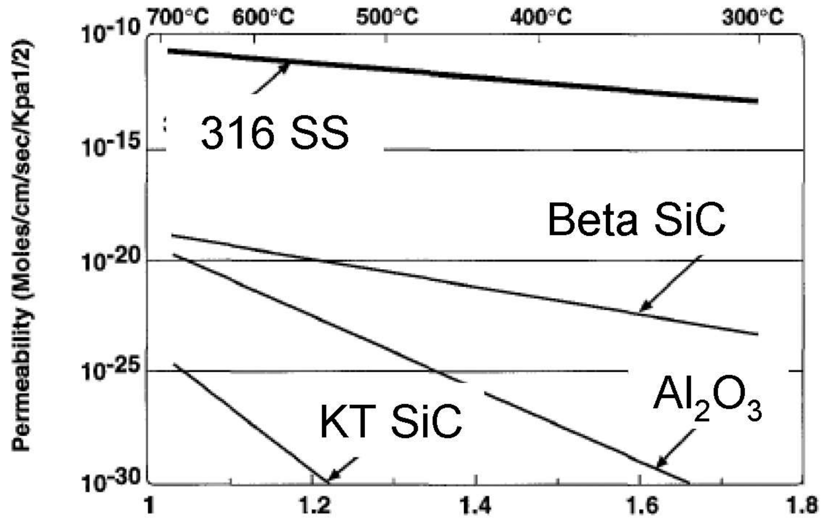
T91tempered @ 760°C test in Ar and LBE
[O] < 1 wppm strain rate $1{\cdot}10^{-5}$ s^{-1}

- **Demonstrated the embrittlement by <u>PbBi on T91 steel</u>**
- **<u>No LME has been found for pure Pb</u> and several papers report some effect in samples notched and tempered @ low temperature - fragile "di per se"**
- **Data are sparse but indicate little or no effect of PbLi on the EUROFER mechanical properties**
- **No systematic evaluation has been carried on PbLi HLM and further work is needed**

T91 in lead Journal of Nuclear Materials 531 (2020) 152021
C. Fazio, I. Ricapito Report on the mechanical properties of RAMF steel in PbLi EFDA 2002

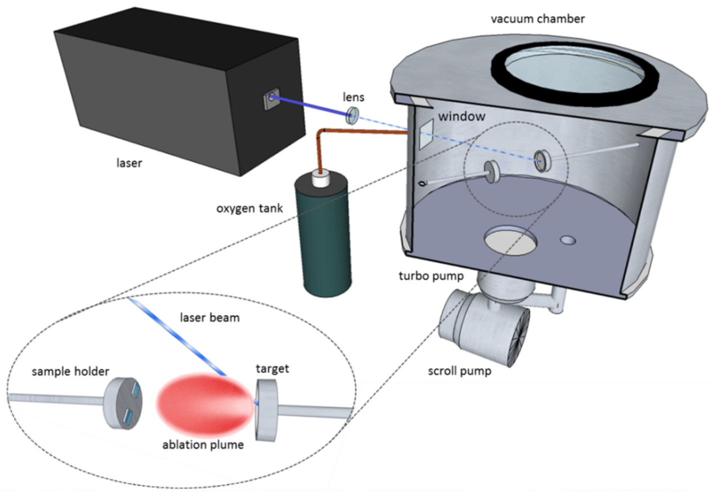
Tritium Permeation

- The piping as well as the rest is made of low activation martensitic
- Tritium generated by the neutron radiation diffuse into the steel contaminating the water coolant
- Tritium substitutes hydrogen atoms in the water
- Tritiated water is a major concern – HTO moves through the environment like ordinary water in living cells, tissues with a half-life of 12.3 years
- Need to impart anti-permeation behaviour to the steel by the use of <u>coatings</u>

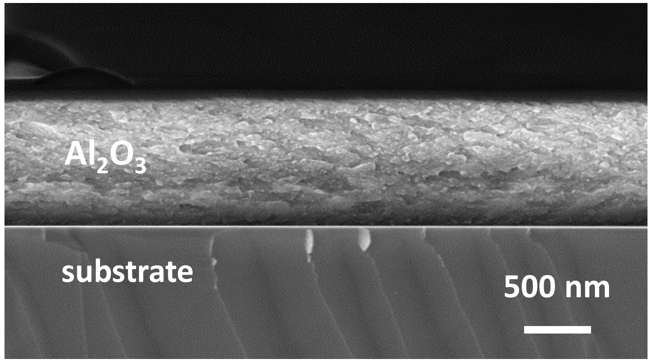


Anti corrosion/anti permeation coatings

Al2O3 by Pulsed Laser Deposition



10 cm long 316L tube + 1 µm Al_2O_3



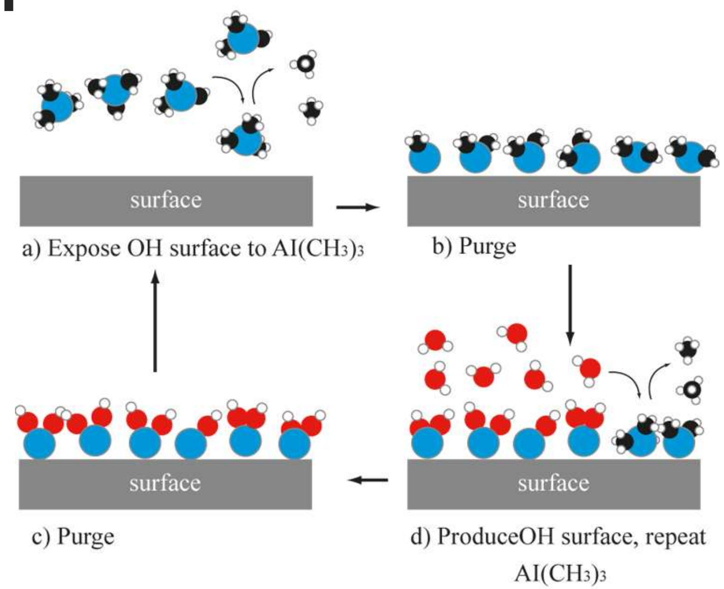
F. Garcia Ferré et al. – ACTA MATER – 2013

- ✓ **high quality coatings**
- ✓ process at **room temperature**
- ✓ amorphous films with **nanodispersed crystalline domains**
- ✓ **high deposition rate (nm/s)**
- ○ **Line of sight deposition**

Anti corrosion/anti permeation coatings

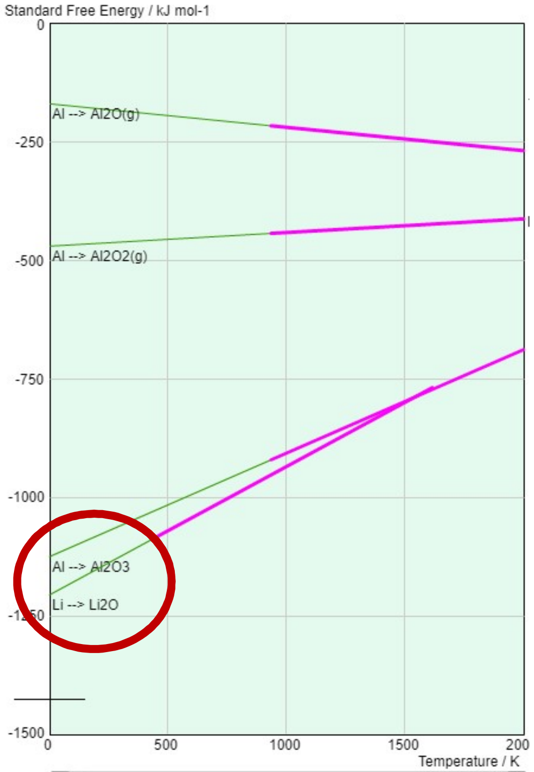
Al2O3 by Atomic Layer Deposition

- ✓ **high quality coatings**
- ✓ custom process: bottom-up approach
- ✓ process at **room temperature**
- ✓ amorphous films
- ✓ **No line-of-sight deposition**
- ○ **Low deposition rate (10^-1^-10^-2^ Å/s)**



Corrosion and mechanical testing are in progress

Chemical stability issues



Alumina is stable but Li has great affinity for oxygen

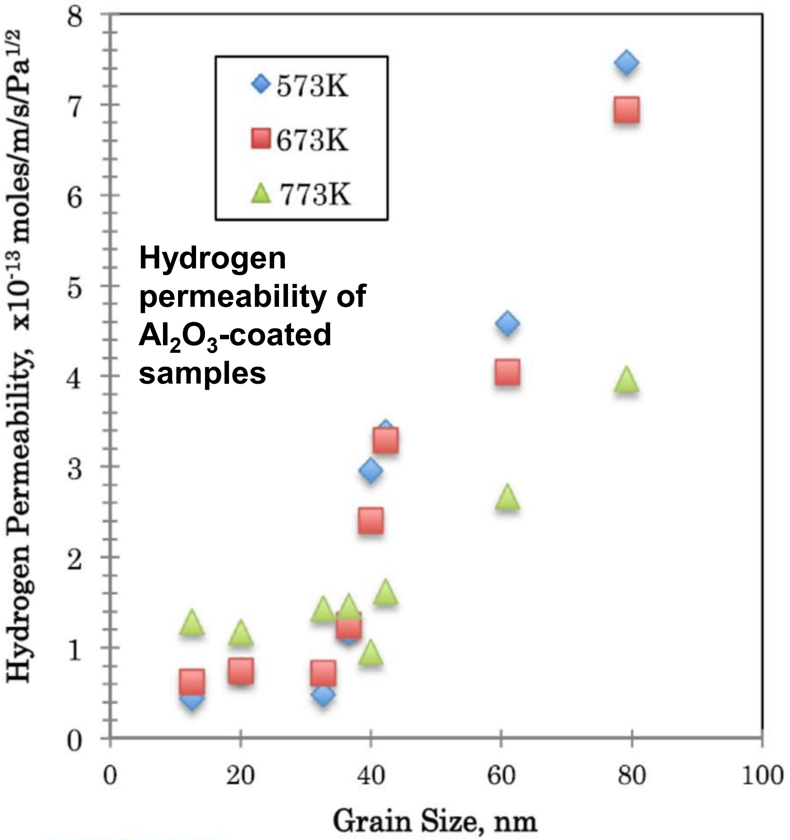
In the temperature range of interest the Li oxide is energetically favoured

Recent studies have shown that in the temperature range 600°-700°C alumina in contact with PbLi reacts to form LiAlO2

At lower temperatures it should be worst

- **Li is subtracted to the breeder**
- **The coating stoichiometry changes, the protection against tritium and corrosion probably fails**
- **Risk of local ruptures of the tubes – water in the PbLi**
- **Contamination of the water coolant**

The coating technique is of the same importance as the material selection



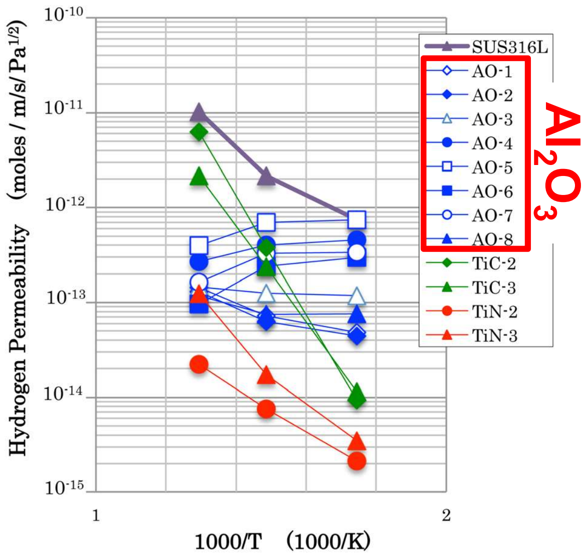
Journal of Vacuum Science & Technology A 33, 041503 (2015)

- **Alumina crystals are excellent barriers but the microstructure change the behaviour**
- **Smaller crystalline grains tend to have lower hydrogen permeability**
- **Equiaxed grains show less permeability than a columnar grains microstructure**

What's next

- Need to assess the real benefits taking into account that Al is not low-activation
- Further study are needed to investigate the correlation between the tritium permeation behaviour and microstructure to develop improved barriers
- Try other materials TiN, TiC, ZrO and deposition techniques
- Performance under neutron irradiation must be demonstrated

TiC and TiN show comparable or better performance than Al_2O_3



Journal of Vacuum Science & Technology A 33, 041503 (2015)

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Conclusions

- ✓ The construction of the DEMO breading Blanket represent a challenge for the materials that have to withstand intense neutron radiation in contact with tritium-containing PbLi at high temperature
- ✓ The only material choice for the structures is the low activation F/M steel EUROFER 97
- ✓ Corrosion and tritium permeation trough the steel are the main issues, LME need verification
- ✓ Corrosion is enhanced by the solubility of complexes in the melt (oxides and nitrides with Pb and Li)
- ✓ Corrosion and tritium permeability impose the adoption of coatings as tritium and PbLi barrier
- ✓ The technological solutions adopted represent a contamination with advanced technological sectors such as microelectronics and nanotechnologies

Acknowledgement
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Thanks for your attention

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