Solid Breeder Blanket Concepts

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Solid Breeder Blanket Concepts

Outline

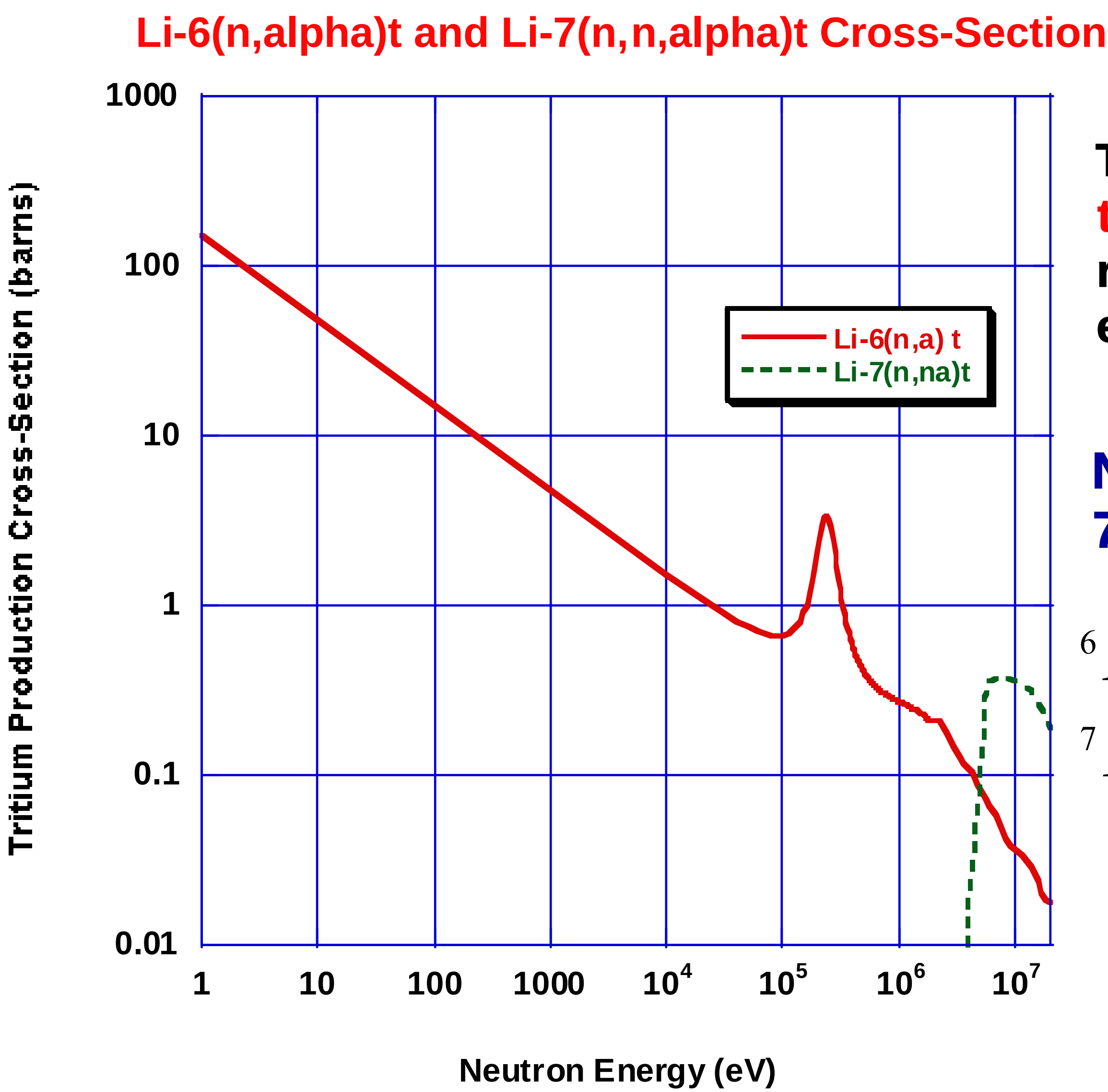
- Introduction to SB and key neutronics aspects
- Types of solid breeders
- Ceramic breeder materials choices and properties and relative advantages
- Configuration and design choices
- Tritium transport and release and extraction modeling and helium purge gas
- Thermo-physical and mechanical properties of pebble beds
- Engineering scaling and ITER TBM design
- R&D issues

Solid Breeder Blanket Concepts

The idea of a solid breeder blanket is to have the lithium-containing tritium breeder as non-mobile and to reduce lithium and tritium inventory as described in M.A. Abdou, L.J. Wittenberg, and C.W. Maynard, "A Fusion Design Study of Nonmobile Blankets with Low Lithium and Tritium Inventories", Nuclear Technology, 26: 400–419 (1975).

- Always separately cooled
- Coolant: Helium or Water
- Solid Breeder: Lithium Ceramic (Li_2O, Li_4SiO_4, Li_2TiO_3, Li_2ZrO_3)
- A neutron multiplier is always required to achieve TBR > 1 (with the possible exception of Li_2O) *because inelastic scattering in non-lithium elements render Li-7 ineffective*
- Only Beryllium (or Be12Ti) is possible (lead is not practical as a separate multiplier)
- Structure is typically Reduced Activation Ferritic Steel (RAFS)

Tritium Breeding



The n(^{7}Li,n,a)t reaction is a threshold reaction and requires an incident neutron energy in excess of 2.47 MeV.

Natural lithium contains 7.5 % ^{6}Li and 92.5 % ^{7}Li.

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

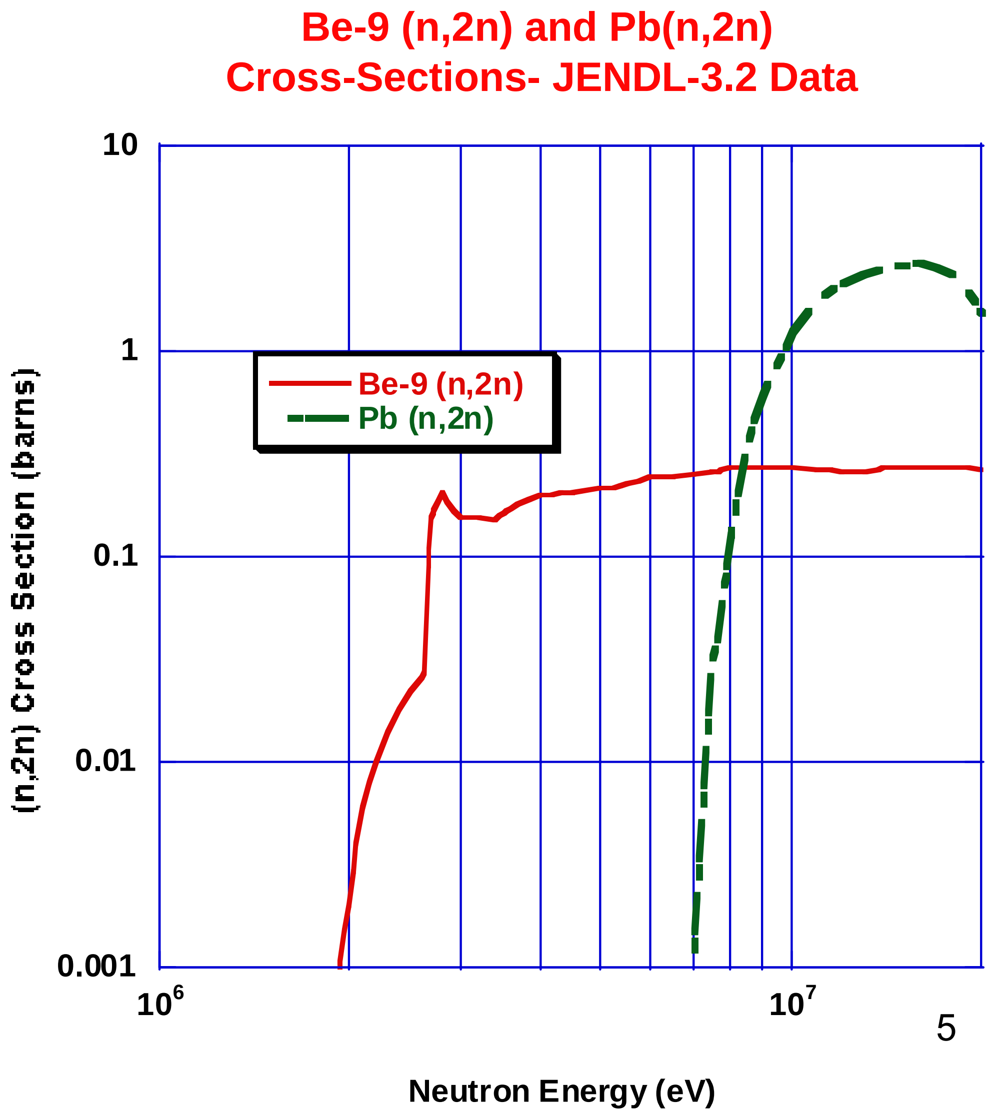
$$^7Li + n \rightarrow t + \alpha + n - 2.47MeV$$

Neutron Multiplication

Neutron Multipliers

- (n,2n) increases the breeding ratio and energy multiplication
- Beryllium has lower threshold(n,2n); hence better neutron and energy multiplication
- Lead is not practical as a separate solid multiplier because of low m.p. 327C
- (Be m.p. ~ 1250C)
- Be resources are limited
- Be chemical reaction with water is a concern. Be12Ti has been proposed because of reduced chemical reactivity

Examples of Neutron Multipliers Beryllium/Beryllides, Lead



Tritium Properties

- T is radioactive

$$t \rightarrow h + \beta^{-}$$

β^{-1} emitter

$$\lambda_t = 1.78x10^{-9}\, s^{-1}\, (\tau_{1/2} = 12.3\, years)$$

- *h* represents the helium-3 nucleus; the maximum β^{-1} energy is 18 keV with an average of 5 keV. This property of nuclear instability is responsible for two important characteristics of tritium: it is naturally scarce and where it does exist, it is a radioactive hazard.
- An indication of the radiation hazard associated with tritium is suggested by calculating the decay rate of, say, 1 kg of tritium. From the definition of **nuclear activity, *Act*,** we have

$$Act = \left| \frac{dN_t}{dt} \right| = \lambda_t N_t \qquad N_t = \frac{M_t}{m_t}$$

M_t is a given mass of tritium and m_t is the mass of one tritium atom

$$Act(1\, kg\, of\, tritium) = \frac{\lambda_t M_t}{m_t} = \frac{1.78x10^{-9}\, x1}{5x10^{-27}} = 3.56x10^{17}\, s^{-1}$$

Translating this quantity into Curies, knowing that 1 Ci = 3.7 x 10^{10} dps (= 3.7 X 10^{10} Bq), the activity of 1 kg of tritium is equal to 10^{7} Ci.

Main Solid Breeder Blanket Material and Configuration Options

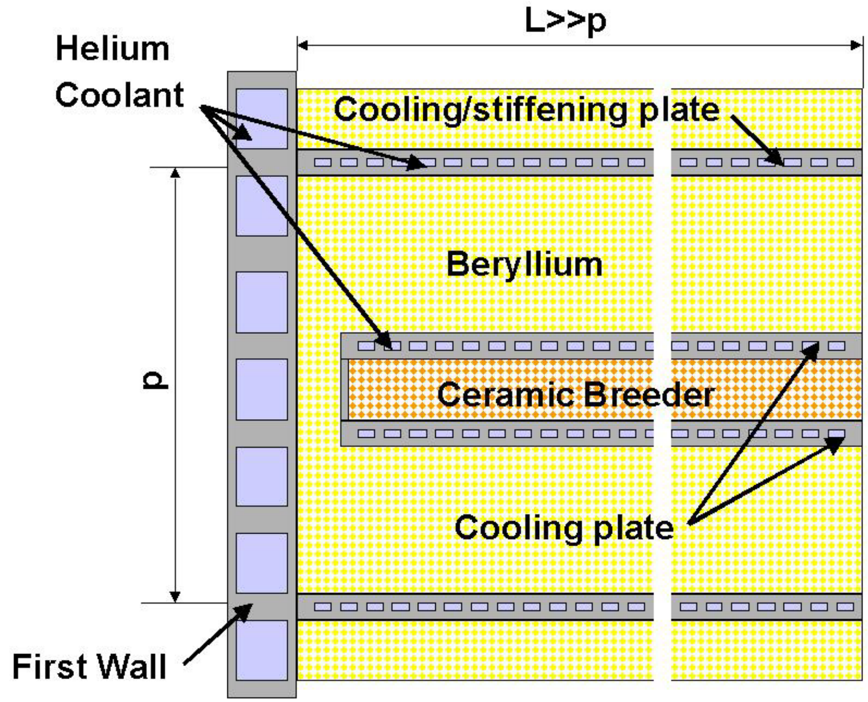
Materials	
Solid Breeder	Li_2O, Li_4SiO_4, Li_2TiO_3, Li_2ZrO_3
Multiplier	Beryllium/Beryllides**
Structure	Ferritic or austenitic (ITER base)
Coolant	Helium or water
Purge	Helium + %H_2
Material form	
Solid breeder and multiplier	Sphere-pac or sintered block
Configuration	BIT, BOT, layers

**High temperature capability and less reactivity

A Helium-Cooled Li-Ceramic Breeder Concept: Example

Material Functions

- **Beryllium (pebble bed) for neutron multiplication**
- **Ceramic breeder (Li_4SiO_4, Li_2TiO_3, Li_2O, etc.) for tritium breeding**
- **Helium purge (low pressure) to remove tritium through the "interconnected porosity" in ceramic breeder**
- **High pressure Helium cooling in structure (ferritic steel)**



Several configurations exist (e.g. wall parallel or "head on" breeder/Be arrangements)

Solid Breeder Concepts: Key Advantages and Disadvantages

Advantages

- Non-mobile breeder permits, in principle, selection of a coolant that avoids problems related to safety, corrosion, MHD

Disadvantages

- Low thermal conductivity, *k*, of solid breeder ceramics
  - Intrinsically low even at 100% of theoretical density (~ 1-3 $W \cdot m^{-1} \cdot c^{-1}$ for ternary ceramics)
  - *k* is lower at the 20-40% porosity required for effective tritium release
  - Further reduction in *k* under irradiation
- Low *k*, combined with the allowable operating “temperature window” for solid breeders, results in:
  - Limitations on power density, especially behind first wall and next to the neutron multiplier (limits on wall load and surface heat flux)
  - Limits on achievable tritium breeding ratio (beryllium must always be used; still TBR is limited) because of increase in structure-to-breeder ratio
- A number of key issues that are yet to be resolved (all liquid and solid breeder concepts have feasibility issues)

Solid breeder material performance requirements and key controlling properties

Primarily focusing on pebble form material

- Tritium breeding performance
  - 6Li enrichment (such a requirement impacts the selection of fabrication process and precursor material choice)
- Tritium release
  - Grain size, microstructure, open porosity
- Breeder material integrity
  - Pebble size, shape, microstructure, mechanical strength, chemical stability
- Need to develop a cost-effective recycling process
  - Li-depletion, feasibility, cost, radioactive isotopes

Which solid breeder ceramic is better?

Parameters:

Lithium density
Tritium residence time
Thermal-physical properties
Mechanical properties
Temperature window
Transmutation nuclides (activation products)
Reactivity
Fabrication

Irradiation effects (e.g, swelling)

Notes:

- Li_2O is highly hygroscopic: $2Li_2O + H_2O \rightarrow 2LiOH$ (ΔH = 128.9 kJ/mole); LiOH is highly corrosive
- Li_2O has been observed to swell under irradiation
- Li_2O is the only ceramic that may achieve the desired TBR without a neutron multiplier (but not assured)

Properties are for 100% TD	Li_2O	Li_4SiO_4	Li_2TiO_3	Li_2ZrO_3
Lithium Density (g/cm³)	0.94	0.51	0.43	0.38
Diameter (mm)	~1.0	0.2~0.7	0.7~0.85	0.9~1.5
Thermal Expansion @ 500 ° C ($\Delta L/L_0$%)	1.25	1.15	0.8	0.5
Thermal Conductivity @ 500 ° C (W/m/ ° C)	4.7 Higher	2.4 design margin	1.8	0.75
Min.-Max. Temp. for Tritium Release (°C)	397-795	325-925 Relatively	Up to 900 narrow T window	400-1400
Swelling @ 500 ° C ($\Delta V/V_0$%)	7.0	1.7	-	< 0.7
Reactivity w/H_20	High	Little	Less	Less
Grain Size (μm)	50	5-15	1-4	0.5-2
Density (%TD) Pore for tritium release	80-85	~98	87~89	93~96
Crush Load (N)	-	~ 10	24-33	68-79
Residence time @400 °C (h)	10	2	2	1

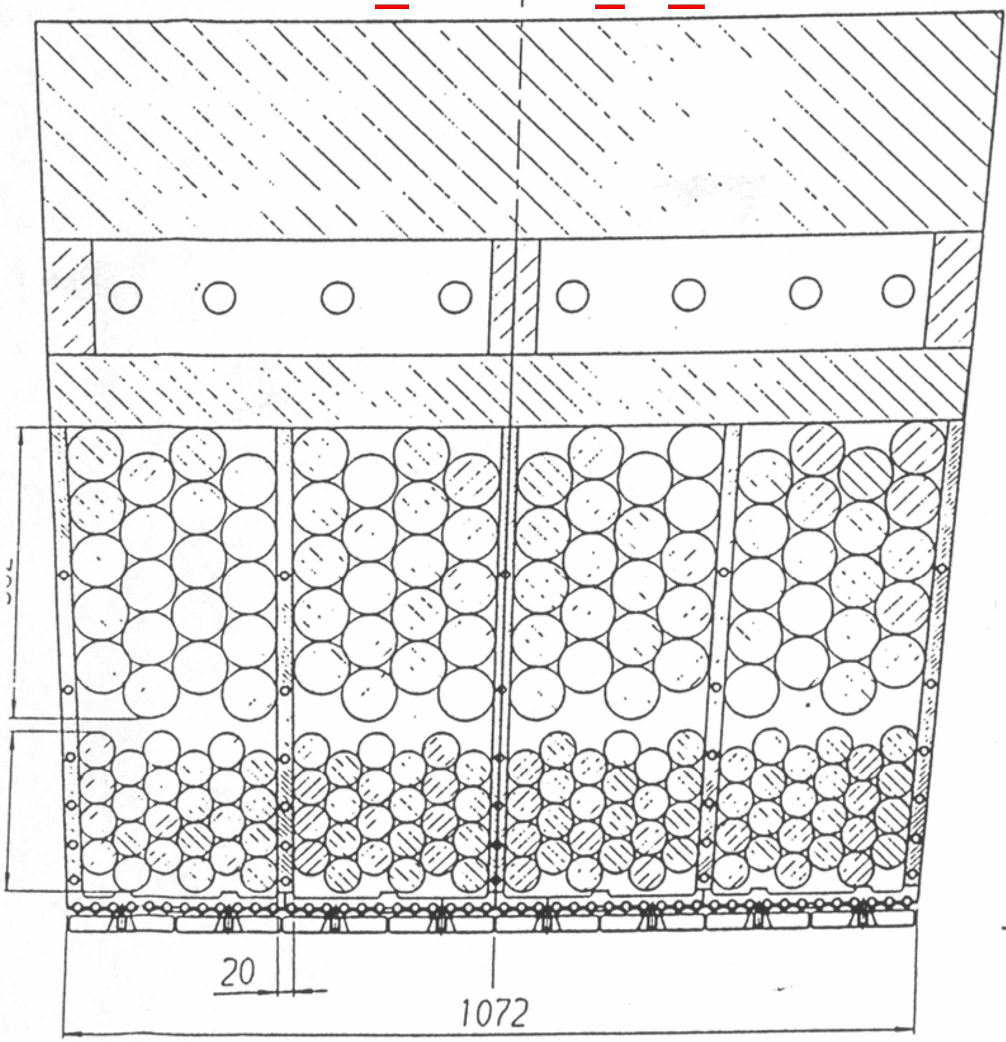
Example : Operational Specifications for DEMO-95 and FPP Model B (EU) for Helium-cooled SB

	DEMO (1995)	FPP Model B (2001)
Structural Material	FM (MANET)	RAFM (EUROFER)
Breeder Packing density ~ 62%	Li-Orthosilicate (Li-Metatitanate) s-sized pebble beds	Li-Orthosilicate (Li-Metatitanate) s-sized pebble beds
Multiplier	binary Be pebble beds (2.0 and 0.1-0.2 mm) Packing density ~ 80%	s-sized Be pebble beds (1mm) Packing density ~ 62%
Coolant (in/out) temperature	250 / 450 °C	300 / 500°C
Coolant pressure	8 MPa	8 MPa
Power conversion system	water-steam	water-steam
Net efficiency of the power conversion system (*)	30 %	40.5%
Lifetime	7.5 MWa/m^2 (= 75 dpa in steel)	15 MWa/m^2 (= 150 dpa in steel)

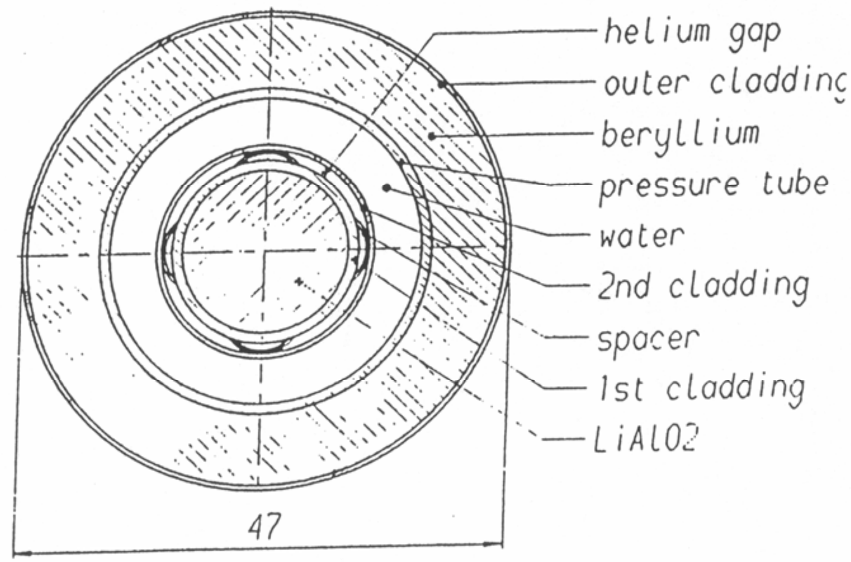
(*) thermal efficiency of blanket/divertor loop (pump power subtracted)

BIT BLANKET DESIGN

Breeder In Tube

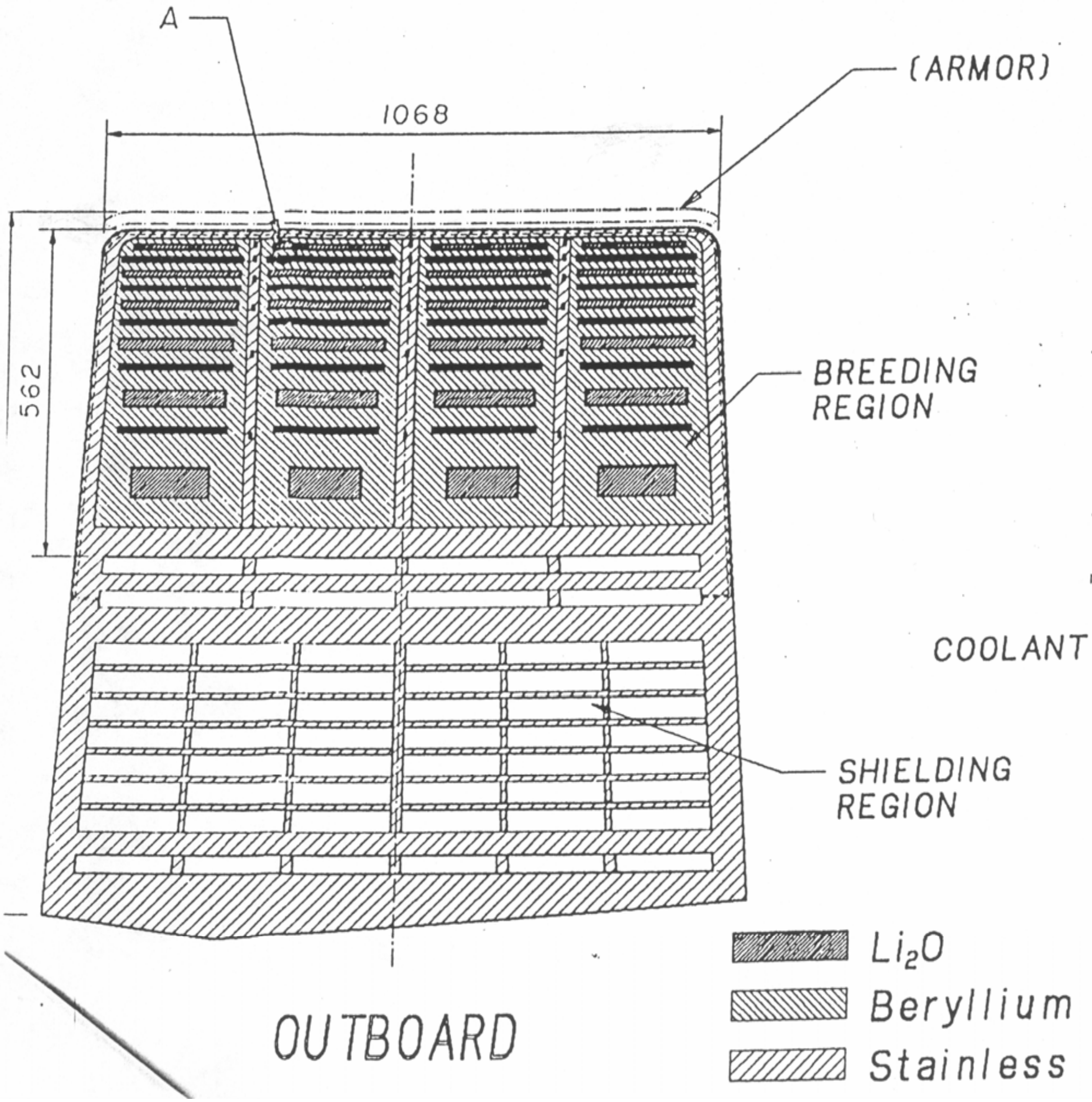


OUTBOARD BLANKET MIDPLANE SECTION

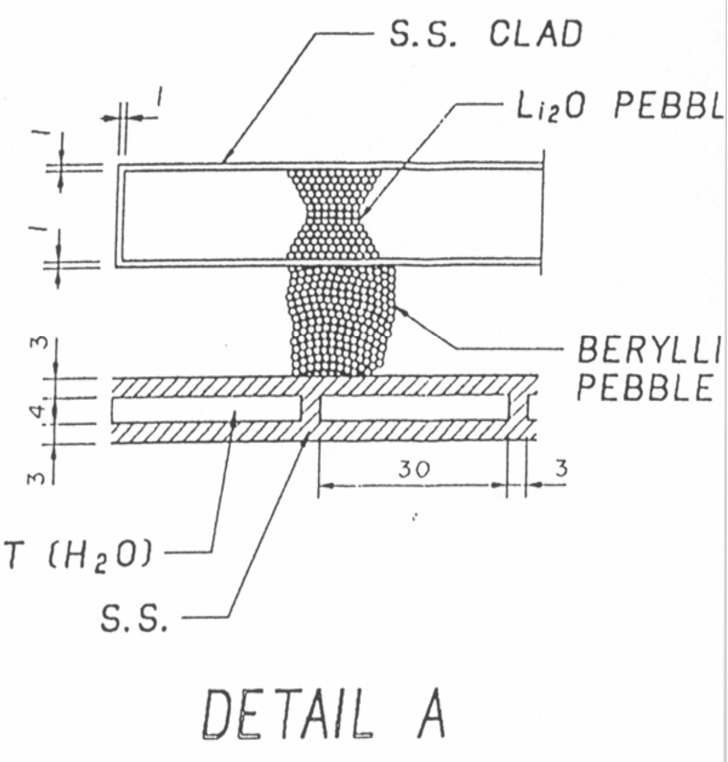


BLANKET MODULE - DETAIL

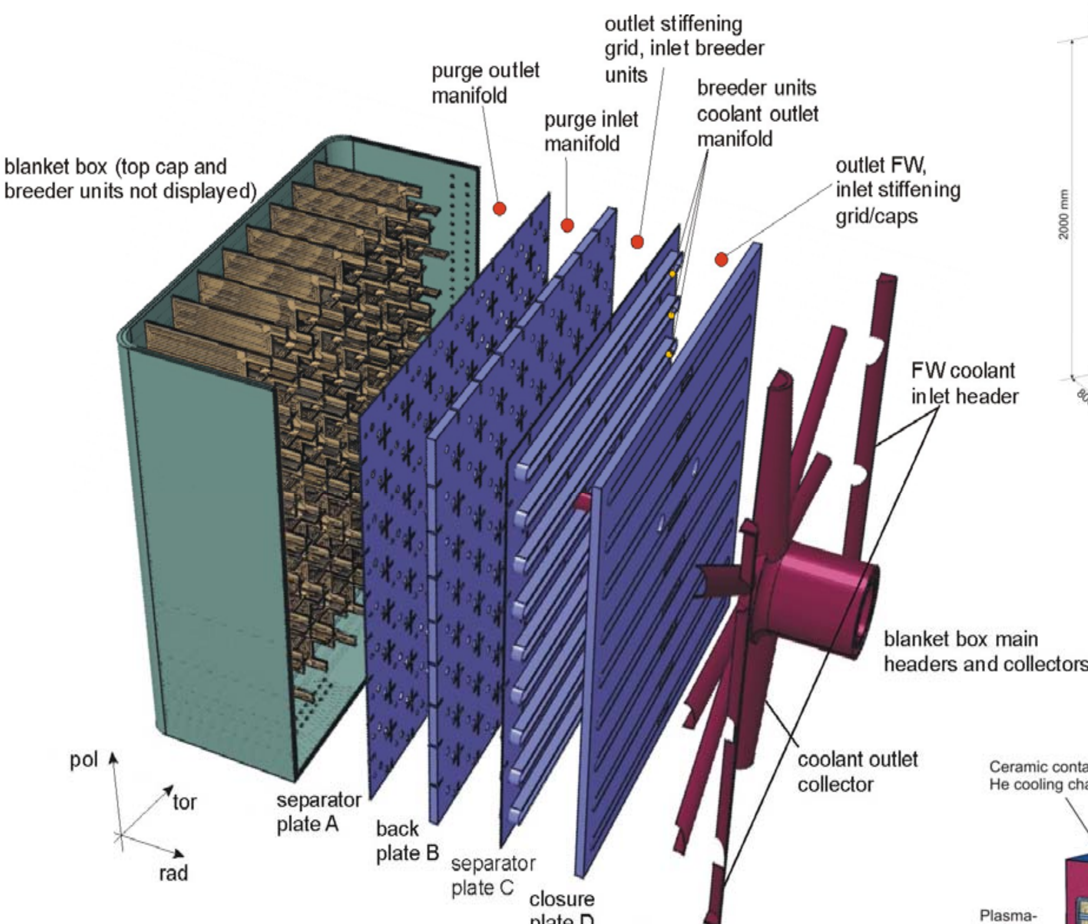
CERAMIC BLANKET "LAYERED" CONCEPT
—PEBBLE BED DESIGN—

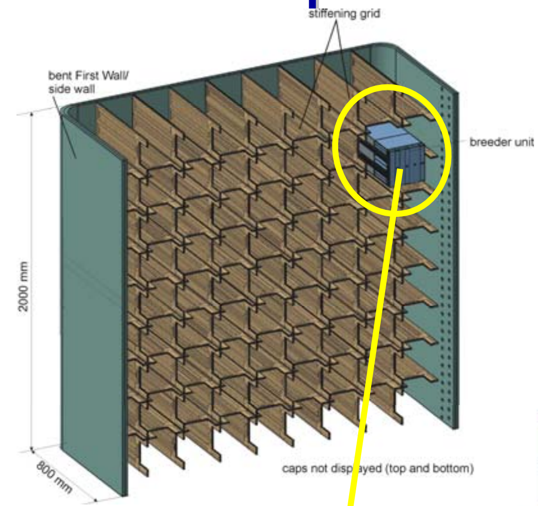


BOT (Breeder-out of – Tube) concept

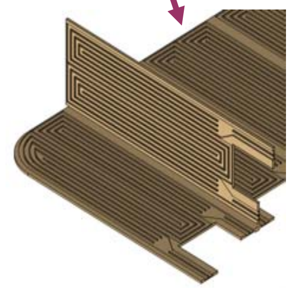


Helium-Cooled Pebble Breeder Concept for EU

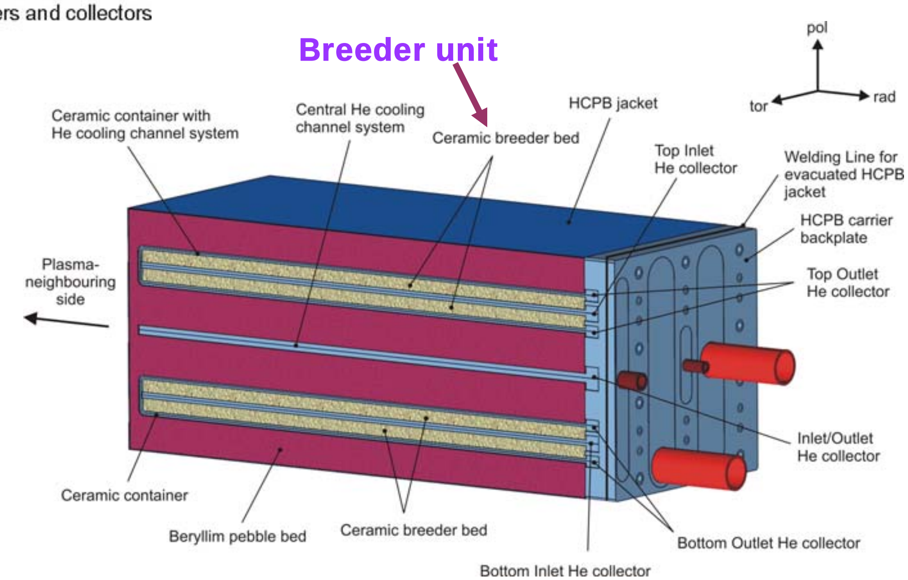




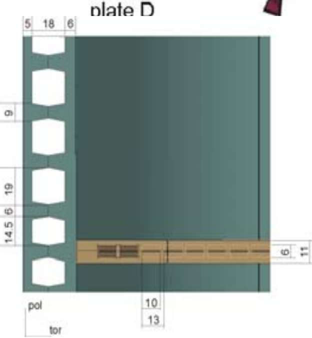
Stiffening grid



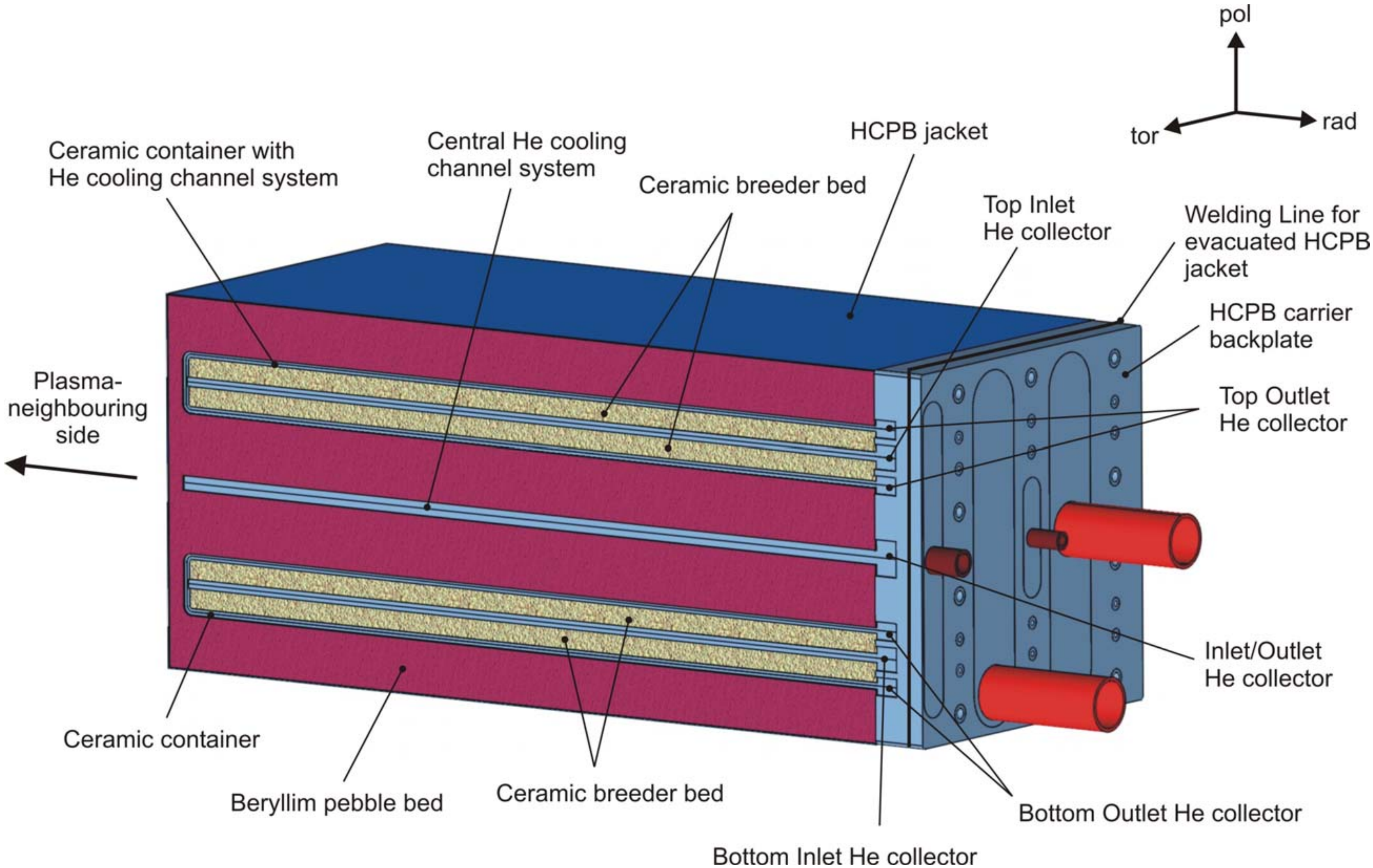
Breeder unit



FW channel

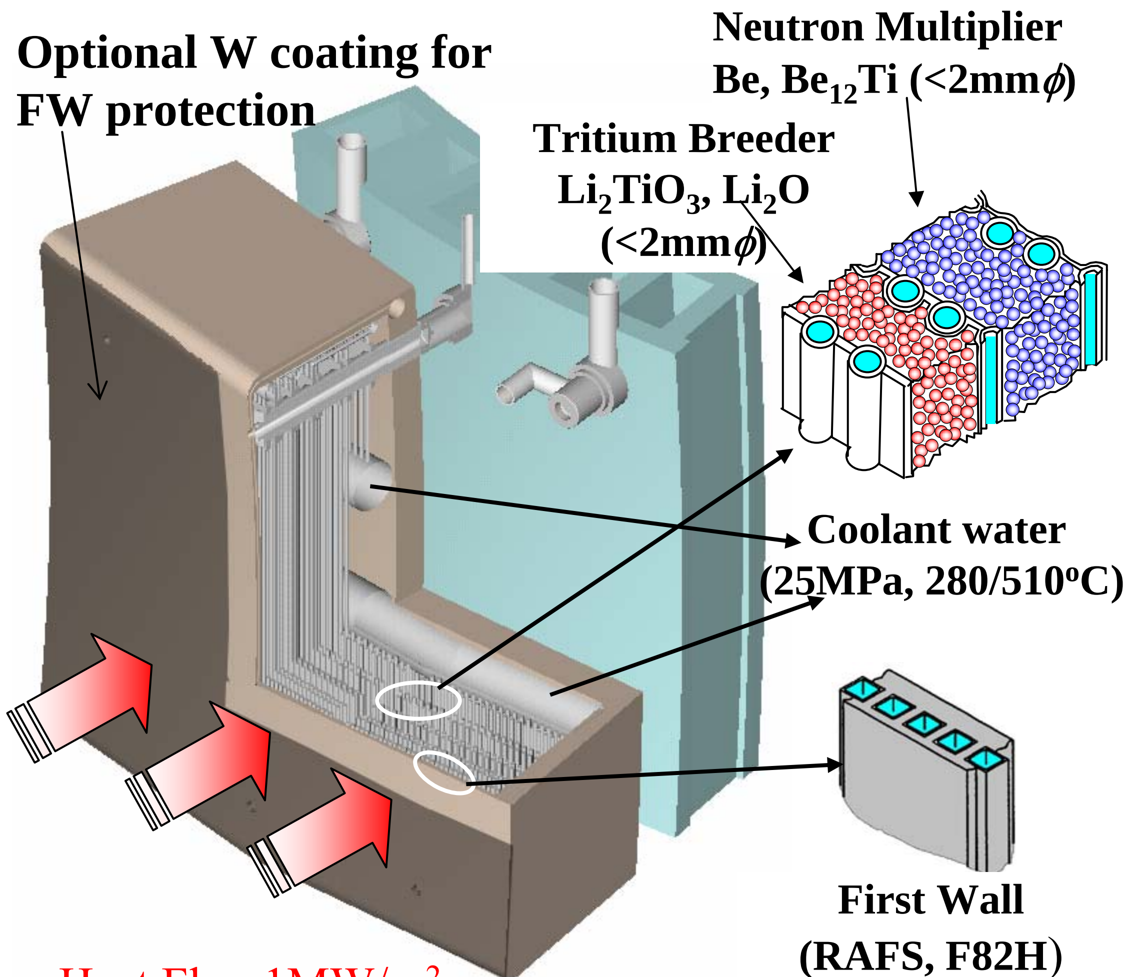


Breeder Unit for EU Helium-Cooled Pebble Bed Concept



JA Water-Cooled Solid Breeder Blanket Design

- Modular type, front access replacement on sight
- Box wall with embedded coolant channels
- Pebble bed type breeder and multiplier layers separate with cooling tubes and partition walls
- Supercritical Water for coolant (25MPa, 280-510^{o}C)
- Coolant flow pattern to cool first walls first and, then, breeder and multiplier layers of multiple blanket modules

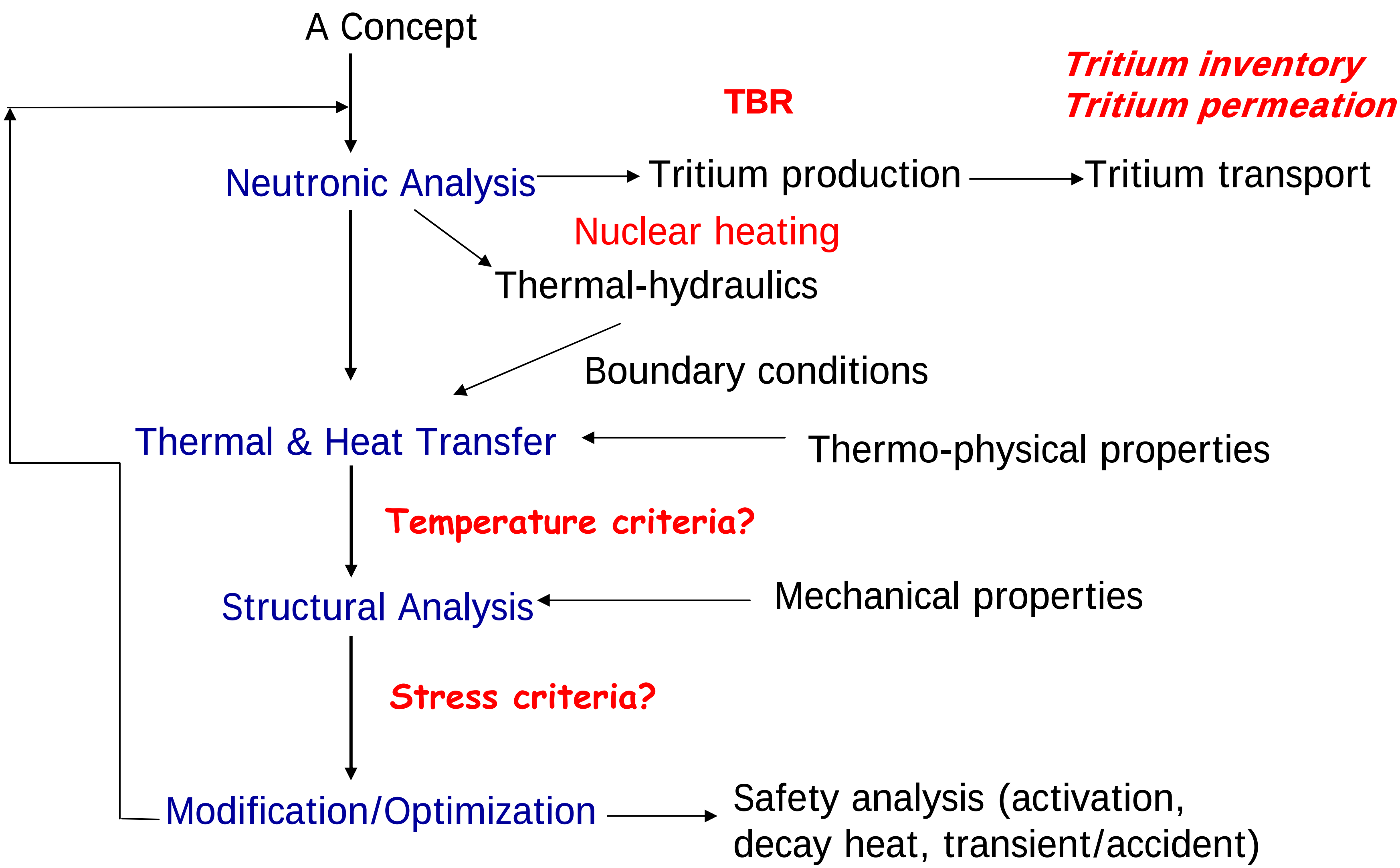


Surface Heat Flux:1MW/m^2

Neutron Wall Load: 5MW/m^2(1.5×10^{15}n/cm^{2}s)

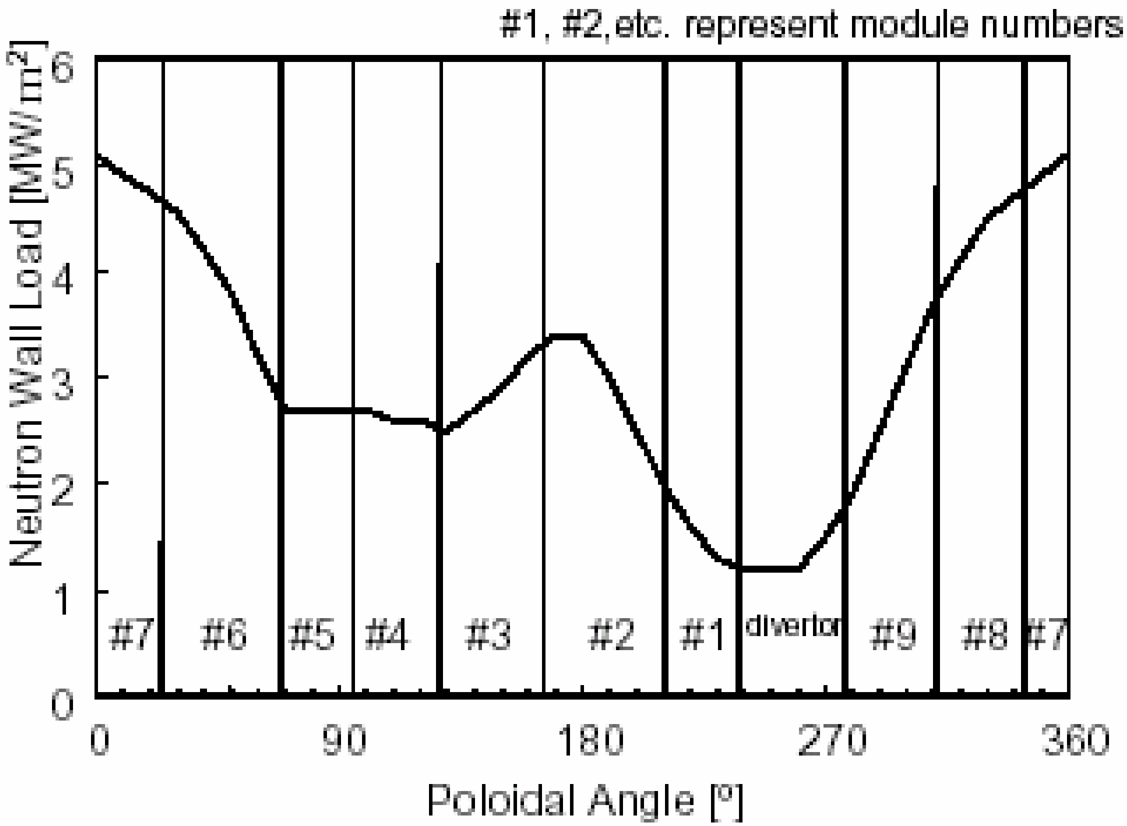
[M. Enoeda, et al., “Design and R&D results of Solid Breeder Blanket Cooled by Supercritical Water in Japan”, FT/P1-08, Fusion Energy 2002 (Proc. 19th Int. Conf. Lyon, 2002) (Vienna:IAEA) CD-ROM file FT/P1-08 and http://www.iaea.org/programmes/ripc/physics/fec2002/html/fec2002.htm.

Solid Breeder Blanket Analysis

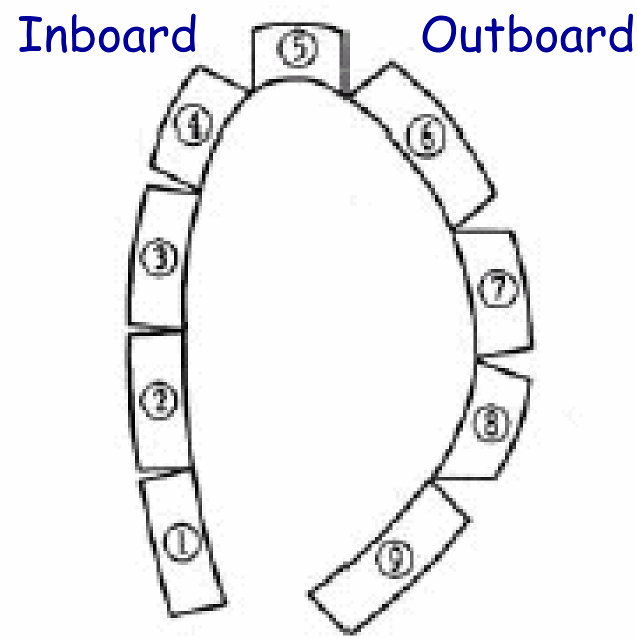


Profile of Neutron Wall Load

Neutron wall load have profile along the poloidal angular (equatorial plane is 0°). Average is about 3.5 MWa/m². Peak is 5 MWa/m² at equatorial module.



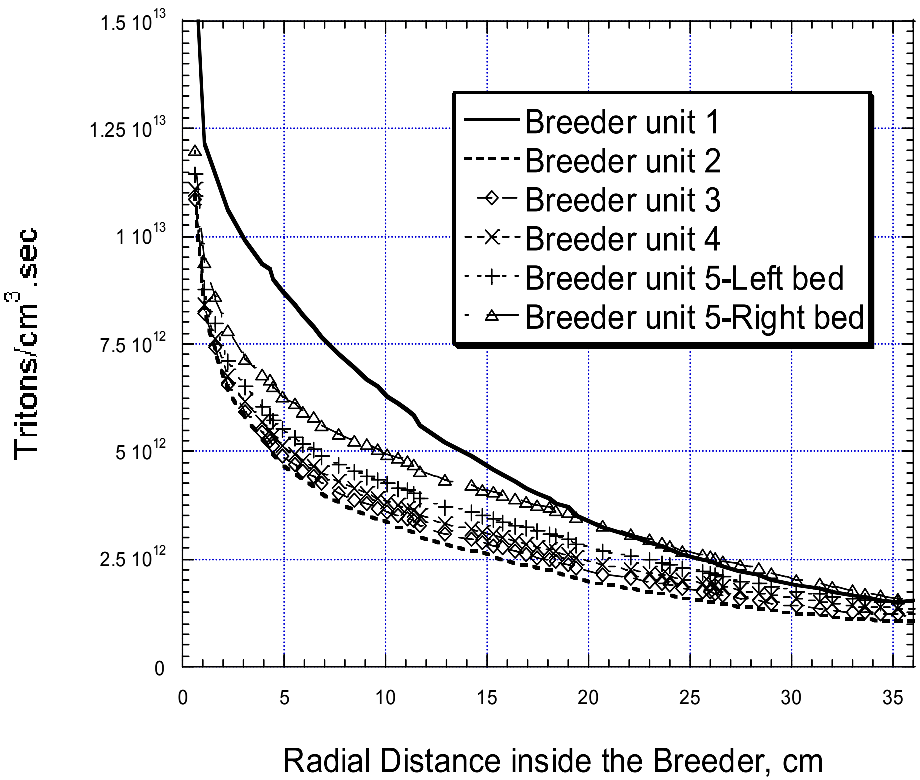
Profile of Neutron Wall Load

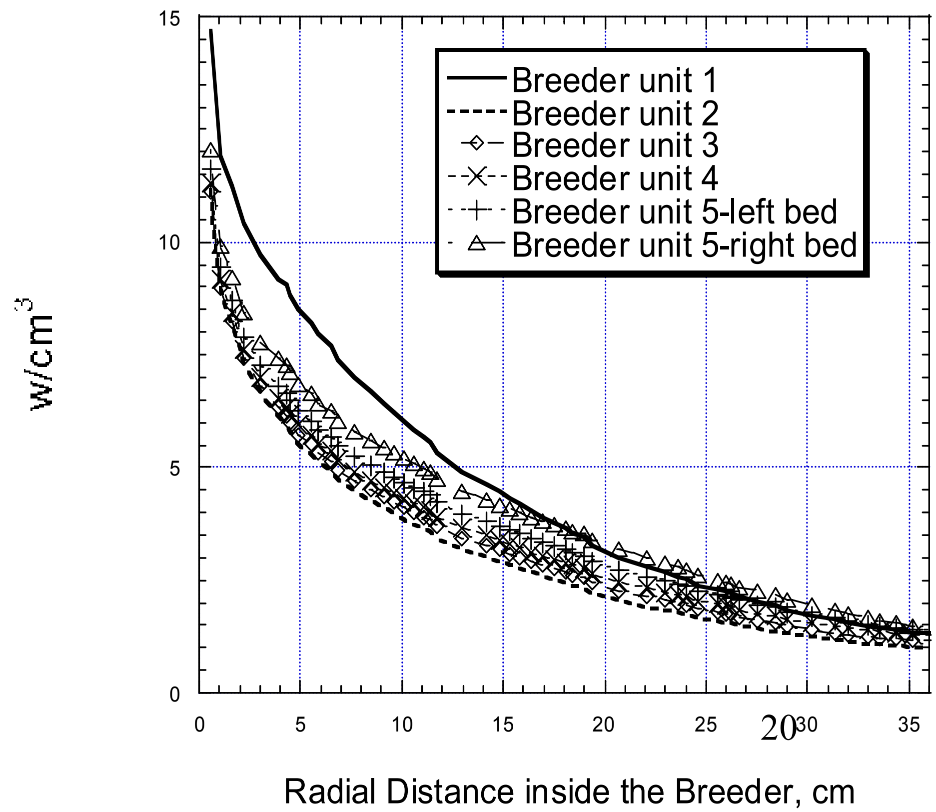


Module #

Neutronics (tritium and nuclear heating profiles)

- Since the blanket is exposed to high energy neutrons entering from the fusion plasma, the neutron density is a maximum in the first wall domain and then attenuates rapidly, even if a reflector zone completes the blanket composition.
- A consequence of this is that energy deposition will similarly vary with the depth of blanket penetration. The general trend of an exponential fall-off from the plasma side to the blanket interior must be considered in designing the coolant flow pattern and also in calculations of breeding, radiation damage, and activation.





Tritium Release - Introduction

Tritium inventory (held up)
Tritium release
Tritium permeation

- The most probable form of a solid breeder in a blanket is illustrated in Figure 10.1.4. The breeding material will be in small grains, which are then formed into particles (-1 mm) with fine porosity. The particles, in turn, are packed into beds with a coarse porosity among particles.
- A low-pressure helium purge gas flows through the packed bed to recover tritium and carry it to an external processing system.
- The tritium produced within the grains must diffuse to the grain surface, desorb as T_20 (HT), migrate through the fine- grain-structure porosity and then "percolate" through the coarse-particle- structure porosity to the helium purge stream.

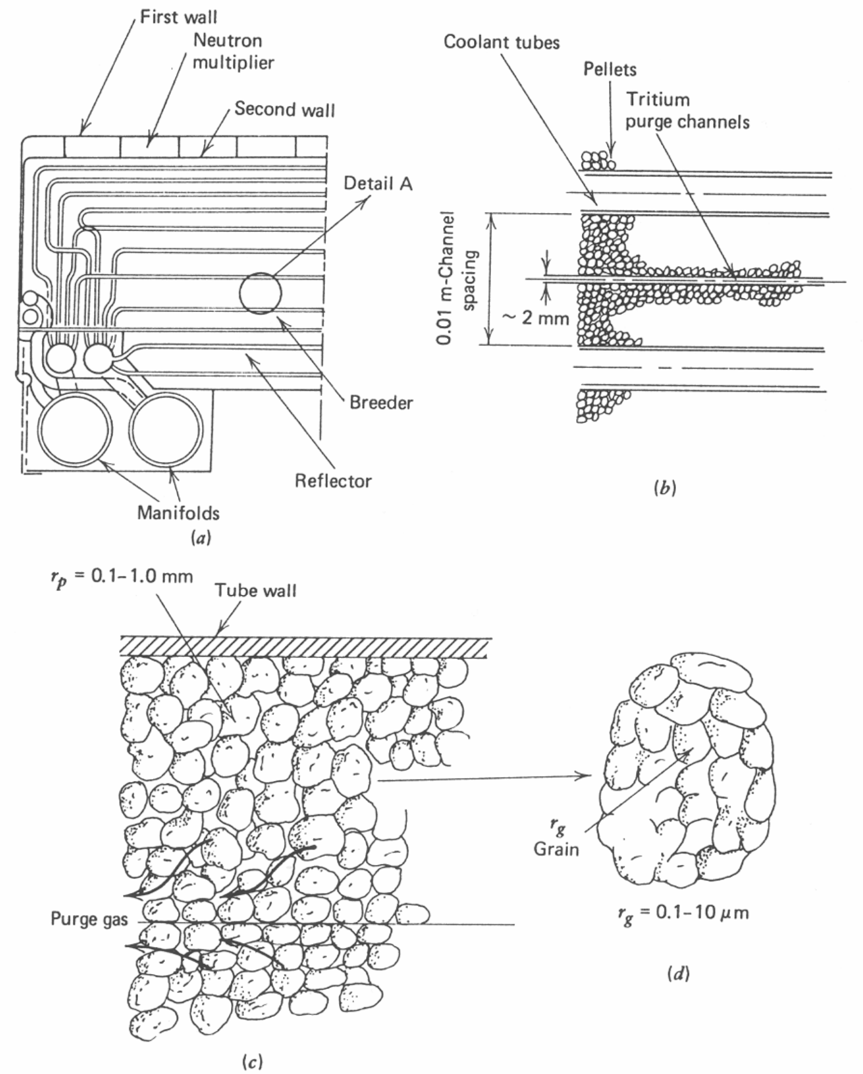


Figure 10.1.4. Schematic diagram of solid breeder blanket concept showing solid breeder microstructure with bimodal pore distribution and tritium removal scheme: (*a*) solid breeder; (*b*) section A–A; (*c*) packed bed; (*d*) pellet. (Reproduced with permission from W. M. Stacey, et al., "US INTOR", Ga. Inst Techn. report, 1981.)

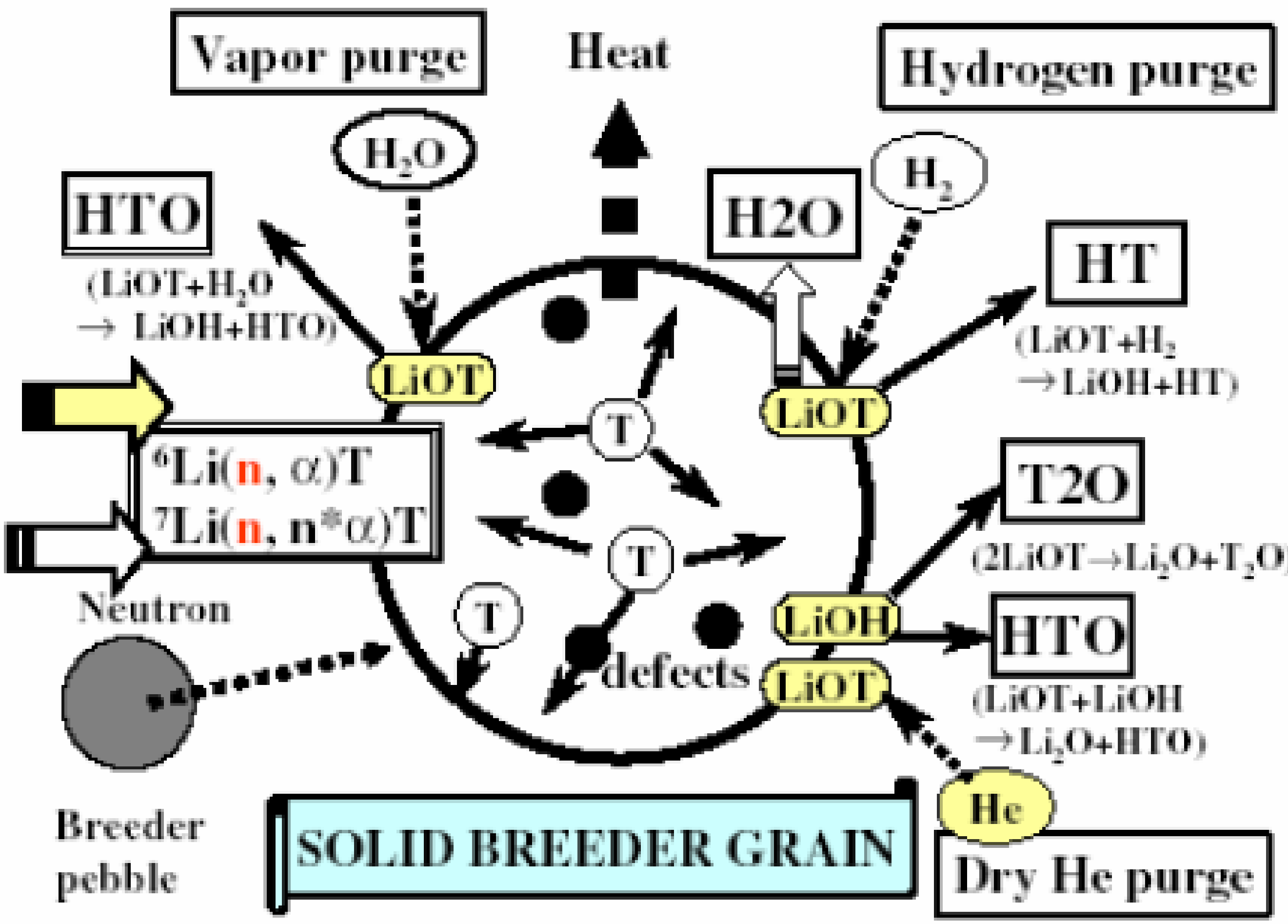
“Temperature Window” for Solid Breeders

- The operating temperature of the solid breeder is limited to an acceptable “temperature window”: T_{min}– T_{max}
  - T_{min}, lower temperature limit, is based on acceptable tritium transport characteristics (typically bulk diffusion). Tritium diffusion is slow at lower temperatures and leads to unacceptable tritium inventory retained in the solid breeder
  - T_{max}, maximum temperature limit, to avoid sintering (thermal and radiation-induced sintering) which could inhibit tritium release; also to avoid mass transfer (e.g., LiOT vaporization)
- The limitations on allowable temperature window, combined with the low thermal conductivity, place limits on allowable power density and achievable TBR

Tritium Release and Temperature Window

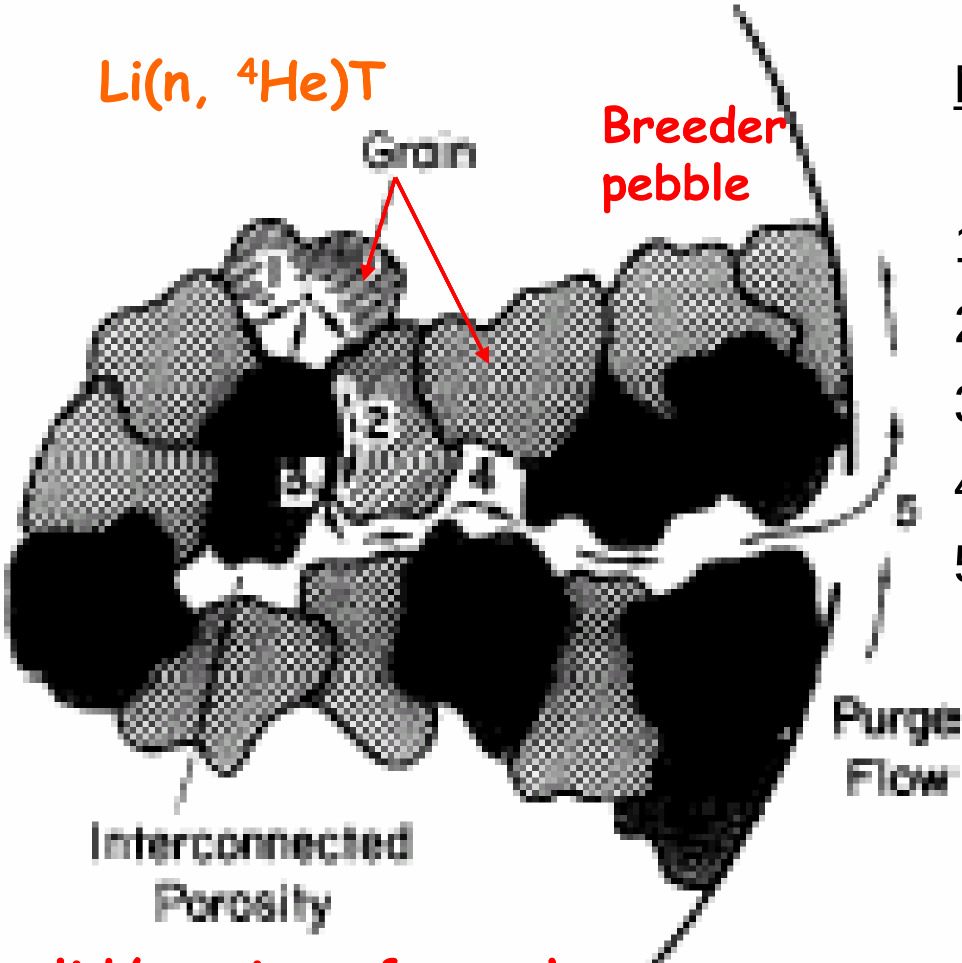
In-situ recovery of tritium from a solid breeding blanket imposes limits on the operating temperature of the breeder. The migration rate of the bred tritium through the bi-level porosity structure (grains/particles) to the purge stream is not very temperature dependent, but the diffusion of the tritium out of the grains increases strongly with temperature. On the other hand, when the temperature exceeds -80% of the melting temperature, restructuring and sintering of the grains may occur, which reduces the porosity and thereby decreases the migration rate. There is some evidence that neutron bombardment may also lead to sintering taking place at lower temperatures (- 60% of the melting temperature). Thus, there are upper and lower temperature limits. A quantification of these limits may be specified by determining the temperature range over which the tritium removal rate is sufficiently large so that the tritium held up in the blanket is less than 1-2 kg for a few thousand thermal megawatt level reactor.

Schematic of tritium breeding and release from a ceramic breeder pebble



Mechanisms of Tritium Transport

Li(n, ^{4}He)T



(solid/gas interface where adsorption/desorption occurs)

Mechanisms of tritium transport

1) Intragranular diffusion
2) Grain boundary diffusion
3) Surface Adsorption/desorption
4) Pore diffusion
5) Purge flow convection

Purge gas composition:

He + 0.1% H_2

Tritium release composition:

T_2, HT, T_2O, HTO

Some Mathematical Formulas

Diffusion model:

Generation rate

$$\frac{\partial C(r,t)}{\partial t} = D(T)\left(\frac{\partial^2 C(r,t)}{\partial r^2} + \frac{2}{r}\frac{\partial C(r,t)}{\partial r}\right) + G(r,t)$$

$$C(r,0) = 0$$

$$C(a,t) = 0$$

$$\left(\frac{\partial C(r,t)}{\partial r}\right)_{r=0} = 0$$

Activation energy

$$D(T) = D_0 \exp(-E_d / RT)$$

$$\boxed{C = \frac{G}{6D}(a^2 - r^2) + \frac{2Ga^3}{D\pi^3 r}\sum \frac{(-1)^n}{n^3}\sin\left(\frac{n\pi r}{a}\right) x \exp\left(-Dn^2\pi^2 t / a^2\right)}$$

First -order tritium release rate estimated:

Surface concentration (atoms/m^2)

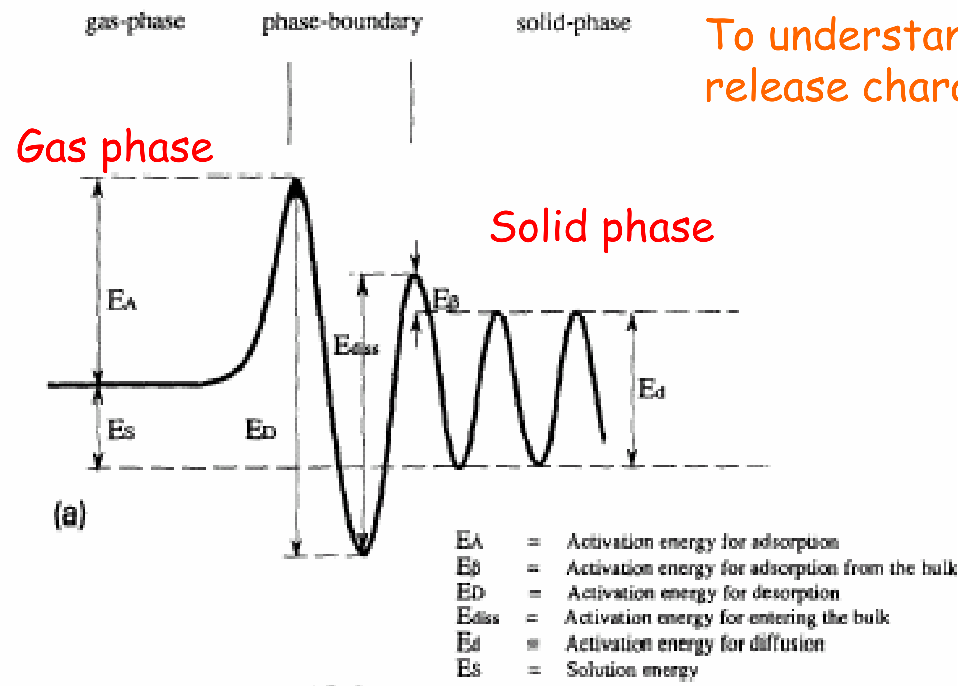
$$R(t) = -dC_s / dt = K_{des}(t) C_s(t) = K_0 C_s(t) \exp(-E_{des} / RT(t))$$

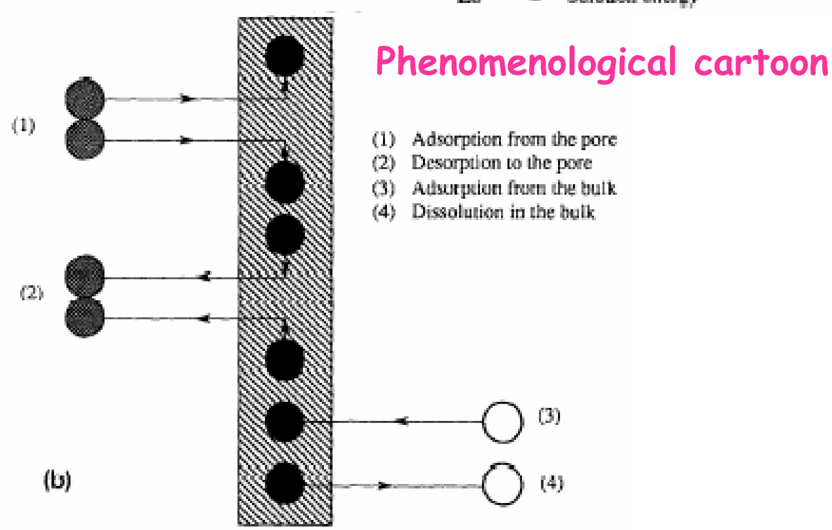
Desorption rate constant

Desorption energy

$$C_s(t) = C_{s0} \exp\left[K_0 \int_0^t \exp(-E_{des} / RT(t'))dt'\right]$$

MISTRAL (Model for Investigative Studies of Tritium Release in Lithium Ceramics) - a code developed at UCLA





To understand and predict tritium release characteristics

Transport mechanisms included:

- grain diffusion
- grain boundary diffusions
- adsorption from the bulk and from the pores to the surface
- desorption to the pores
- diffusion through the pores

Features

- includes details of the ceramic microstructure
- includes coverage dependence of the activation energy of surface processes (adsorption/ desorption)

Effect of helium purge flow rate on pressure drop and tritium permeation

$$\Delta P = 175\frac{(1-\alpha)^2}{\alpha^3}\frac{\mu_f NRTL}{(\varphi d_p)2A_b(P_0+\Delta P/2)}$$

α =Porosity,
φ = pebble sphericity =1 for spherical pebble
N = moles/s
R = ideal gas constant
T = temperature

μ_f= helium gas viscosity
A_b= gas flow cross-sectional area
P_0= inlet pressure
L = flow path
d_p = particle diameter

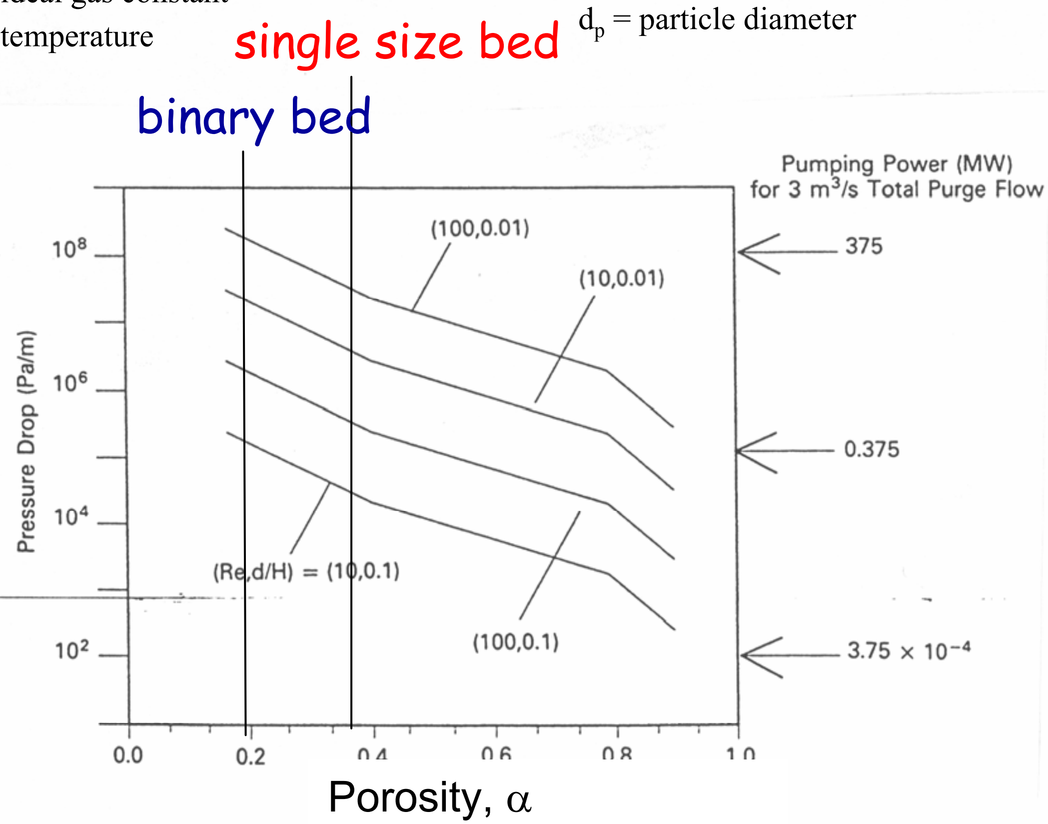


Fig. 18. Purge flow pressure drop per unit length as a function of porosity, Reynolds number, and particle-diameter-to-half-channel-width ratio for a 2-cm-wide channel.[65]

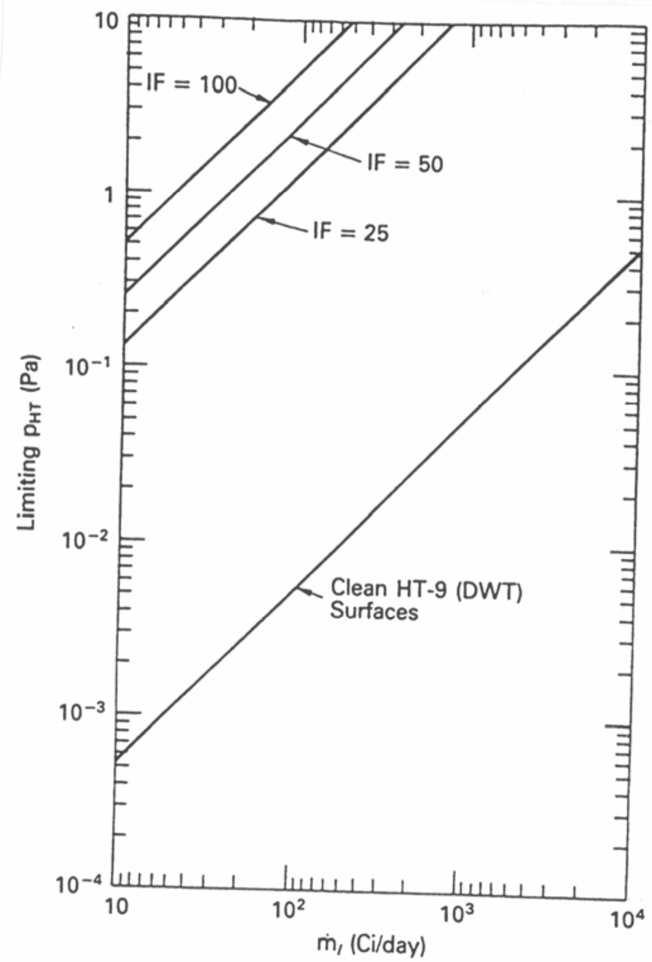


Fig. 19. Limiting tritium partial pressure in the purge channel as a function of maximum tritium leakage rate $\dot{m}_l$ into the primary coolant loop for different oxide IF ($LiAlO_2/H_2O/HT\text{-}9/Be$ blanket).[6]

Purge Flow Analysis

Governing equations

- Momentum equation

(Darcy-Brinkman-Forchheimer equation)

$$\rho \frac{\partial}{\partial x_\beta}\left(\phi \left\langle u_\alpha \right\rangle^i \left\langle u_\beta \right\rangle^i\right) = -\frac{\partial}{\partial x_\alpha}\left(\phi \left\langle p \right\rangle^i\right) + \mu \frac{\partial^2}{\partial x_\beta^2}\left(\phi \left\langle u_\alpha \right\rangle^i\right)$$

Permeability K for macroscopic shear effect

$$-\frac{\mu_{\text{eff}}}{K}\phi^2 \left\langle u_\alpha \right\rangle^i - \frac{F\rho}{\sqrt{K}}\phi^3 \left|\left\langle u_\beta \right\rangle^i \cdot \left\langle u_\beta \right\rangle^i\right| \left\langle u_\alpha \right\rangle^i$$

$$K = \frac{\phi^3 d_p^2}{150\left(1-\phi\right)^2} \qquad F = \frac{1.75}{\left(150\phi^3\right)^{1/2}}$$

= Inertia coefficient

$$\left\langle \varphi \right\rangle^i = \frac{1}{\Delta V_f}\int_{\Delta V_f} \varphi \, dV$$

Intrinsic (fluid-based average) value

Packed Bed Properties

Void Fraction distribution inside the bed

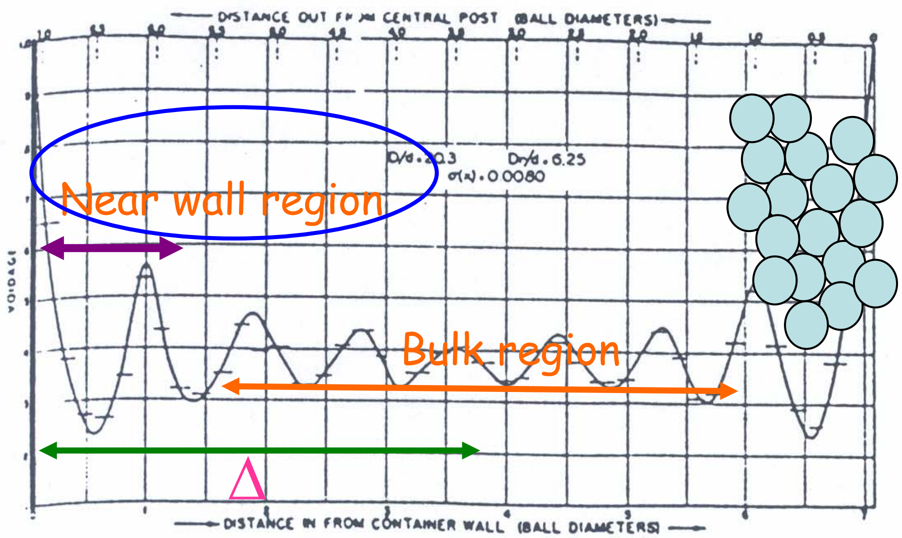


Fig. 4. Void fraction in a large bed of uniform spheres containing a central post.

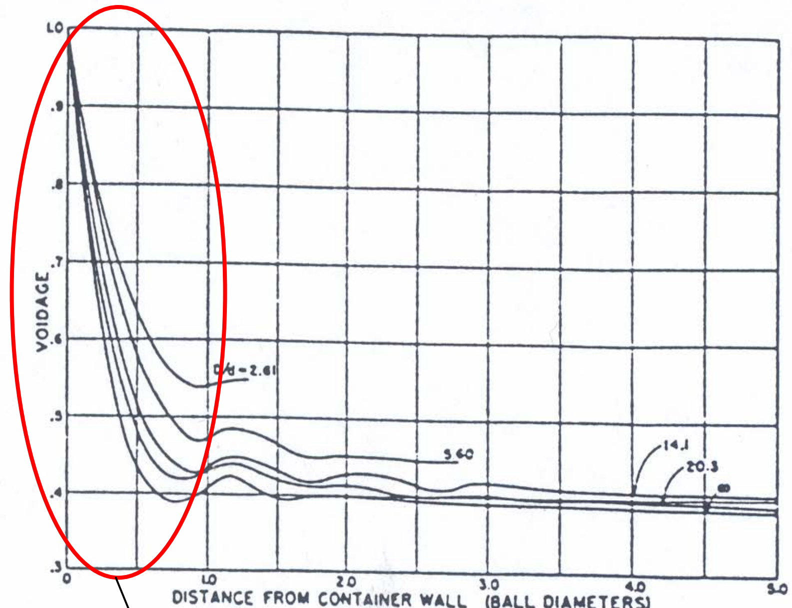


Fig. 5. Integrated void fractions in beds of uniform spheres for various D/d ratios.

A higher void fraction in the near-wall region results in a much higher purge gas velocity

Pebble bed thermal resistance

$$R = \frac{1}{h} + \frac{\Delta}{k}$$

h: interface conductance

k: effective thermal conductivity

Δ: half bed width

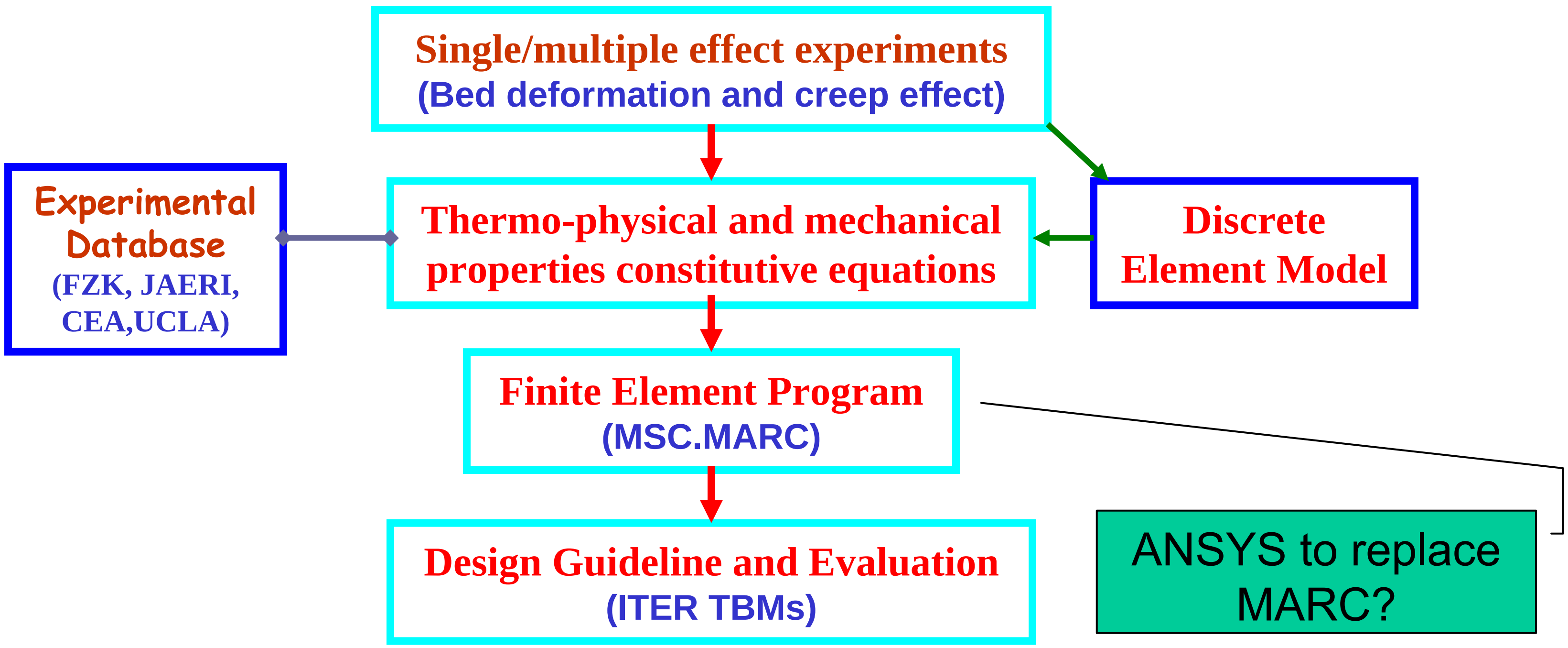
Thermo-mechanical Behaviors of Breeder Pebble Bed Systems

Variables:

- Pebble materials
- Bed properties
- Boundary conditions
- Operation loadings

Primary Reactants:

- Stress magnitude/distribution
- Particle breakage
- Thermal properties/Temperature gradient
- Plastic/creep deformation
- Gap formation at breeder/structure interface

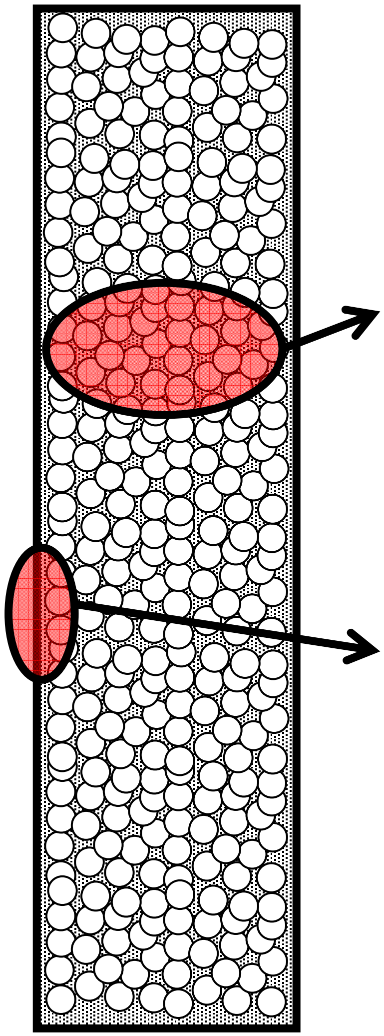


Breeder/Multiplier/Structure Thermo-mechanical Interactions

- Maintaining a good contact between the solid breeder (SB) and clad boundaries is a key to the solid breeder blanket performance.
- The contact integrity can be damaged during operation due to a number of processes:

    1. differential thermal expansion between SB and structural materials
    2. SB cracking and relocation
    3. SB densification due to thermal/ radiation-induced sintering
    4. SB thermal- and radiation-induced creep
    5. SB radiation induced-swelling
    6. deformation of the structural materials

Engineering Data of Pebble Bed Thermo-mechanics



Pebble bed

Pebble bed thermo-physical and mechanical data

(1) Effective thermal conductivity
(2) Effective modulus
(3) Thermal creep correlation
(4) Effective thermal expansion rate
(5) Pebble bed failure data
(6) Increase of effective thermal conductivity with compressive and creep strain
(7) Criteria of pebble surface roughness and sphericity

Pebble bed – wall interface thermo-mechanical data

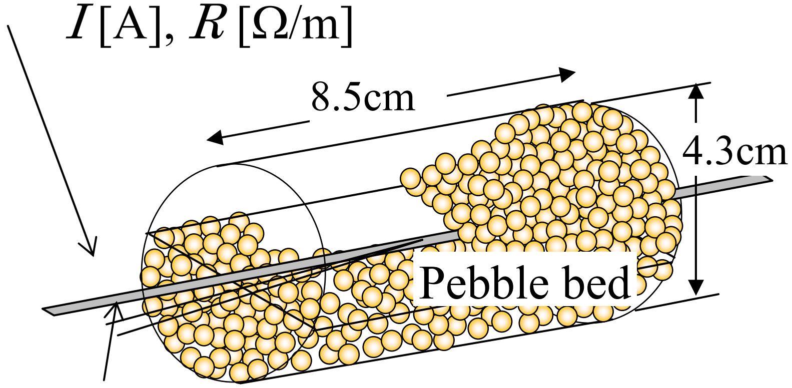
(1) Heat conductance
(2) Friction coefficient

Modeling and analysis method

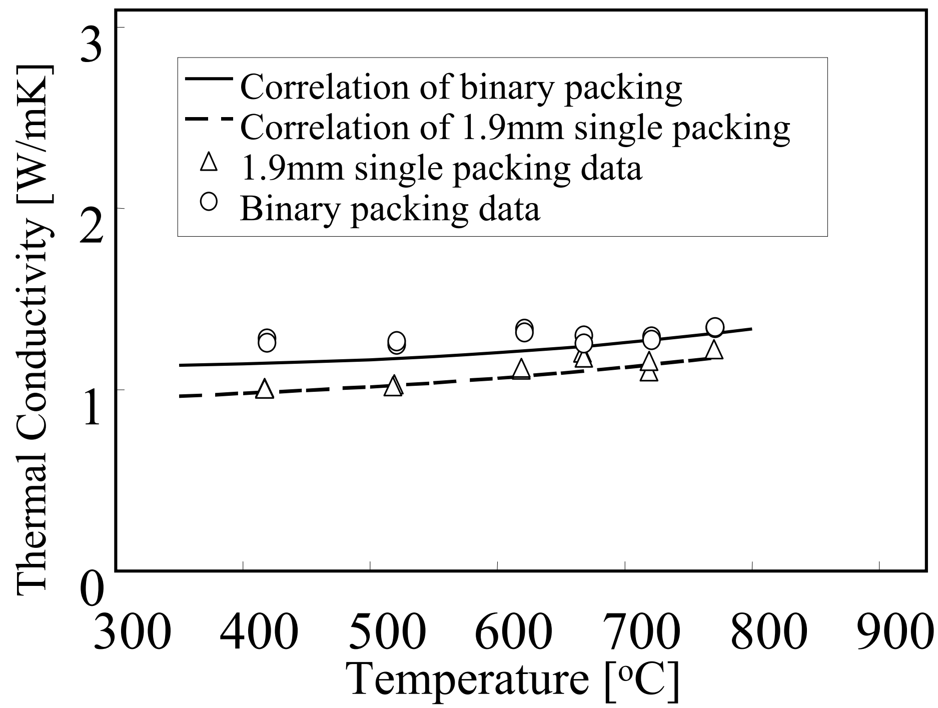
(1) Modification of continuous model for large scale analysis
(2) Discrete Element Method (DEM) for investigation of contact characteristics

Evaluation of Thermo-Mechanical Performance of Pebble Bed Structure

Effective thermal conductivity was measured by Hot Wire Method.
Hot wire method has merits of,
- small amount of pebble specimen
- uniform bed temperature and less than 10 °C heat-up of hot wire
- short observation time of transient

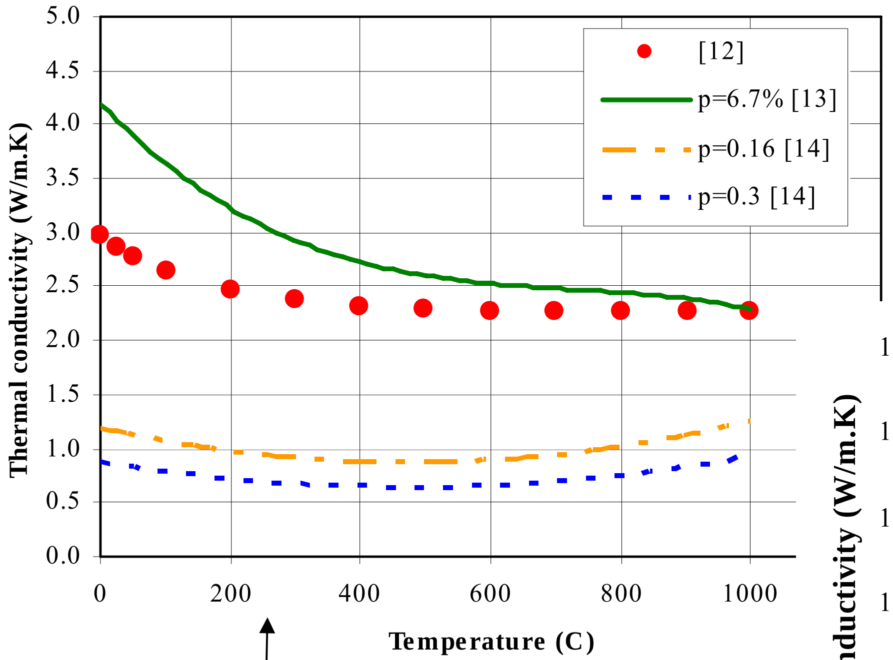


Concept of Hot Wire Method for Pebble Bed



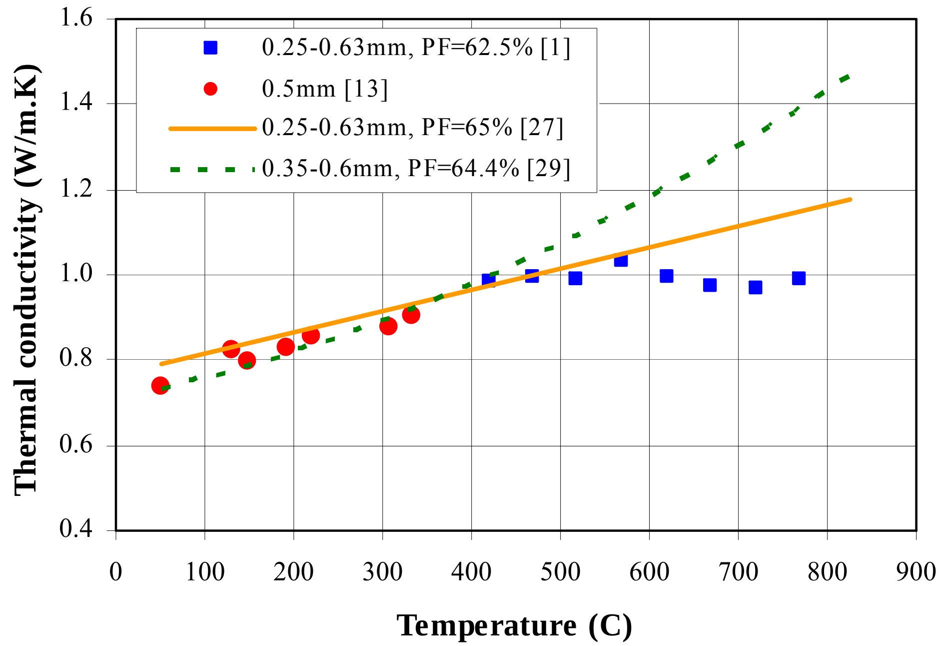
Recent results of Sol-Gel Li_2TiO_3, (single and binary beds)

Sintered Pellet vs Pebble Bed Thermal Conductivity



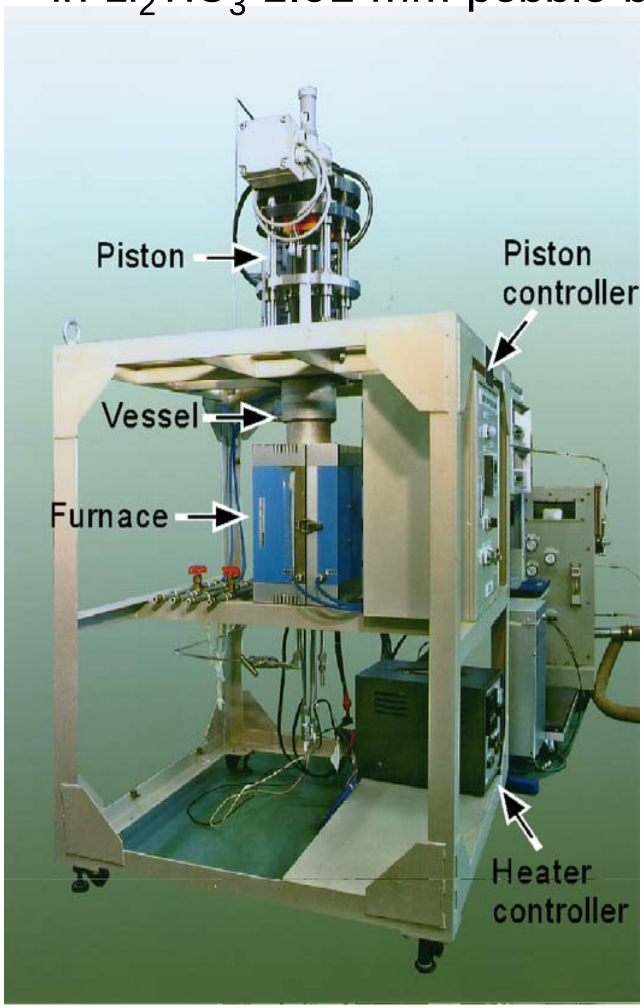
Sintered Li_4SiO_4 Pellet

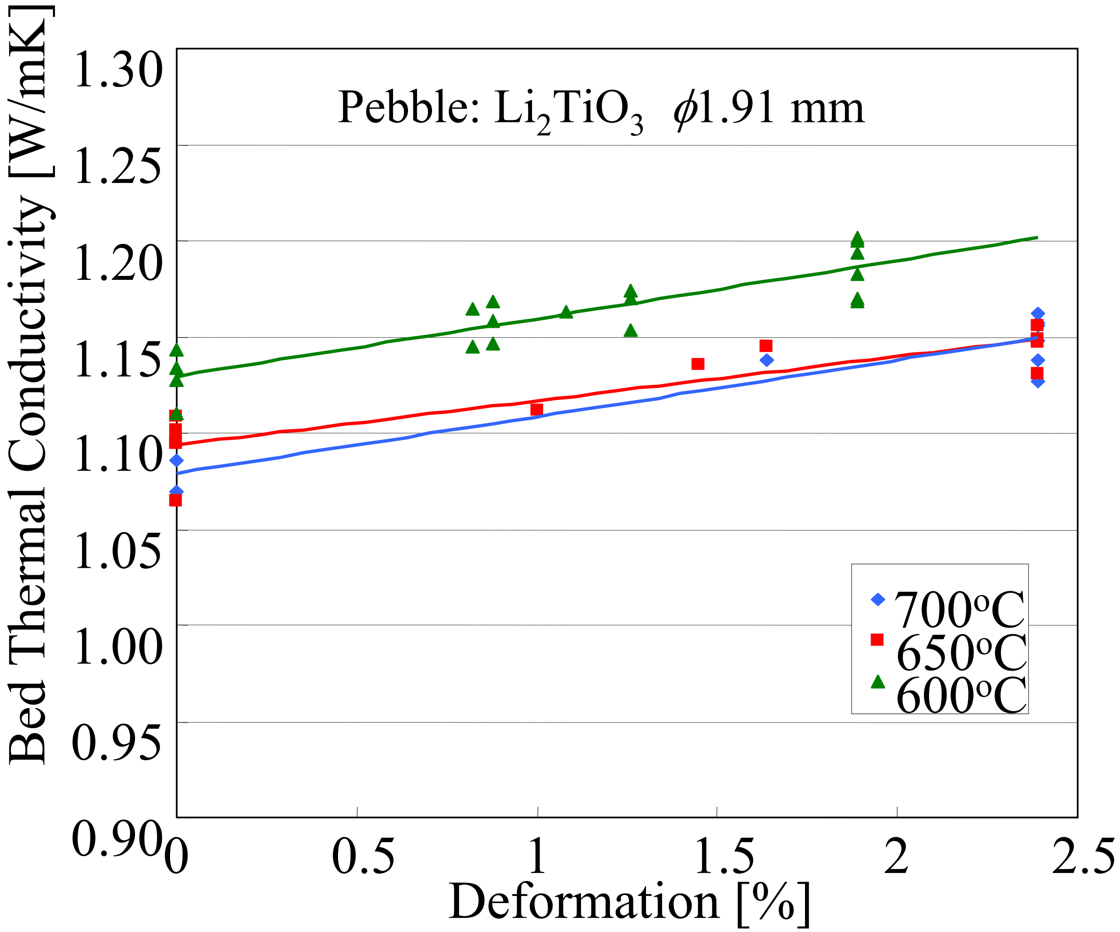
Pebble bed: Li_4SiO_4 pebbles +He gas



Effect of Compressive Strain on Bed Thermal Conductivity

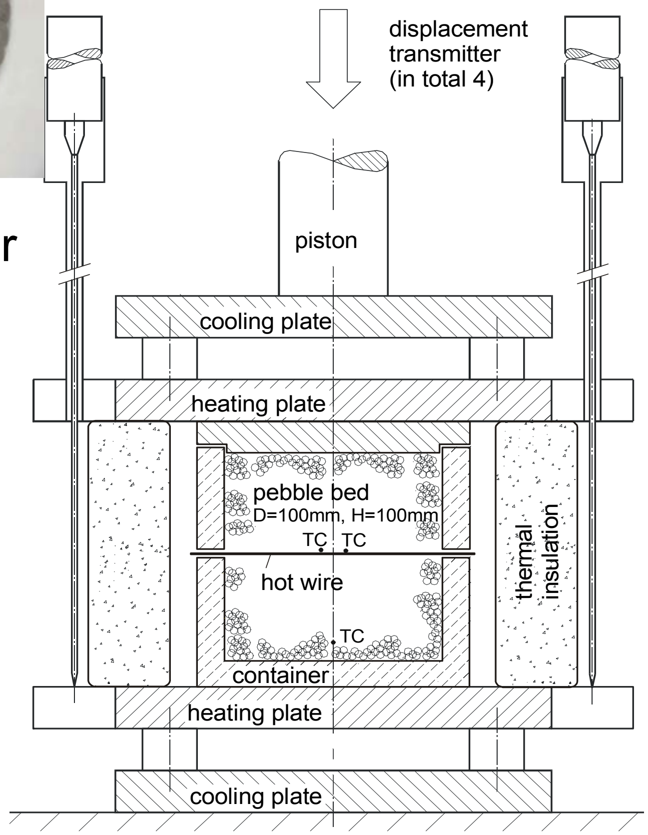
Relationship between effective thermal conductivity and compressive stress was measured by Hot Wire Method. Preliminary result showed slight dependency of the effective thermal conductivity on the compressive stress in Li_2TiO_3 1.91 mm pebble bed.



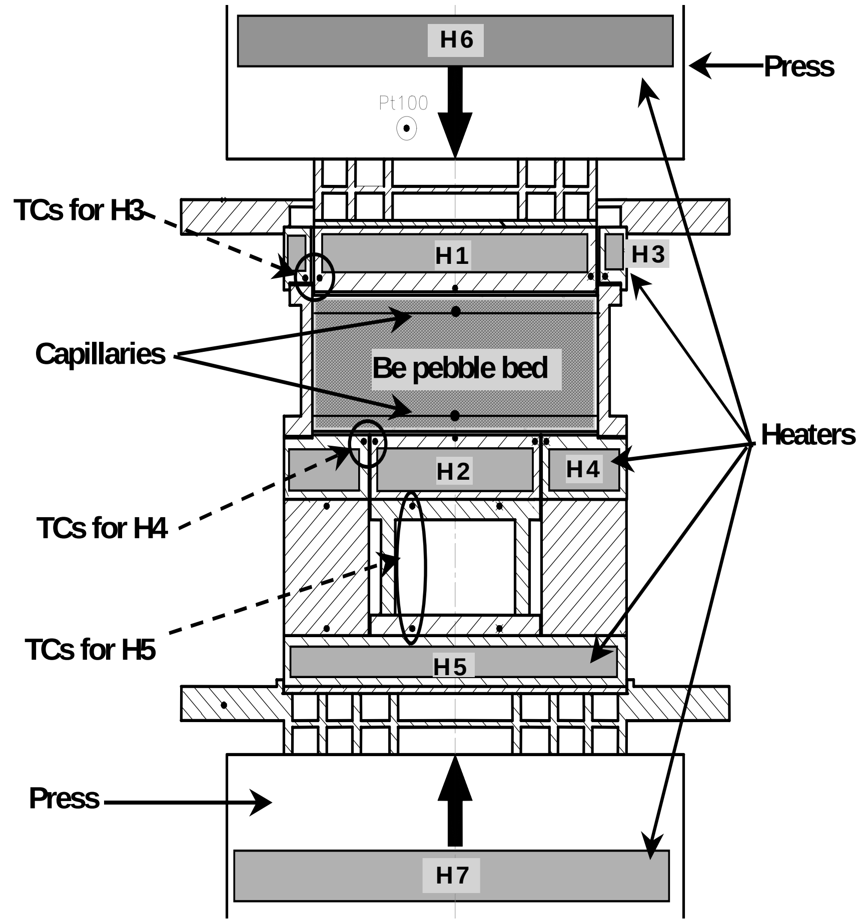


Measurement of the Effective Thermal Conductivity of Beryllium Pebbles Beds

Be Pebbles after compression



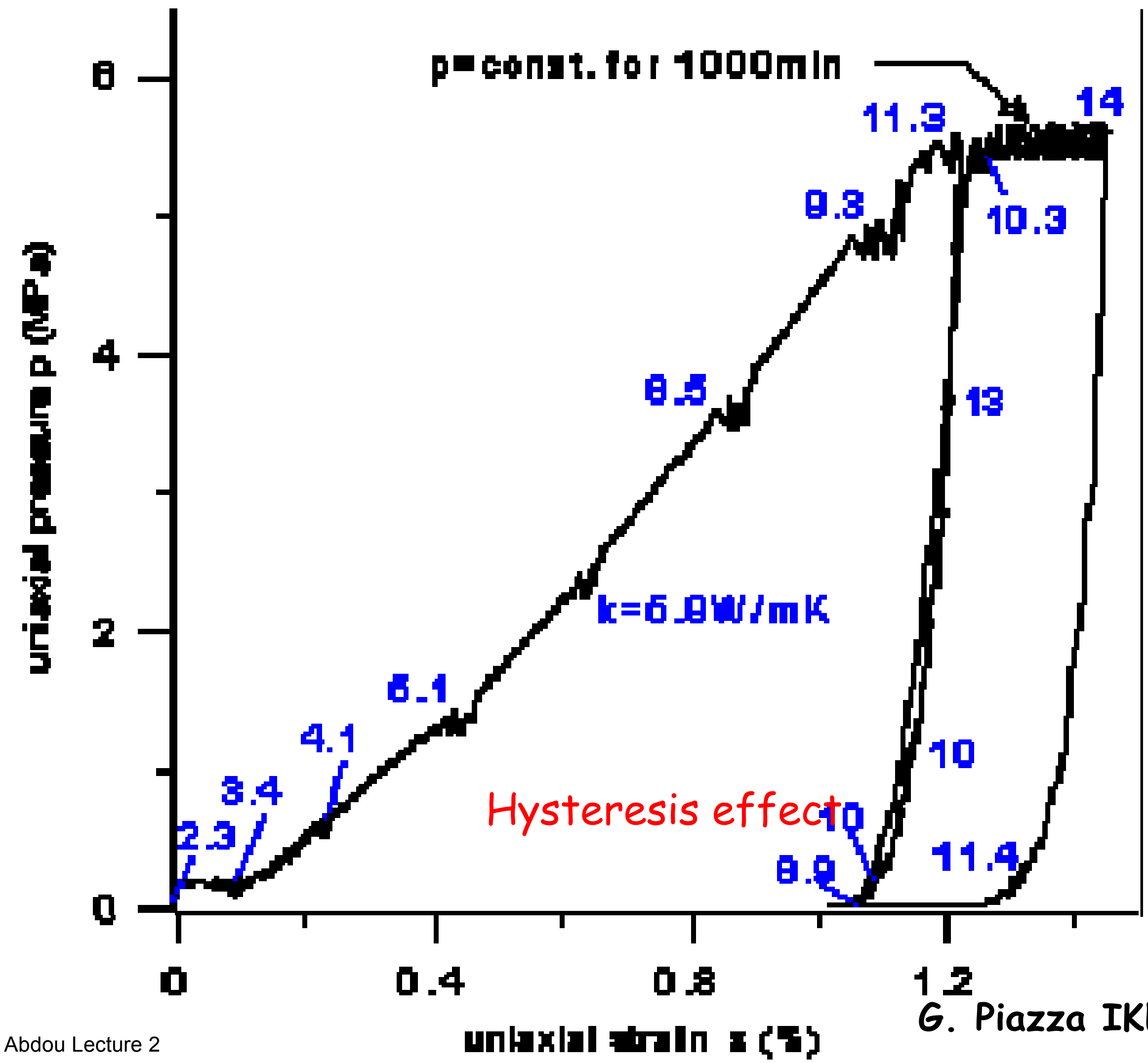
Application of Hot Wire Method



HECOP
Steady-state method

G. Piazza IKET-FZK

Effective thermal conductivity of 1 mm Be pebble bed (475 °C, Hot Wire Method) - strongly depends on the compressive strain



point contact

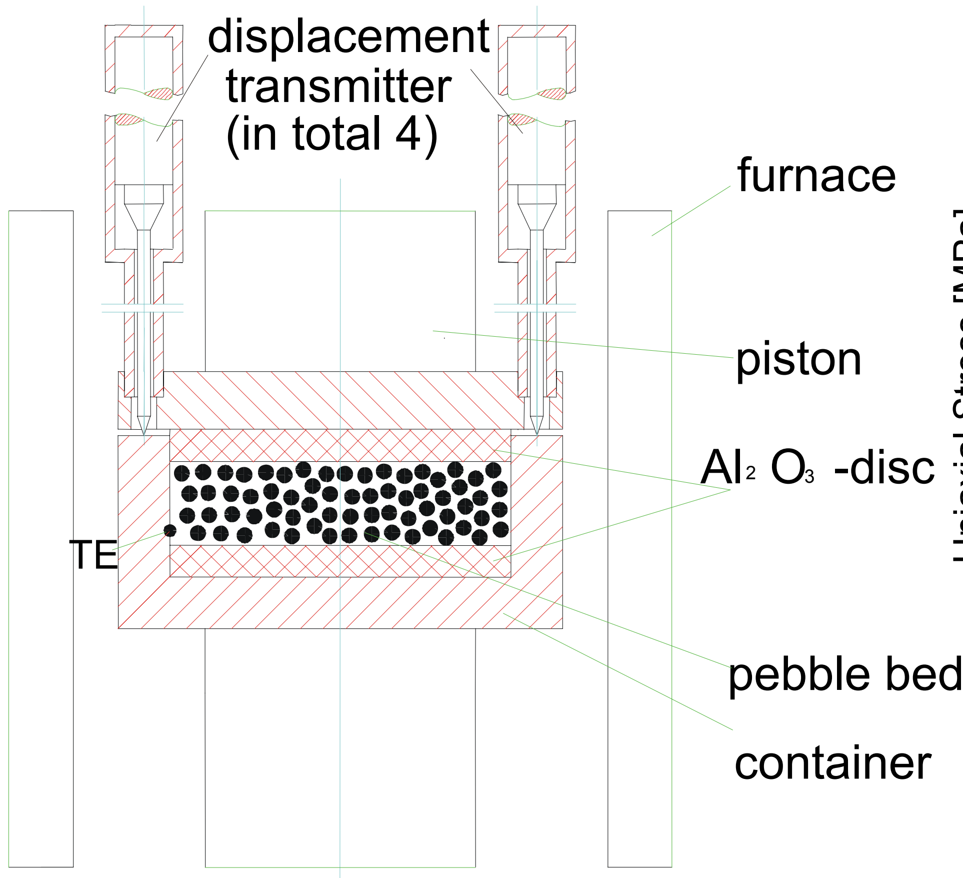
compression

area contact
(increase in k)

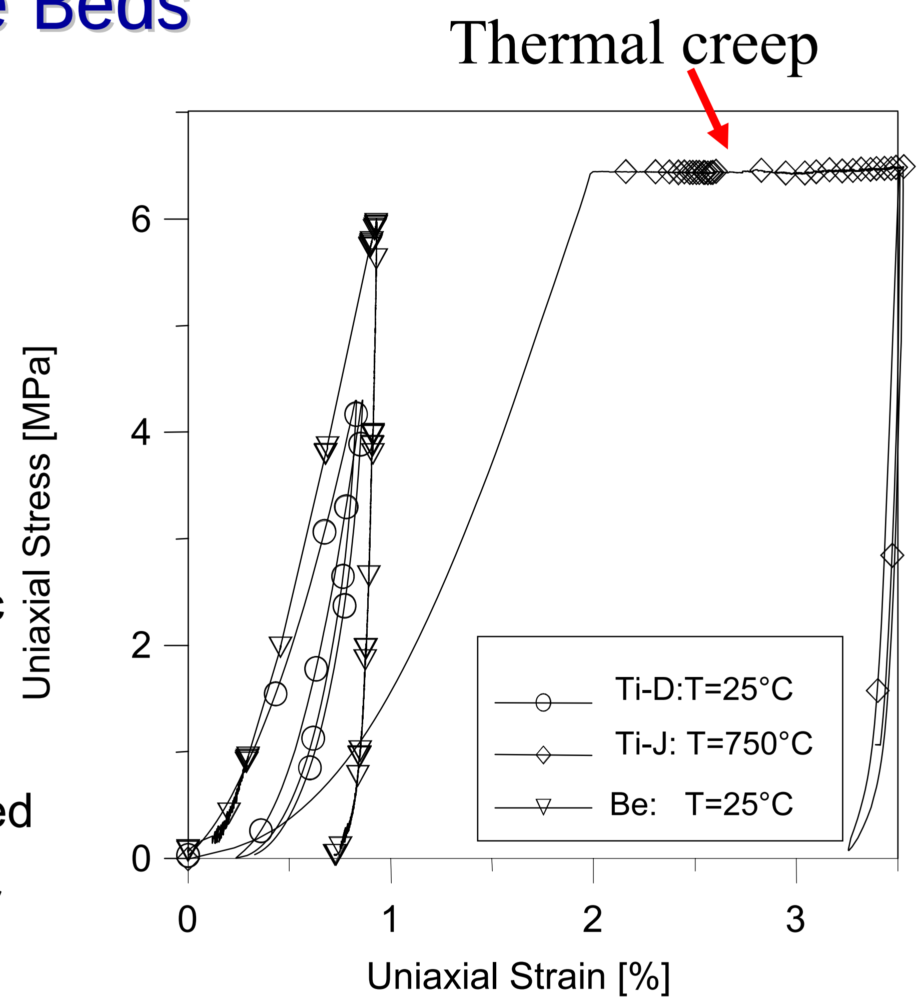
stress or swelling

G. Piazza IKET-FZK

Effective Modulus and Creep Rate for Solid Breeder Pebble Beds



Uni-axial test cell



Stress-Strain Curve by Uni-axial tests

Ti-D:Li_2Ti_3O (CEA)1.2mm pebble
Ti-J:Li2TiO3 Wet process (Japan) 2mm pebble
Be: Rotating Electrode method 1mm pebble

Effective Constitutive Equations of Pebble Bed Mechanical Properties

The effective mechanical constitutive equations for the pebble bed are different from those of the bulk materials. Commonly, the effective mechanical properties of the packed pebble beds are functions of stress, temperature, and material properties.

- **Nonlinear elastic modulus**

$$\boxed{E = B_0 \cdot (1 + B_1 \cdot T^{B_2}) \cdot (1 + B_3 \cdot \sigma^{B_4})}$$

where

E : Young's modulus [MPa]

σ : Von Mises Stress [MPa]

T : Temperature [℃]

B_i : Coefficients

- **Thermal creep strain**

$$\boxed{\varepsilon_c = c_0 \cdot \sigma^{c_1} \cdot \exp(c_2 / T) \cdot t^{c_3}}$$

where

ε_c : Creep strain

σ : Von Mises Stress [MPa]

T : Temperature [℃]

t : Time [s]

c_i : Coefficients

Concepts of Thermal Creep

- **Creep rate depends on stress and temperature magnitudes**
  - **Diffusion Creep model at lower σ**

$$\dot{\varepsilon} = B_{vol} \frac{\sigma}{d^2} \exp(-\frac{E_{vol}}{kT})$$ Nabarro-Herring

$$\dot{\varepsilon} = B_{gb} \frac{\sigma}{d^3} \exp(-\frac{E_{gb}}{kT})$$ Coble's grain-boundary

  - **Power Law Creep at higher stress**

$$\dot{\varepsilon} = B' \sigma^n \exp(-\frac{E_c}{kT})$$ Power law creep

Where B is a constant and E is the activation energy of atom self-diffusion in the solid

  - **Effective macro-creep model for sintered solid breeder material**

For σ < 40 MPa

ITER Solid Breeder Blanket Materials Database

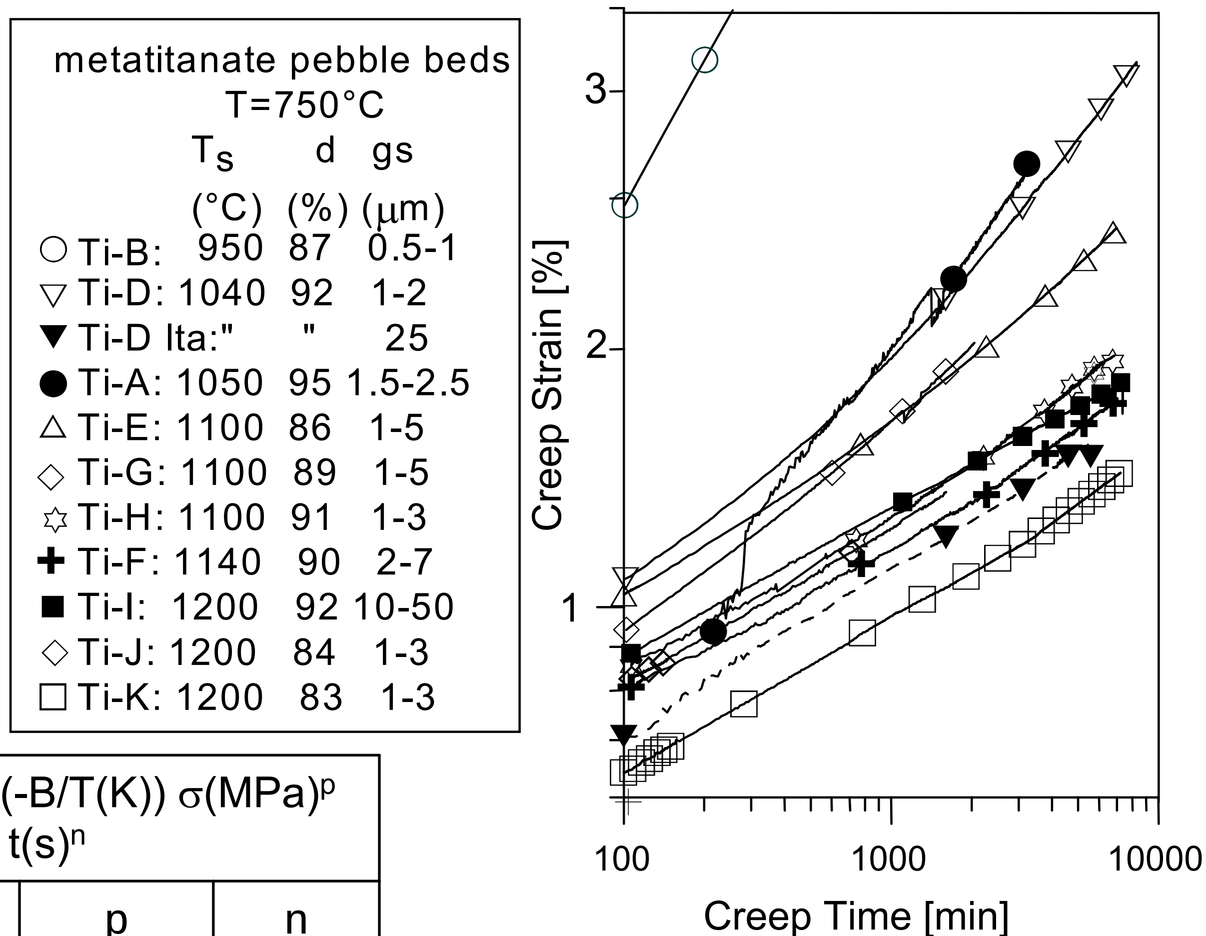
$$\frac{d\varepsilon}{dt} = 1.4x10^{-2} \exp(29P) \exp(-21.5x10^{-3} / T)\sigma$$

$P = \text{Porosity}$

Creep Properties of Li_2TiO_3 and Li_4SiO_4 Pebble Beds

(1) Uni-axial compression test apparatus

(2) Experimental data was used to develop constitutive correlation of creep strain as a function of T, σ, and t

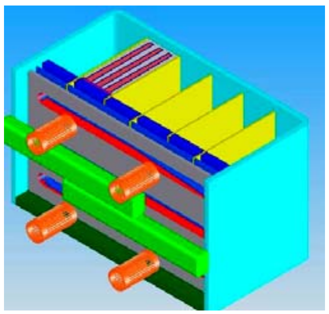


Granular material	$\varepsilon_{cr}(t) = A \exp(-B/T(K))\, \sigma(MPa)^p\, t(s)^n$			
	A	B	p	n
FZK-Li_4SiO_4	12.12	10220	0.65	0.2
CEA-Li_2TiO_3	0.67	7576	0.65	0.18
JAERI-Li_2TiO_3	0.37	6947	0.65	0.19

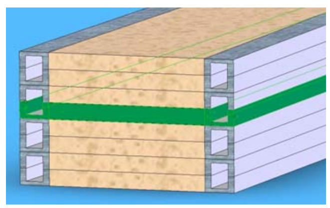
Experimental feature: Creep propagates under a fixed loading

Breeding Zone FEA Base Thermo-mechanics Analysis

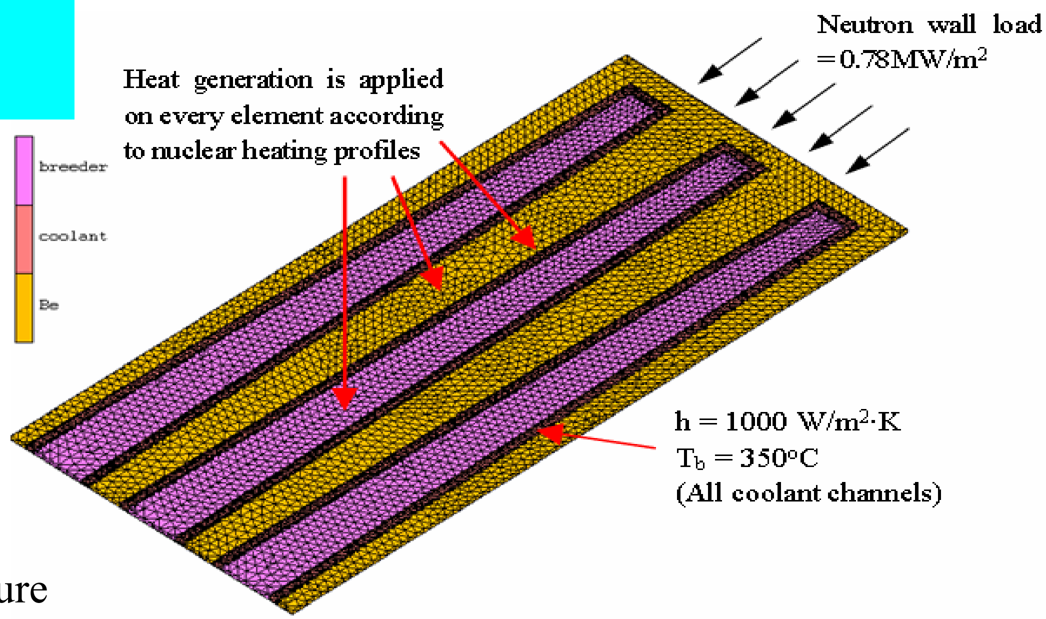
- Stress/Temperature profile
- Cyclic thermal effects

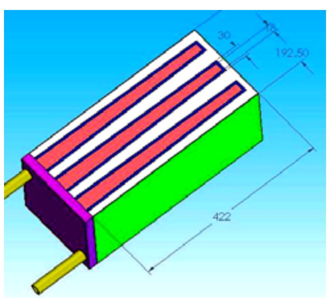


(a) The unit cell of ITER

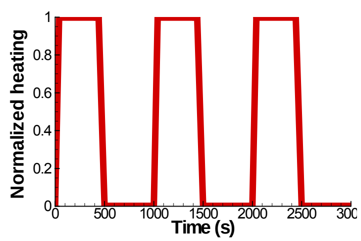


(c) Coolant structure





(b) Box cell



Burn cycle = 400s
Cooling period = 500s
One cycle time = 1000s

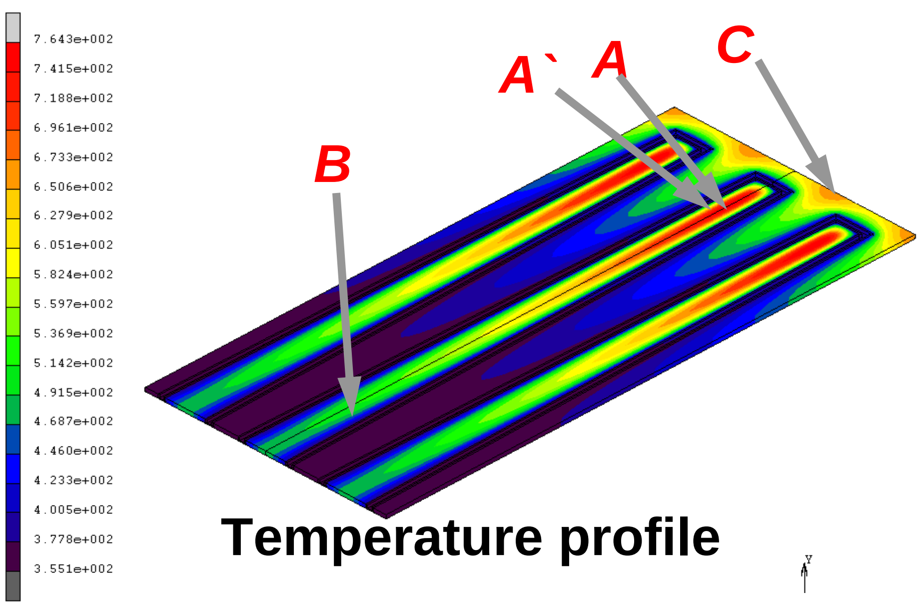
- Pulsed cycles in test:
  - Total time of one cycle is 1000s
    - Burn time is about 400s
    - Transient time is 100s
      - 40s to start burning and 60s to stop burning
    - Interval time between two pulses is 500s

Example FEA Results
--- *Temp. & Stress distribution*

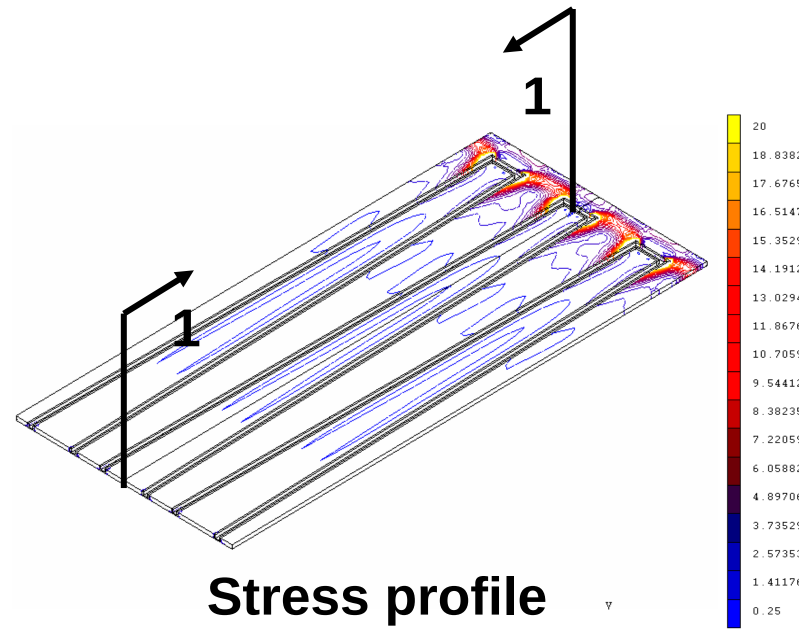
Numerical data:

~ 770ºC (max. T in Breeder); ~ 540ºC (max. T in Beryllium)

~ < 2.0MPa (max. σ_v in Breeder); ~ 50MPa (max. σ_v in Beryllium)



Temperature profile



Stress profile

A: Center of max. *T* in breeder bed; *A*`: Interface between breeder bed and coolant structure;
B: Near the end of breeder pebble bed; *C*: Center of max. T in Beryllium.

Solid Breeder Fabrication Techniques in Practice

- Melt-Spraying (Li_4SiO_4 at EU/FZK)
- Extrusion/Spheronization-Sintering (Li_2TiO_3 at EU/CEA; Li_4SiO_4 at SCICAS)
- Wet processes including direct and indirect (Li_2TiO_3 at JAEA; Li_2TiO_3 at SCICAS)
- Slurry dipping dehydration (SCICAS)

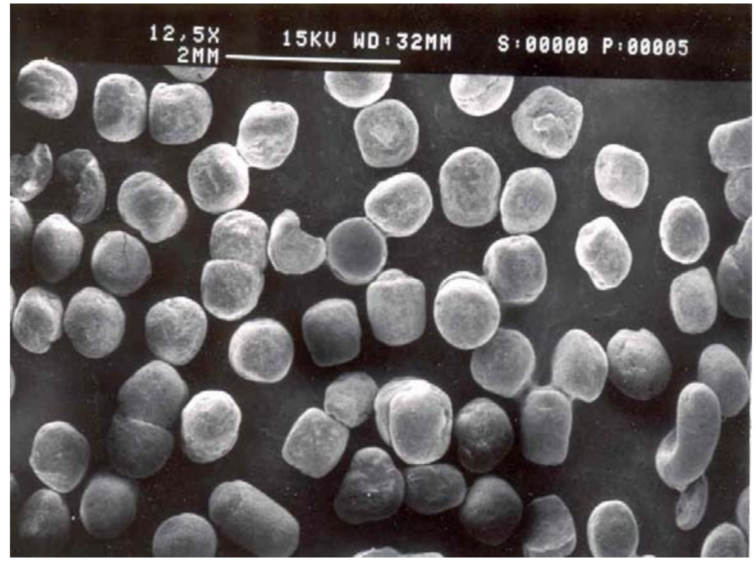
- (**Note : ON Fabrication and Recycling Technology of Be Multiplier, talk to NGK company in Japan**)

Shape and Size of Fabricated Pebbles

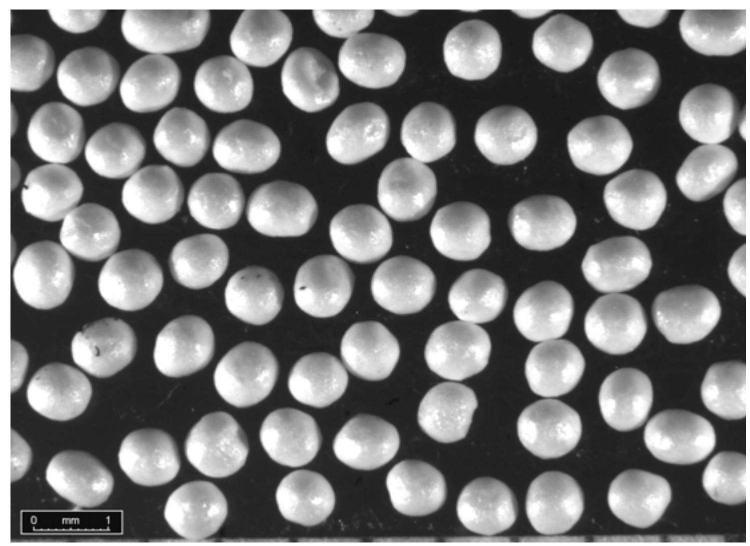
CEA

- ❑ Achieve a uniform packing within the active breeding area of the blanket
- ❑ Reduced thermal stress in the pebble
- ❑ Avoid using powder (d> 0.2 mm)

  - Pebbles produced by extrusion-spheronisation-sintering process with size distribution ranging from 0.6 to 0.8 mm (shown)



  - A better sphericity of the pebbles have been achieved based on a revised formulation of extrusion paste



Pebble Density and Porosity

A high density is desired for TBR, pebble mechanical strength, and thermal conductivity. However, too a high density can lead to a low/slow tritium release.

- Irradiation swelling can further increase porosity

Porosity, Density and Crush Load

FZK

		OSi 03/2-9	OSi 03/2-9c
		as received	annealed at 970°C/1 week
He-pycnometry			
inner density	/ g/cm^3	2.39	2.37
closed porosity (calc.)	/ %	0.5 ± 0.1	1.1 ± 0.1
Hg-porosimetry			
density	/ g/cm^3	2.25 ± 0.02	2.26 ± 0.03
density	/ %	94.0 ± 0.8	94.3 ± 1.1
open porosity	/ %	5.2 ± 0.3	3.0 ± 0.4
Crush load (Ø 500 µm)	/ N	8.5 ± 1.9	8.2 ± 1.4

Status of Li_2TiO_3 Pebble Characteristics

CEA

Reference of batch	Pebble size (mm)	Open porosity (%)	Closed porosity (%)	Bed density (g/cm^3) >1.8	Grain size (µm)	Crush load (N)
2 kg-batch (CTI 273)	0.6 - 0.8	1.7	5.3	1.94	1 - 3	37 [14 - 65]
		93.0% of T.D.				
^{6}Li enriched samples (CTI 1233)	0.6 - 0.8	2.0	5.8	1.88	1 - 4	33 [25 - 52]
		92.2% of T.D.				
1 kg-batch (CTI 2964)	0.6 - 0.8	3.0	5.8	1.81	1 - 3	26 [15 - 42]
		91.2% of T.D.				

Engineering Scaling and ITER TBM Design

Engineering Scaling is a Process to Develop Meaningful Tests at Experimental Conditions and Parameters Less than those in a Reactor

- **Testing is for DEMO Blanket. We need to see how the blanket behaves in DEMO conditions.**
- **Since ITER has a factor of 3 or 4 lower power density than DEMO, we need to alter the test module to "Act Alike" rather than "Look Like" DEMO to preserve behavior.**

"Look-Alike" Test Modules Do Not Provide Meaningful Information Under Scaled-Down Conditions

Examples:

- **Thermal Stresses are not maintained at lower values of surface heat flux and/or neutron wall load.**
- **Tritium Transport, inventory altered because of different neutron wall load, temperature profiles.**
- **Cycling, burn and dwell times affect time to reach quasi-equilibrium, temperatures, stresses, tritium recovery, etc.**
- **Corrosion rates and fluid flow characteristics cannot be maintained at lower surface heat flux, neutron wall load, temperature.**

“Act-Alike” Test Modules Are Necessary

Simple Examples

At lower surface heat flux, neutron wall load:

- **Increase structure thickness to increase (preserve) thermal stresses**
  - Hoop stress: Lower at larger thickness, Can preserve total stress
  - Temperature Gradient: Cannot be preserved; Important?
- **Increase solid breeder plate thickness, preserve temperature window for tritium recovery**
  - Tritium production rate: lower; important for tritium recovery? Effect on TBR

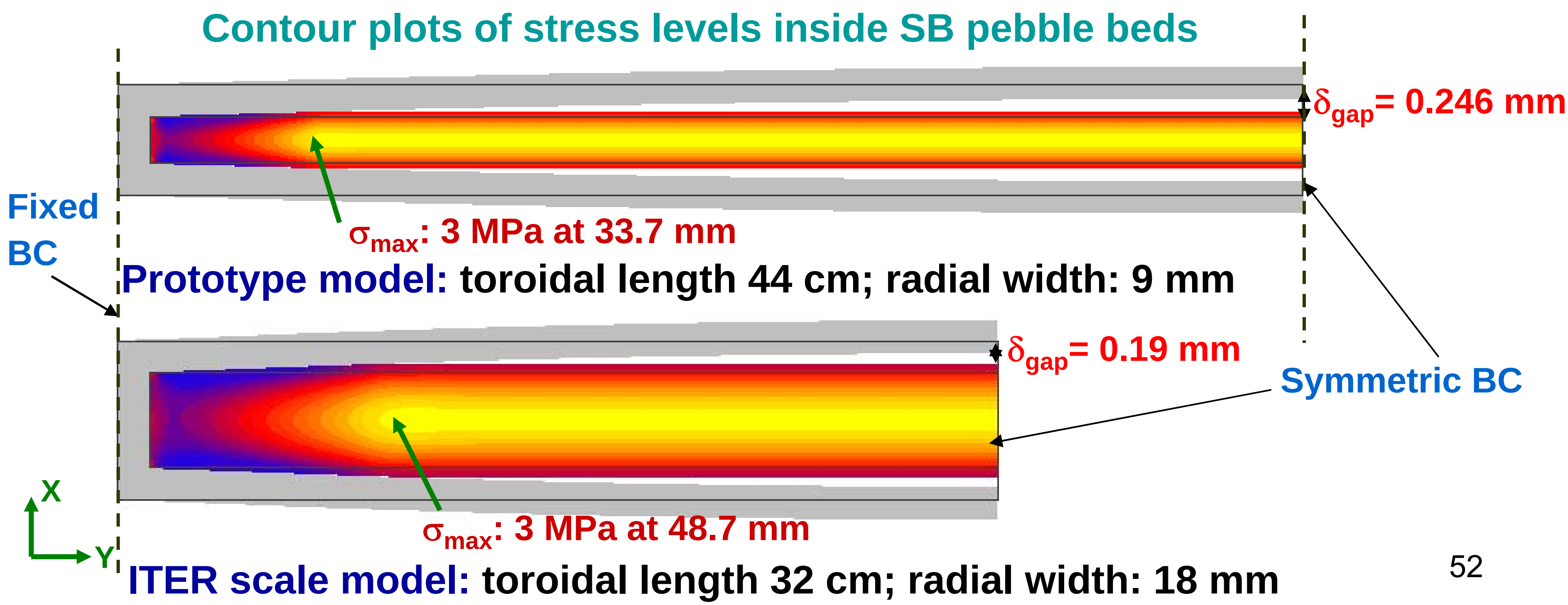
Limited size for liquid metal blanket test: shorten blanket test module; But, temperatures and fluid flow are not always fully developed in fusion liquid metal blankets; many important parameters (e.g., heat transfer coefficient, MHD pressure drop, etc.) sensitive to geometry (also to B field, nuclear heating)

Cycling, Burn and Dwell Times substantially alter many effects: Time to reach equilibrium, values at quasi-equilibrium, failure modes, etc.

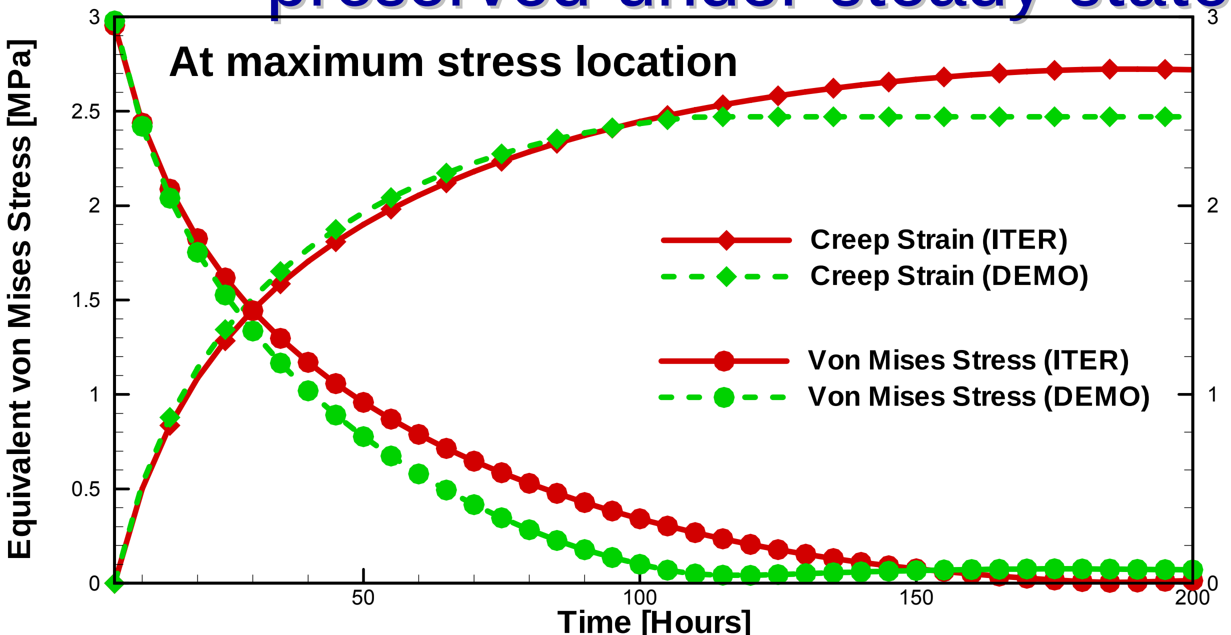
Prototype stress levels have been preserved in the scale model (layer configuration)

- FEM analysis using experimentally derived ceramic breeder pebble bed modulus, stress-strain consecutive equations.
- Similar stress levels found in prototype and scale models with a maximum stress in the bed of about 3 MPa.
- The coolant plate deformation is a combined effect of thermal expansion, mechanical constraints, and dimensions.

Laboratory R&D goal is to predict thermo-mechanical parameters accurately.

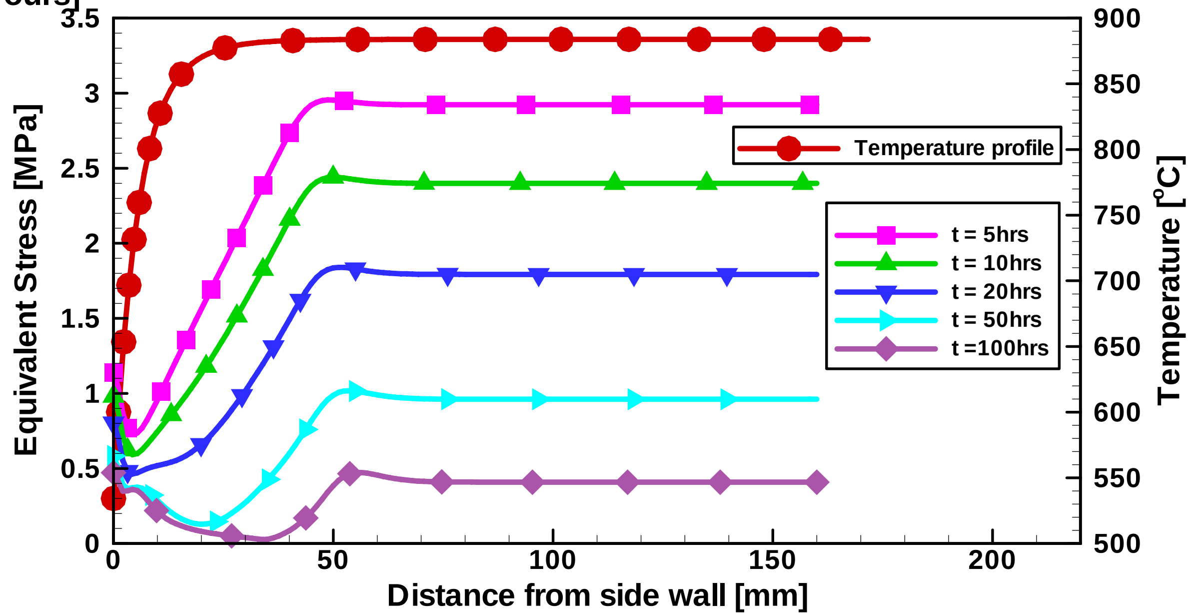


Creep and stress relaxation evolutions are preserved under steady state operations



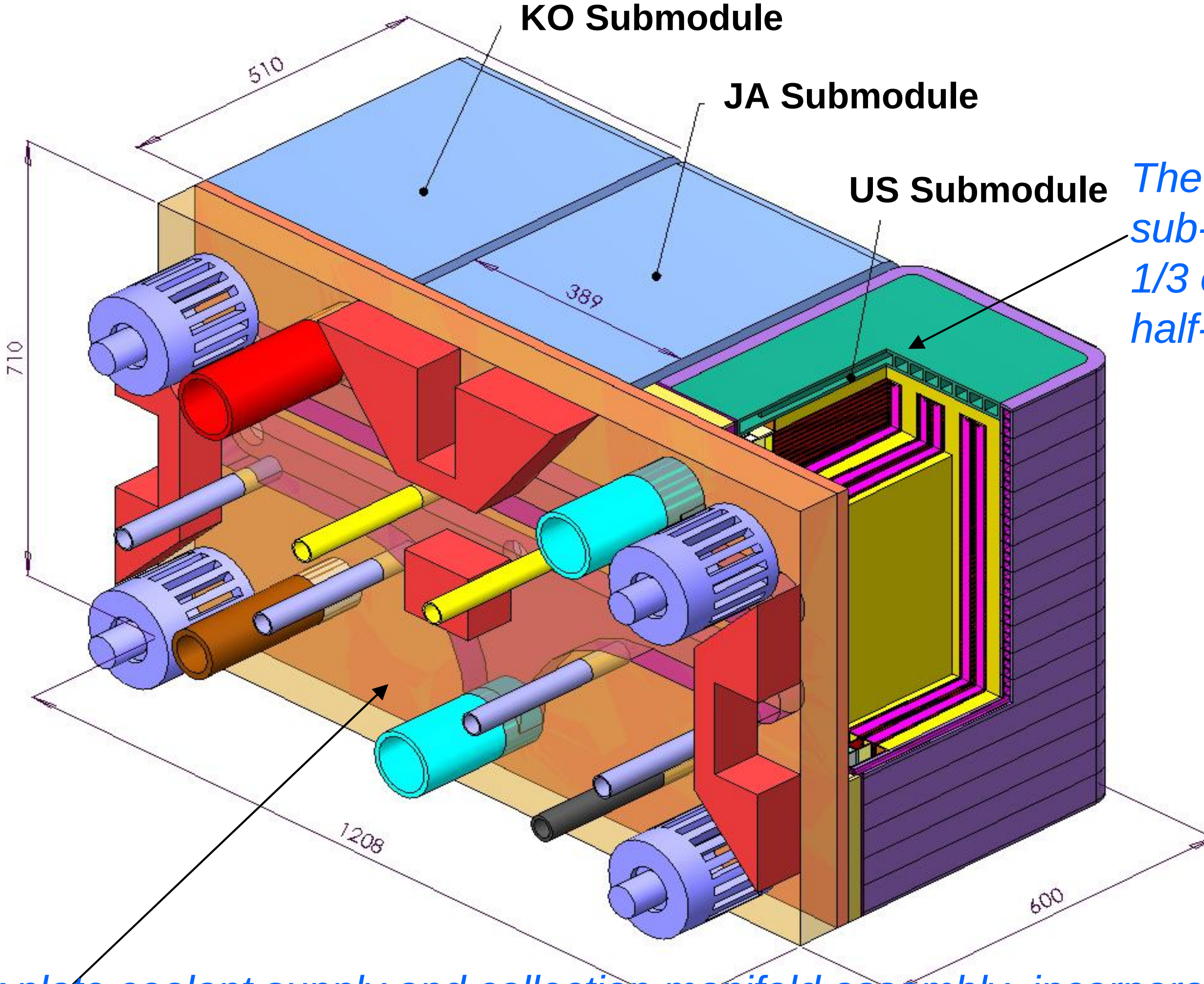
- A R&D goal is to address and model the effect of pulsed operations on the pebble bed integrities and performance

von Mises stress evolution at the mid-plane of the ITER scale model



HCCB Joint Partnership

Different sub-module can address different material options, operating conditions such as breeder temperatures, and design configurations.



The proposed US HCCB sub-module will occupy 1/3 of an ITER horizontal half-port

The back plate coolant supply and collection manifold assembly, incorporating various penetration pipes, flexible supports, and keyways, should be collaboratively designed by partner Parties. A "Lead Party" takes responsibility for fabrication of the back plate and integration of the three sub modules.

Solid Breeder Blanket Issues

- Tritium self-sufficiency
- Breeder/Multiplier/structure interactive effects under nuclear heating and irradiation
- Tritium inventory, recovery and control; development of tritium permeation barriers
- Effective thermal conductivity, interface thermal conductance, thermal control
- Allowable operating temperature window for breeder
- Failure modes, effects, and rates
- Mass transfer
- Temperature limits for structural materials and coolants
- Mechanical loads caused by major plasma disruption
- Response to off-normal conditions

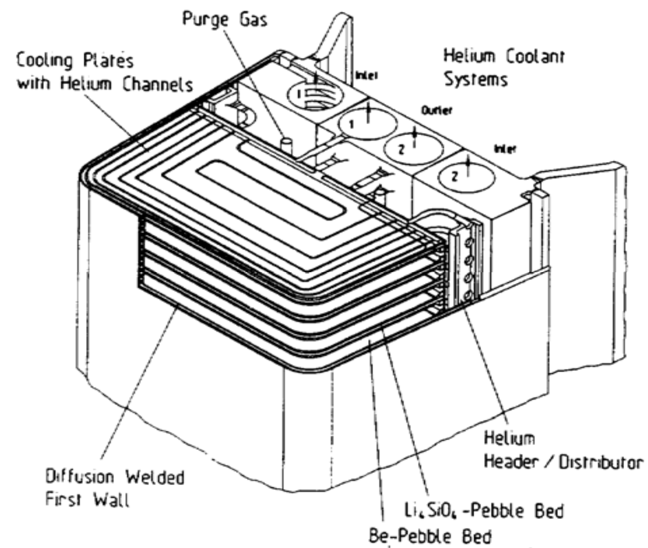
Configurations and Interactions among breeder/Be/coolant/structure are very important and often represent the most critical feasibility issues.

- Configuration (e.g. wall parallel or "head on" breeder/Be arrangements) affects TBR and performance
- Tritium breeding and release

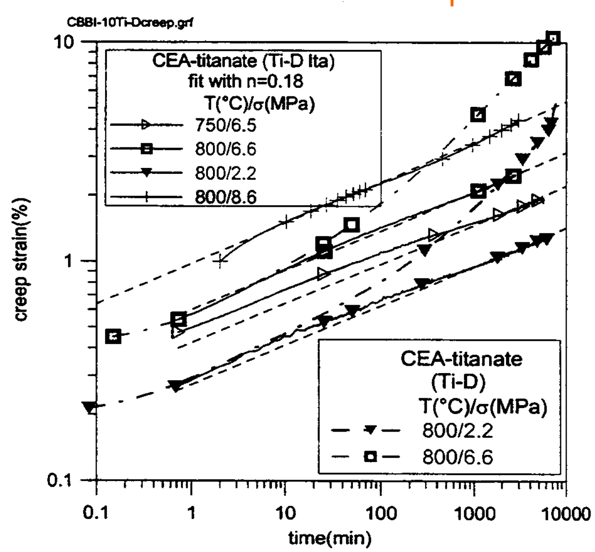
  - Max. allowable temp. (radiation-induced sintering in solid breeder inhibits tritium release; mass transfer, e.g. LiOT formation)

  - Min. allowable Temp. (tritium inventory, tritium diffusion

  - Temp. window (Tmax-Tmin) limits and k_e for breeder determine breeder/structure ratio and TBR
- Thermomechanics interactions of breeder/Be/coolant/structure involve many feasibility issues (cracking of breeder, formation of gaps leading to big reduction in interface conductance and excessive temperatures)



Thermal creep trains of Li_2TiO_3 pebble bed at different stress levels and temperatures



Major R&D Tasks for Solid Breeder Blanket

- Solid breeder material development, characterization, and fabrication
- Multiplier material development, characterization, and fabrication
  - Tritium inventory in beryllium; swelling in beryllium irradiated at temperature, including effects of form and porosity
- Breeder and Multiplier Pebble Bed Characterization
  - Pebble bed thermo-physical and mechanical properties, thermomechanic interactions
- Blanket Thermal Behavior
- Neutronics and tritium breeding
- Tritium Permeation and Processing
- Nuclear Design and Analysis (Modeling Development)
- Advanced In-Situ Tritium Recovery (Fission Tests)
- Fusion Test Modules Design Fabrication and Testing
- Material and Structural Response