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COATING TECHNOLOGY FOR TRITIUM PERMEATION BARRIERS IN FUSION SYSTEMS

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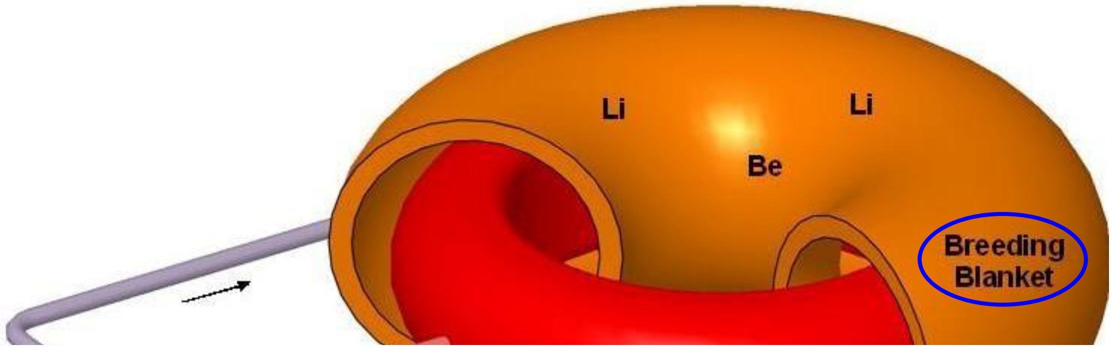
Outline

1. Introduction
   - What is tritium permeation barrier?
   - Spin-off effects
2. Hydrogen permeation mechanism in Er_2O_3 coatings
   - Preparation and characterization
   - Modeling of hydrogen permeation
3. Latest progress and future prospects
   - Potential of multi-layer coatings
4. Summary

Tritium in fusion systems

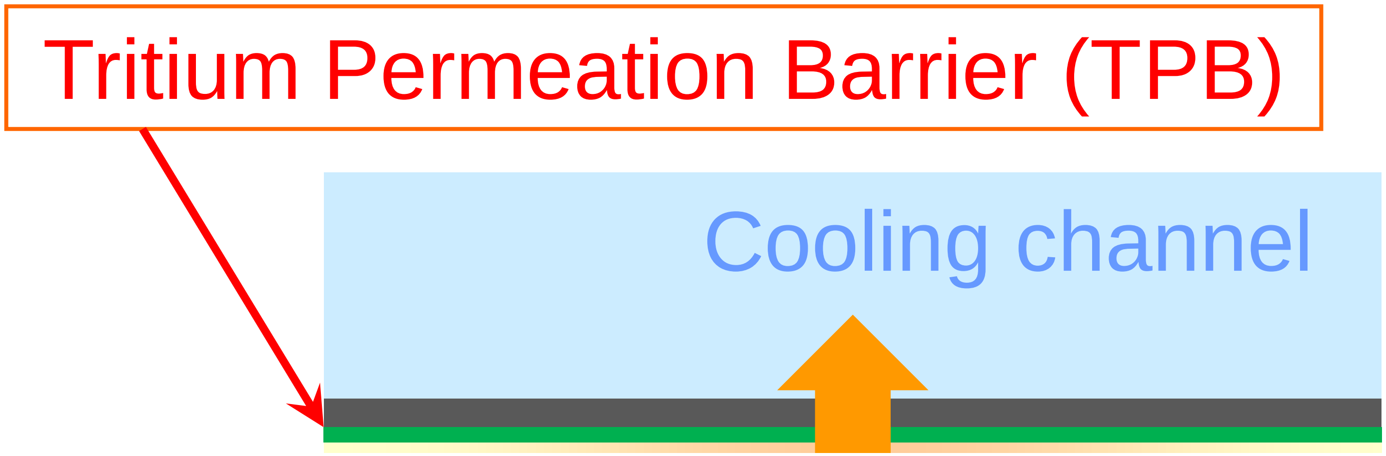


- In a GW-class fusion reactor, a blanket system must produce and recover ~100 kg tritium a year
- Main metals for structural materials of fusion blankets (Fe, V, Ti, etc.) has high permeability of hydrogen isotopes

Critical fuel loss and radiological hazards

http://www.iter.org/doc/www/edit/Lists/WebsiteText/Attachments/16/fueling_5.jpg

Tritium permeation barrier



Requirements:

- High permeation reduction factor (PRF)
  PRF = $J_{uncoated}/J_{coated}$ >10^2-10^3
- Compatibility with blanket materials
  especially corrosive breeding materials
- Tolerance for thermal cycles, irradiation etc.

Variety of applications of TPB

1) Hydrogen loss by permeation
2) Constraint in structural material due to hydrogen embrittlement

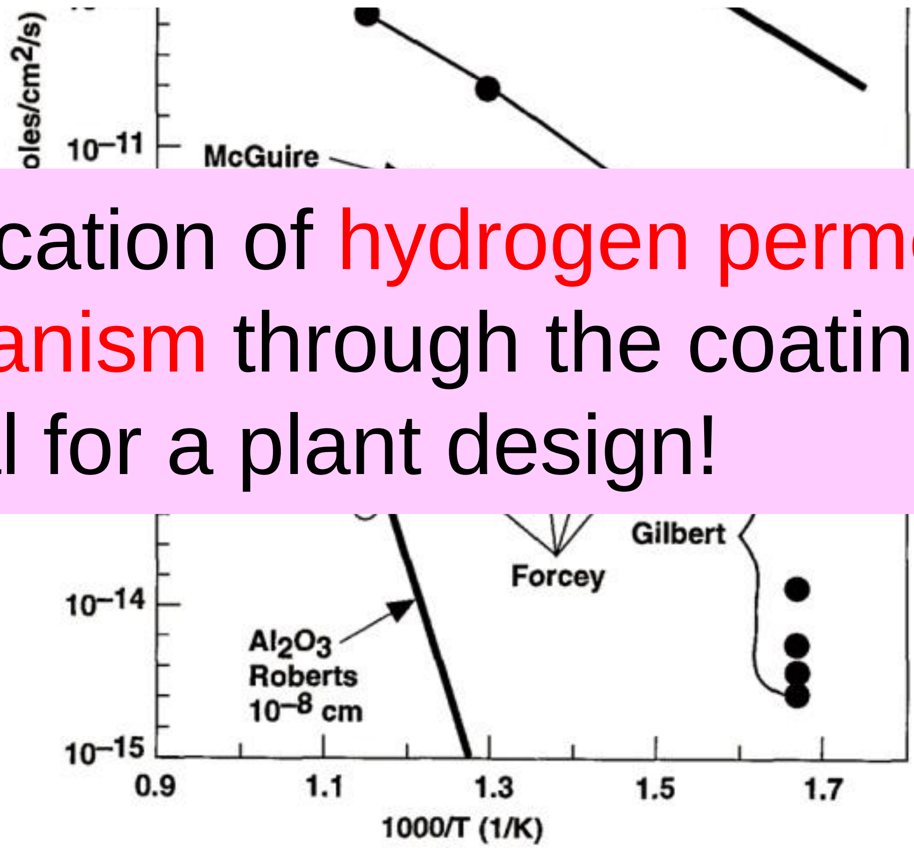
Possible applications:

- Solid oxide fuel cell (SOFC)
- Solar concentrator for H_2 production
- Fast breeder reactor (hydride control rod)
- Light-water fission reactor (Zr-H_2O reaction at fuel cladding)

Issues and challenges

Problems of TPB coating research

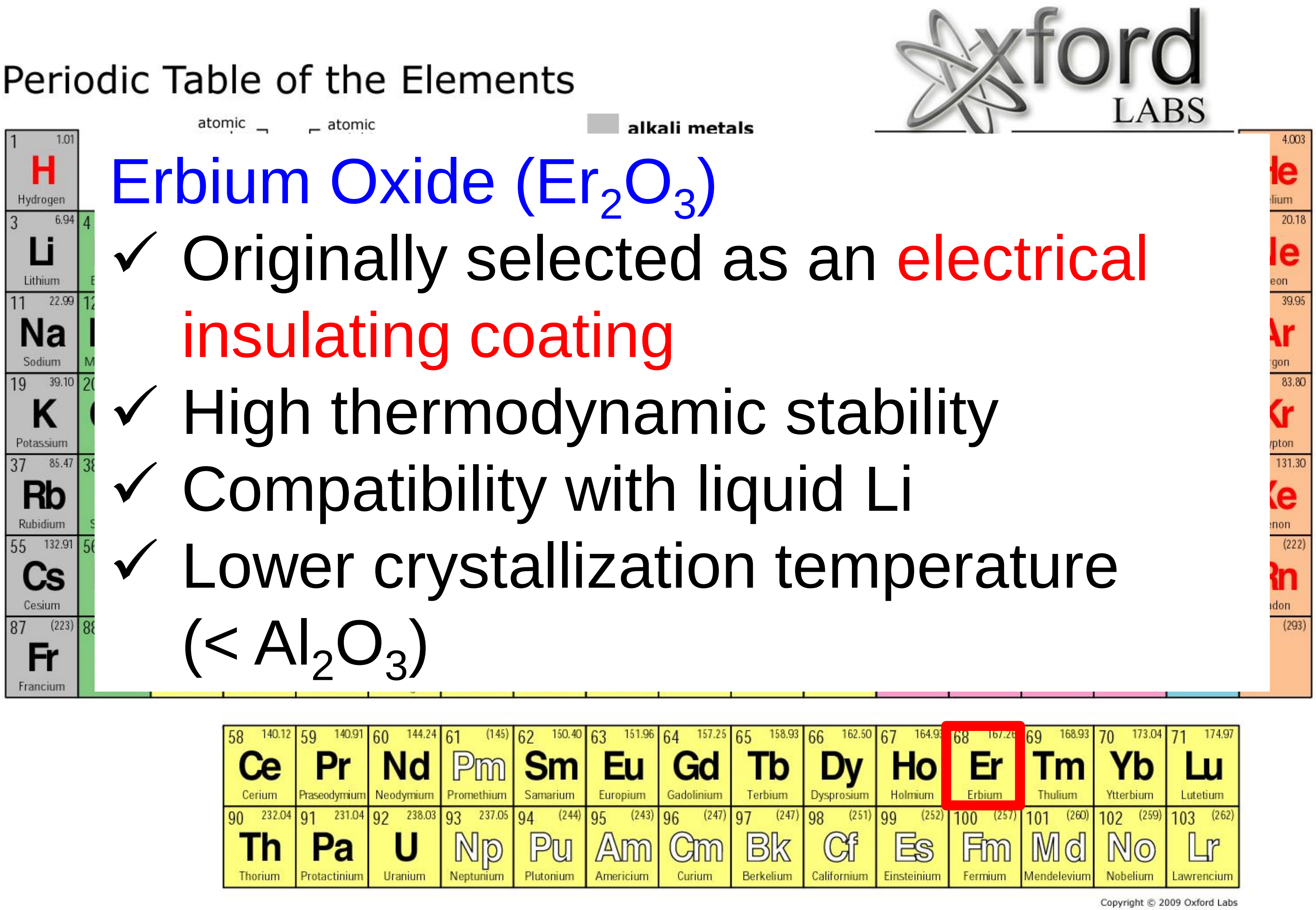
- ✓ Much higher permeability than bulks
- ✓ 4 orders of magnitude scattered data



Clarification of hydrogen permeation mechanism through the coatings is crucial for a plant design!

G.W. Hollenberg, *et al.*, *Fusion Eng. Des.* 28 (1995) 190–208.

Coating material and methods



Erbium Oxide (Er_2O_3)

- ✓ Originally selected as an electrical insulating coating
- ✓ High thermodynamic stability
- ✓ Compatibility with liquid Li
- ✓ Lower crystallization temperature (< Al_2O_3)

http://oxford-labs.com/wp-content/uploads/2009/04/periodic-table.jpg

Coating material and methods

(1) Metal-organic decomposition

- Ability to coat on complex shapes
- Potential to apply plant-scale
- → Clarification of precise permeation behaviors

Coating precursor: **Er-03**®

Kojundo Chemical Laboratory Co. Ltd.

Er content: 3%

Dip-coating

1) Spin-coating: rotation speed
2) Dip-coating: withdrawal speed

Drying

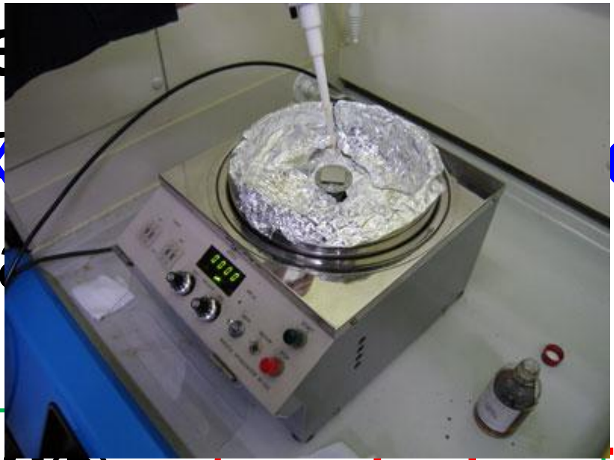
At 120 ºC for 10 min, in air

Heat treatment

Atmosphere:
1) Ar 2) H_2 + 0.6% H_2O
Temperature: 600–700 ºC
Time: 10–30 min
Heating rate: 20–30 K/min

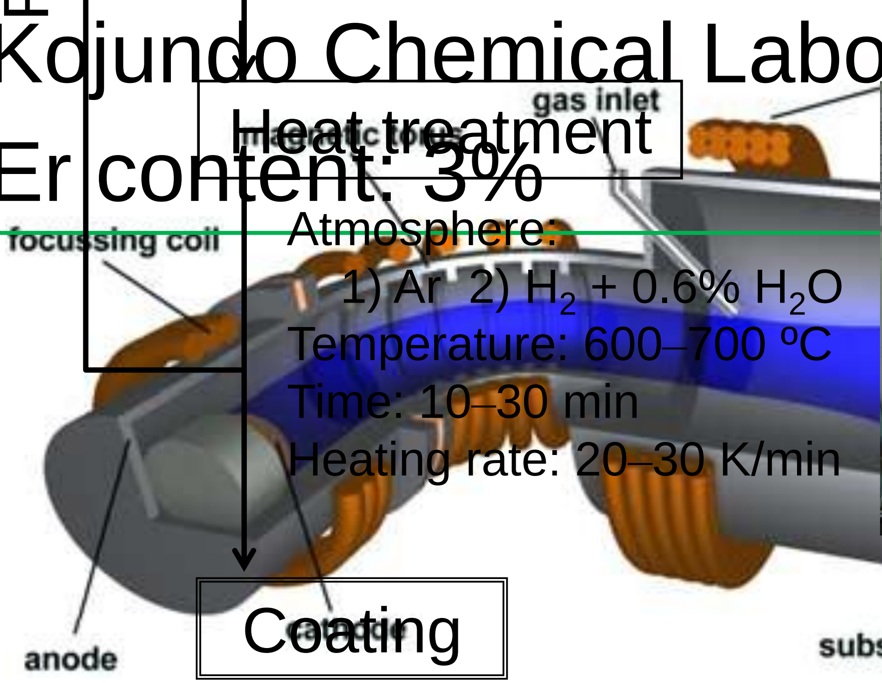
Coating

Repeat



(2) Filtered arc

- A physical vapor deposition
- Good adhesion on substrate
- Low impurity



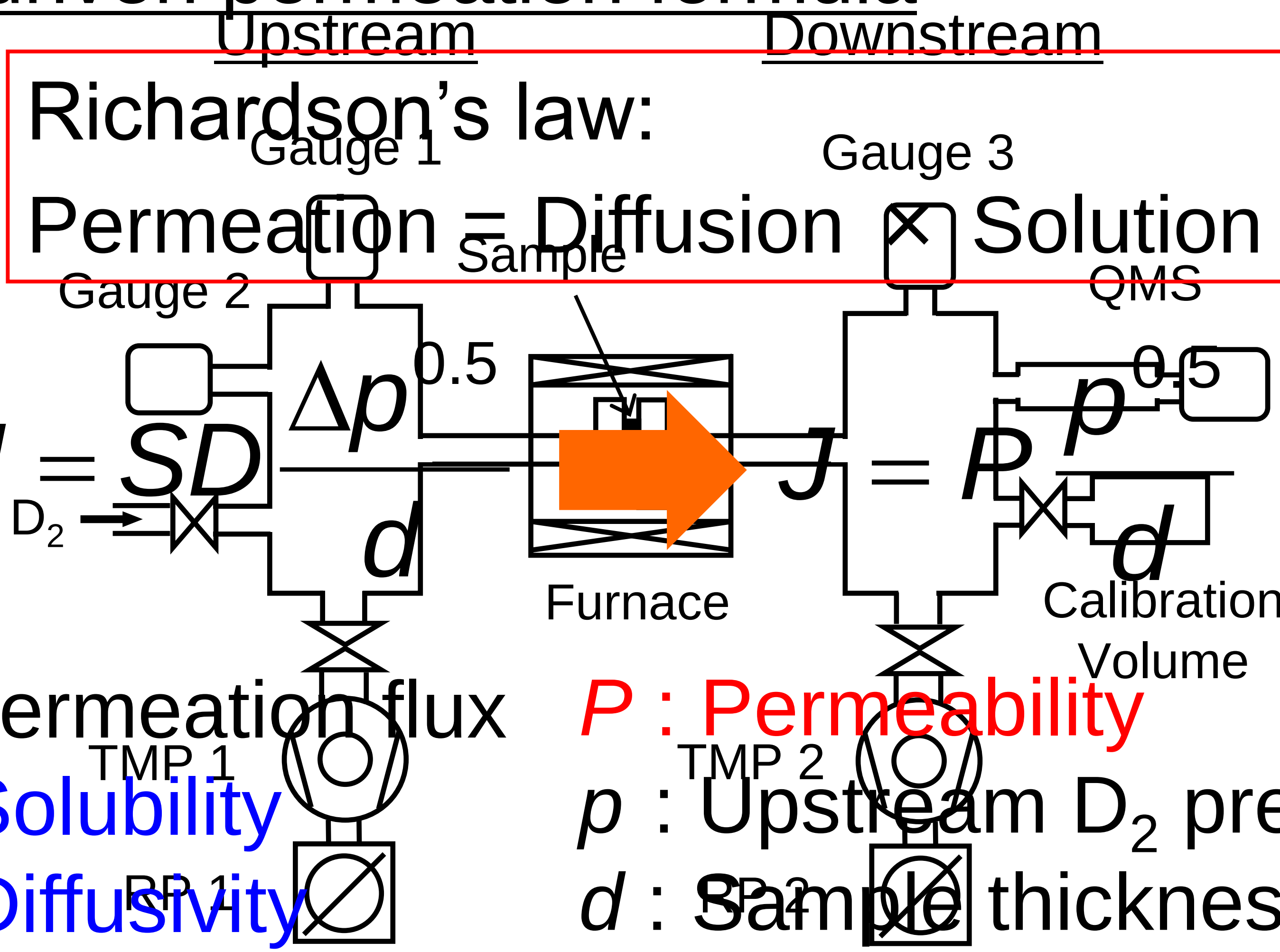
Deuterium permeation experiment

Gas-driven permeation formula

Richardson's law:

Permeation = Diffusion × Solution

$$J = SD\frac{\Delta p^{0.5}}{d} \quad J = P\frac{p^{0.5}}{d}$$



J : Permeation flux

S : Solubility

D : Diffusivity

P : Permeability

p : Upstream D_2 pressure

d : Sample thickness

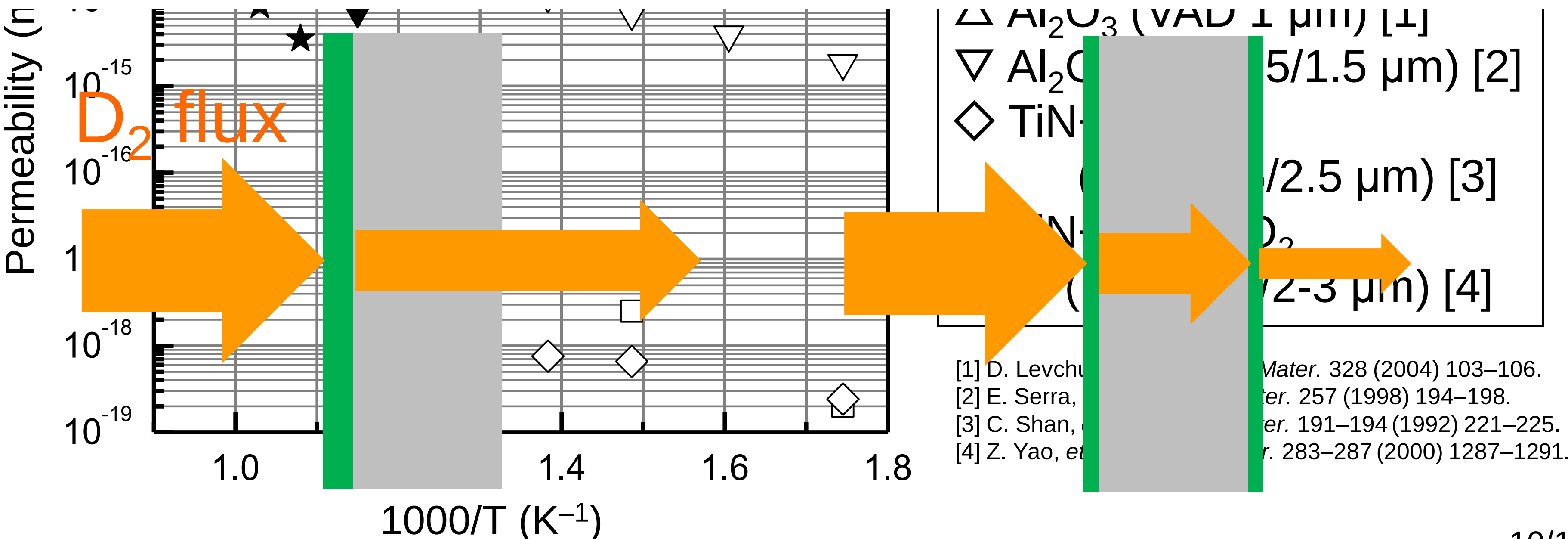
Comparison of permeation reduction factors

T (ºC)

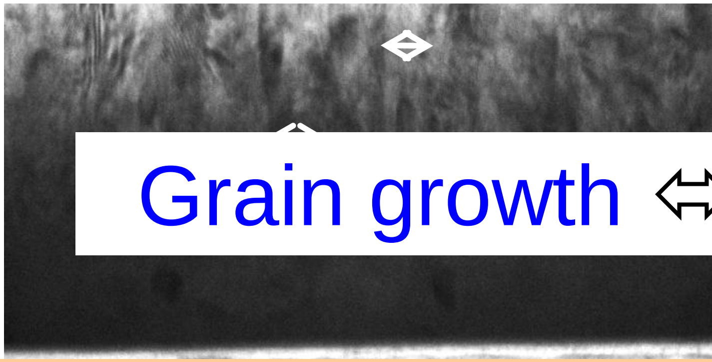
The world largest PRF (10^5) by both-side-coated samples has been achieved!

PRF: one-side-coated < both-side-coated

→ Multiplication of permeation steps are effective for permeation reduction

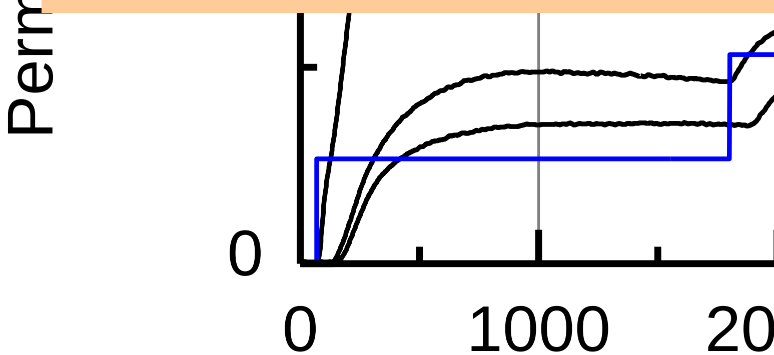


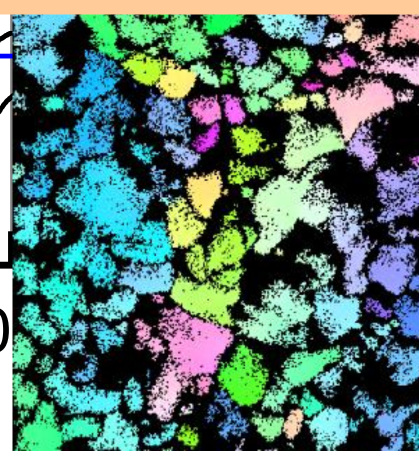
Permeation mechanism in Er_2O_3 coating

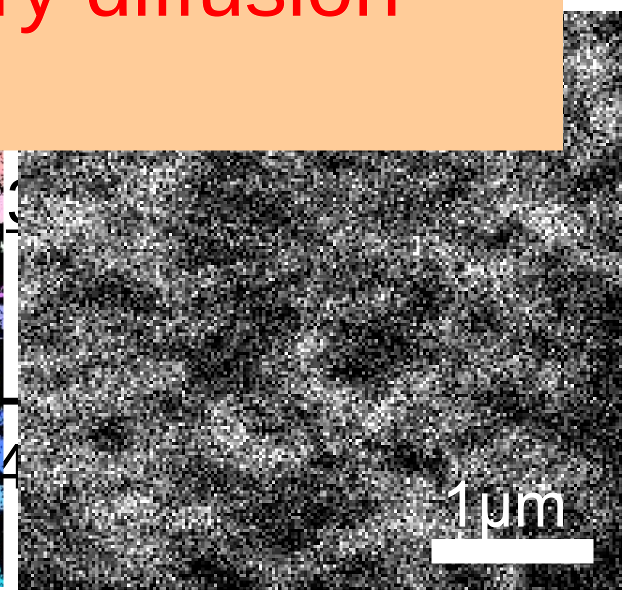


Grain growth ⬄ High TPB efficiency

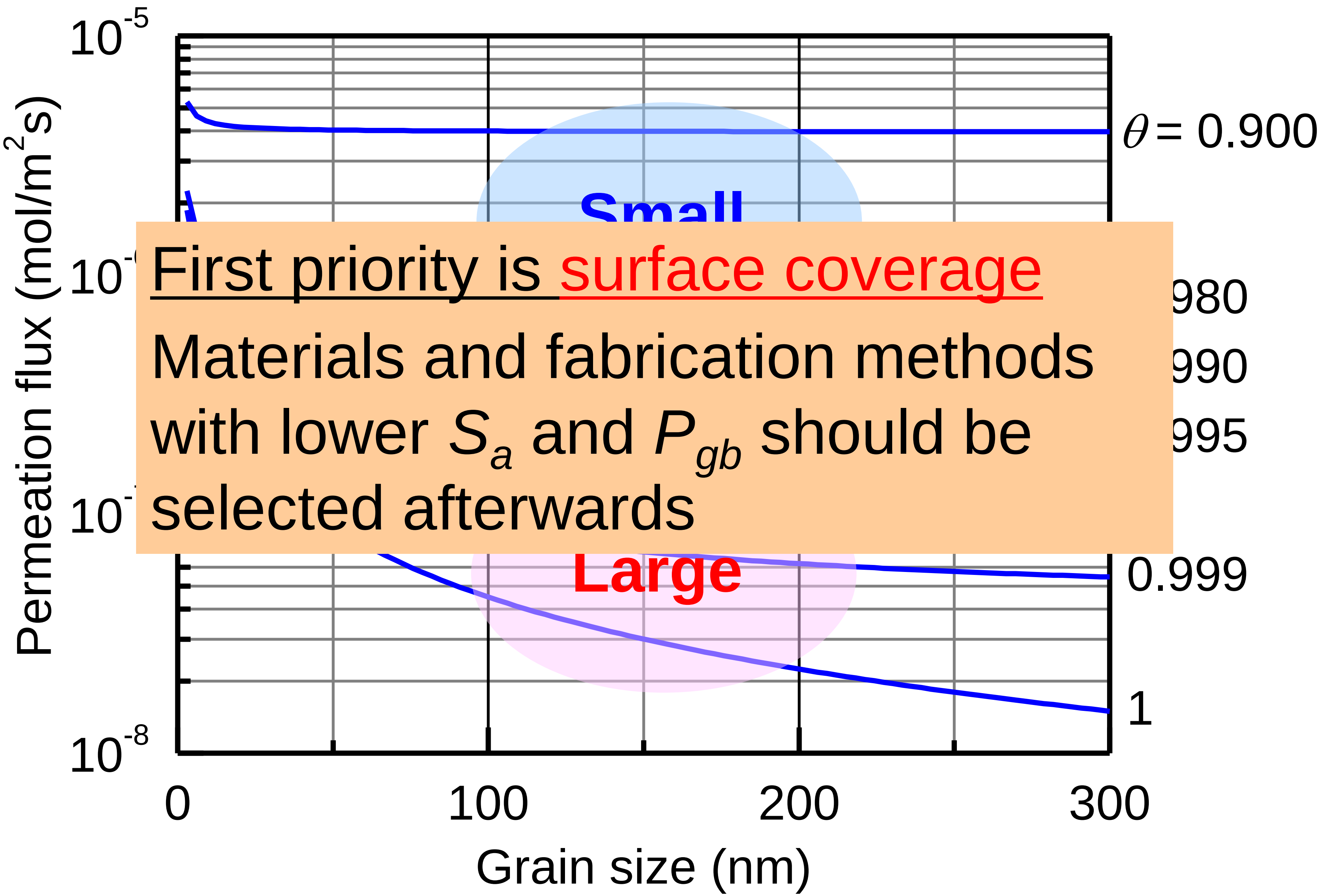
Deuterium permeation through the coating is dominated by grain boundary diffusion rather than lattice diffusion







Modeling of hydrogen permeation



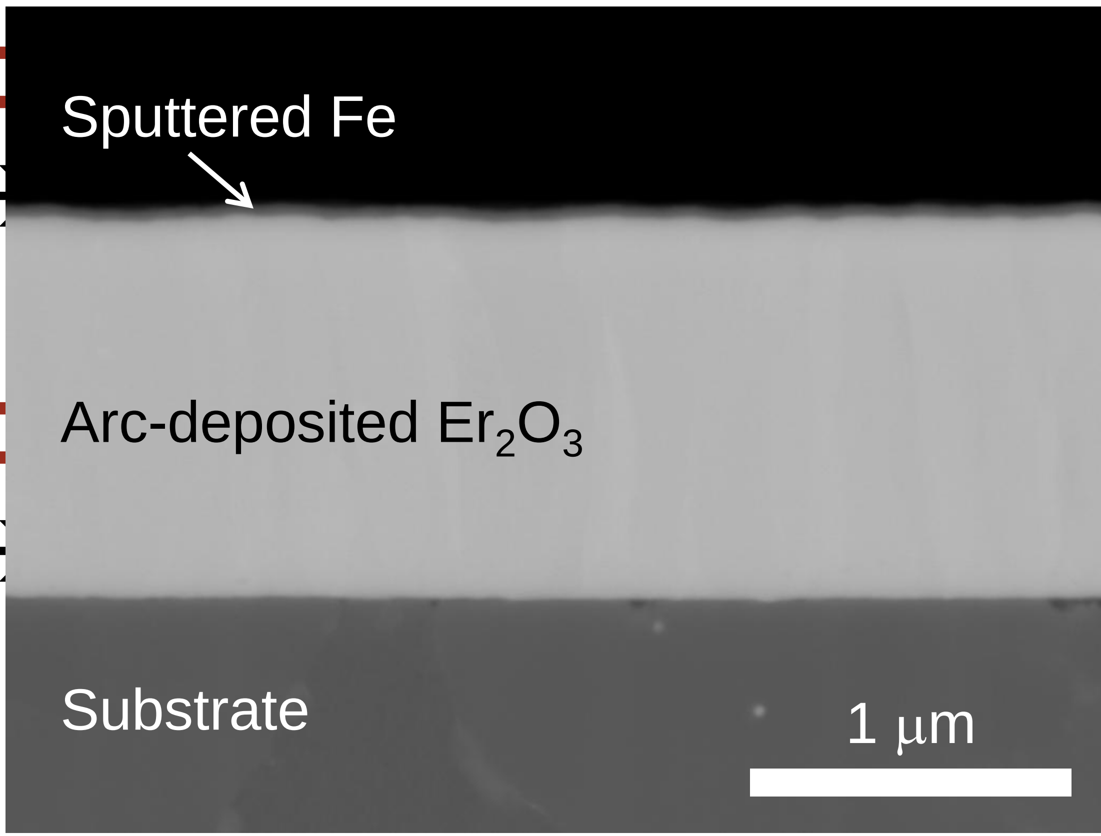
First priority is surface coverage

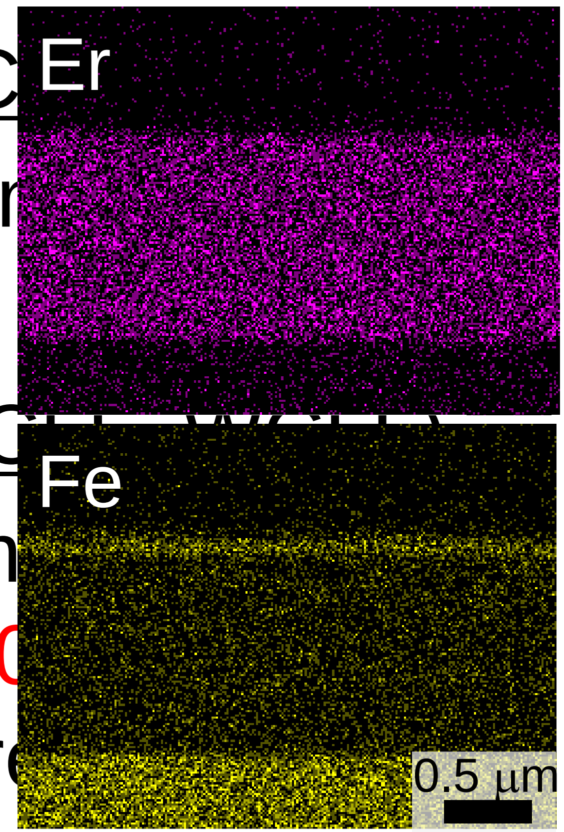
Materials and fabrication methods with lower S_a and P_{gb} should be selected afterwards

Potential of multi-layer coatings (3)

Independent contributions of each layer have been verified by Er_2O_3-Fe two-layer coatings

→ Schemes of layer structure can be optimized depending on requirements





Potential of multi-layer coatings (4)

Application

Structural materials
Contacting materials
Atmosphere
Temperature range

Layer structure

Materials
Number of layers
Methods
Thickness

Gas / Liquid / Solid

Optimized barrier coating

Structural material

Summary (1)

This presentation showcased R&D of TPB for fusion systems and possible spin-offs

1) Methodology for the fabrication of high-quality Er_2O_3 coatings has been established using gas/liquid phase methods

→ PRFs of up to 10^5 have been achieved (world record at > 600 ºC)

2) Various permeation behaviors have been clarified by microstructural analysis and deuterium permeation measurements

Summary (2)

3) Modeling of tritium permeation through Er_2O_3 coating provided useful information for a guidance of further TPB development

→ Surface coverage must primarily be secured

4) Optimization of materials and layer structures may be one solution for the development of TPB coatings and other applications

→ Multi-layer coatings have a possibility to satisfy strict requirements by allocating functions to each layer http://www.iter.org/newsline/264/1566

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Fusion World

Fusion draws on Japanese traditions

-EFDA

Thank you for your kind attention!

The Japanese people have a long history of creating ceramics of great beauty and elegance. Now they are putting their skills towards the search for materials for future fusion plants — in this case not crafting elegant forms, but elegant solutions:

coating, erbium oxide, which may prove to be a vital coating for use in tritium-carrying pipework. "Without solving this problem it will be impossible to operate a fusion reactor," he stated.

Assistant Professor Takumi Chikada's studies show that a layer of erbium oxide only tens of microns thick on a steel surface could reduce permeation of tritium by 100 000 times.© Rob-Keller from flickr.com

Because of its very small size, tritium tends to permeate through materials readily — an undesirable characteristic in a tritium processing plant, where tritium would be exposed to a large surface area as it passes through cooling, ducting and processing pipework.
Assistant Professor Chikada's results showed that a layer of erbium oxide only tens of microns thick on a steel surface could reduce permeation of tritium by 100 000 times.

Erbium oxide was originally chosen as an insulation coating because it has a high thermodynamic stability and is resistant to liquid lithium-lead — a proposed blanket material for fusion plants, which is corrosive to many materials.

Read more on the EFDA website.

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