EU Gap Study for Fusion Power Plant

	Issue	Approved devices	ITER	IFMIF	DEMO Phase 1	DEMO Phase 2	Power Plant
Plasma physics/ Plasma performance	Disruption avoidance	2	3		R	R	R
	Steady-state operation	2	3		r	r	r
	Divertor performance	1	3		R	R	R
	Burning plasma (Q>10)		3		R	R	R
	Start up	1	3		R	R	R
	Power plant plasma performance	1	3		r	R	R
Enabling technologies	Superconducting machine	2	3		R	R	R
	Tritium inventory control & processing	1	3		R	R	R
	Power plant diagnostics & control	1	2		r	R	R
	Heating, current drive and fuelling	1	2		r	R	R
	Remote handling	1	2		R	R	R
Materials & Component Nuclear performance & lifetime	Materials characterisation			3	R	R	R
	Plasma-facing surface	1	2		3	4	R
	Vessel/First Wall /blanket/divertor materials		1	1	3	4	R
	Vessel/ First Wall /blanket/divertor components		1	1	2	4	R
	T self sufficiency		1		3	R	R
Final System	Licensing for power plant	1	2	1	3	4	R
	Electricity generation at high availability				1	3	R

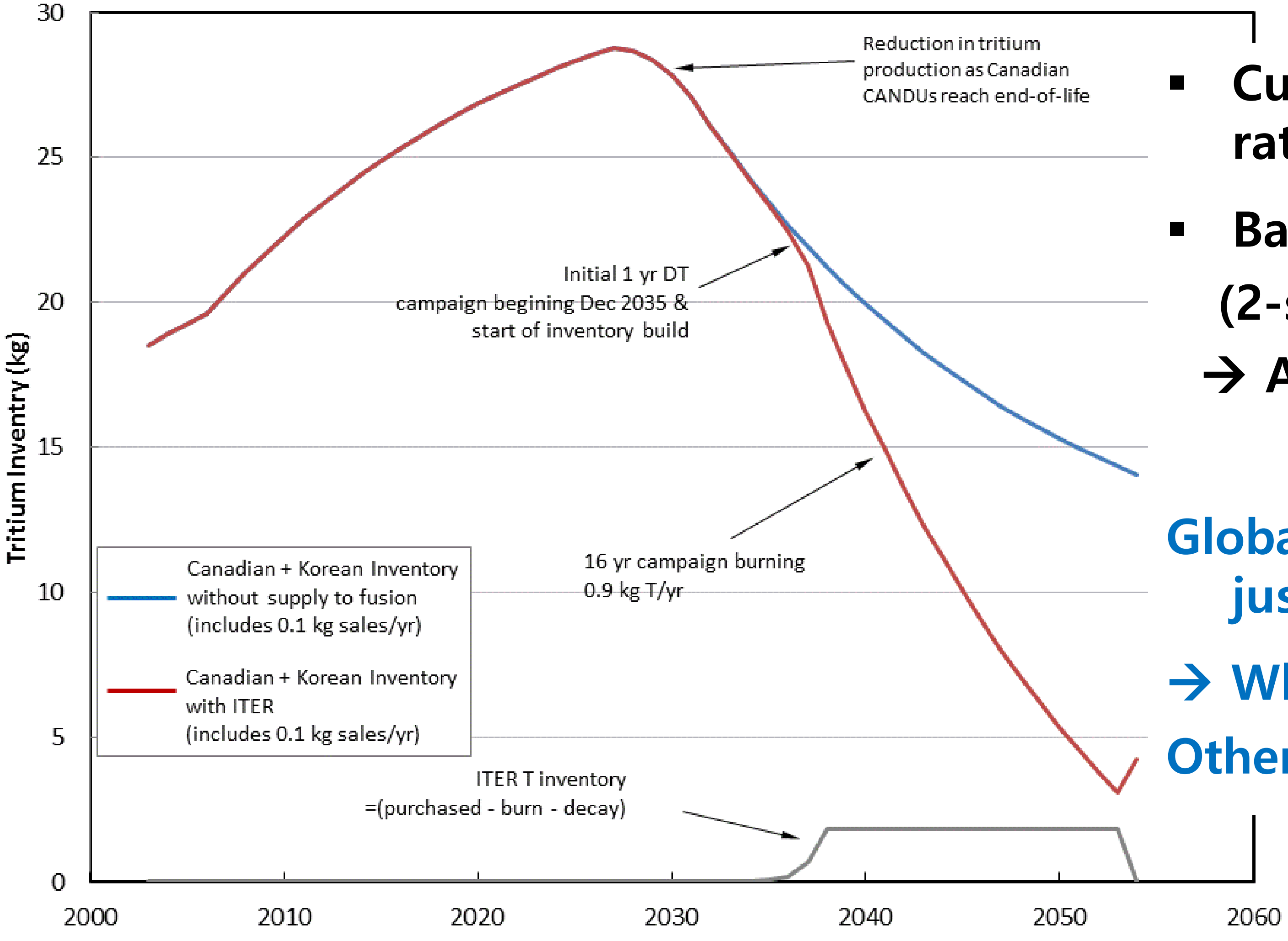
Outputs:		
	1	Will **help to resolve** the issue
	2	**May resolve** the issue
	3	**Should resolve** the issue
	4	**Must resolve** the issue

Inputs:		
	r	**Pre-existing Solution is desirable**
	R	**Pre-existing Solution is a requirement**

UKAEA October 2007 (revised/improved version of original table in **UKAEA FUS 521, 2005**).

Do we have sufficient tritium inventory?

Availability of External Tritium Supply for "startup" of ITER and early DT devices such as DEMO



- Current T inventory and annual production rates in Canada and Korea
- Based on the ITER DT operation plan

  (2-shift pattern, 12/14 days,16/24 months)

  → Average T consumption rate of 0.9 kg/yr

Global inventory of tritium predicted to be just sufficient to meet ITER's needs

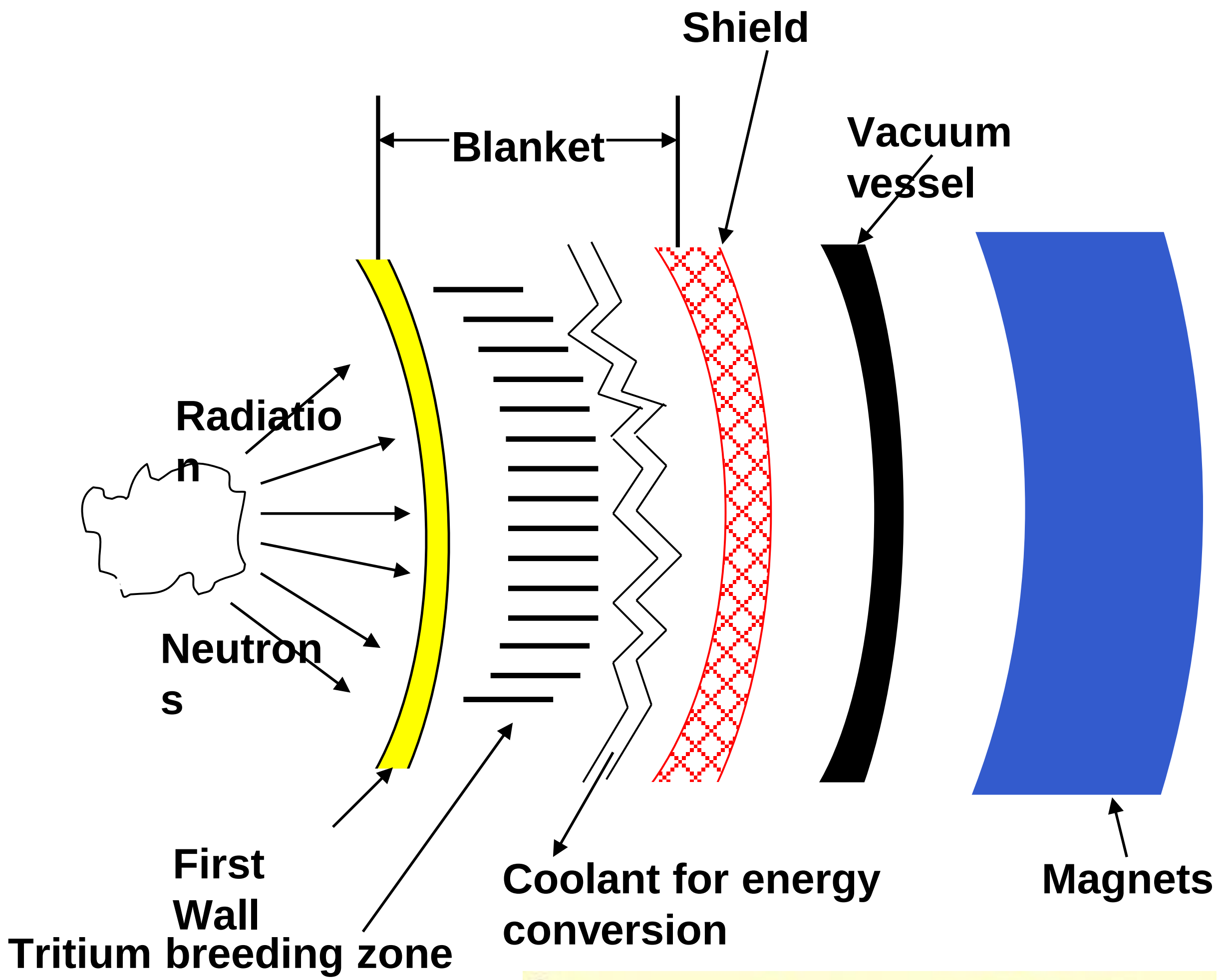
→ What happen if more delay happens ?

Other DT devices need tritium self-sufficiency !

Blanket: tritium breeding, heat exchange and shielding

Li (breeder) ←→ U (fuel)

Coolants



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

$$^{7}Li + n \rightarrow T + \alpha + n - 2.47MeV$$

- Breed tritium fuel **(Lithium)**
  - ☞ TBR (Tritium Breeding Ratio) > 1
    ~50 kg/yr is required for 1,000 MWe
- Transfer thermal energy **(Coolant)**
  - ☞ High blanket temperature
    for thermal conversion efficiency
- Contribute to shielding and energy multiplication
  - ☞ it has the highest activation and after-heat **(Structural material)**

Key Blanket Element Materials

1. **Tritium Breeding Material** (Lithium in some forms)
   - Liquid: Li, LiPb (^{83}Pb ^{17}Li), lithium-containing molten salts
   - Solid: Li_2O, Li_4SiO_4, Li_2TiO_3, Li_2ZrO_3

→ **Liquid metal, Molten salt, Ceramic**

2. **Neutron Multiplier** (for most blanket concepts)
   - Beryllium (Be, $Be_{12}Ti$)
   - Lead (in LiPb)

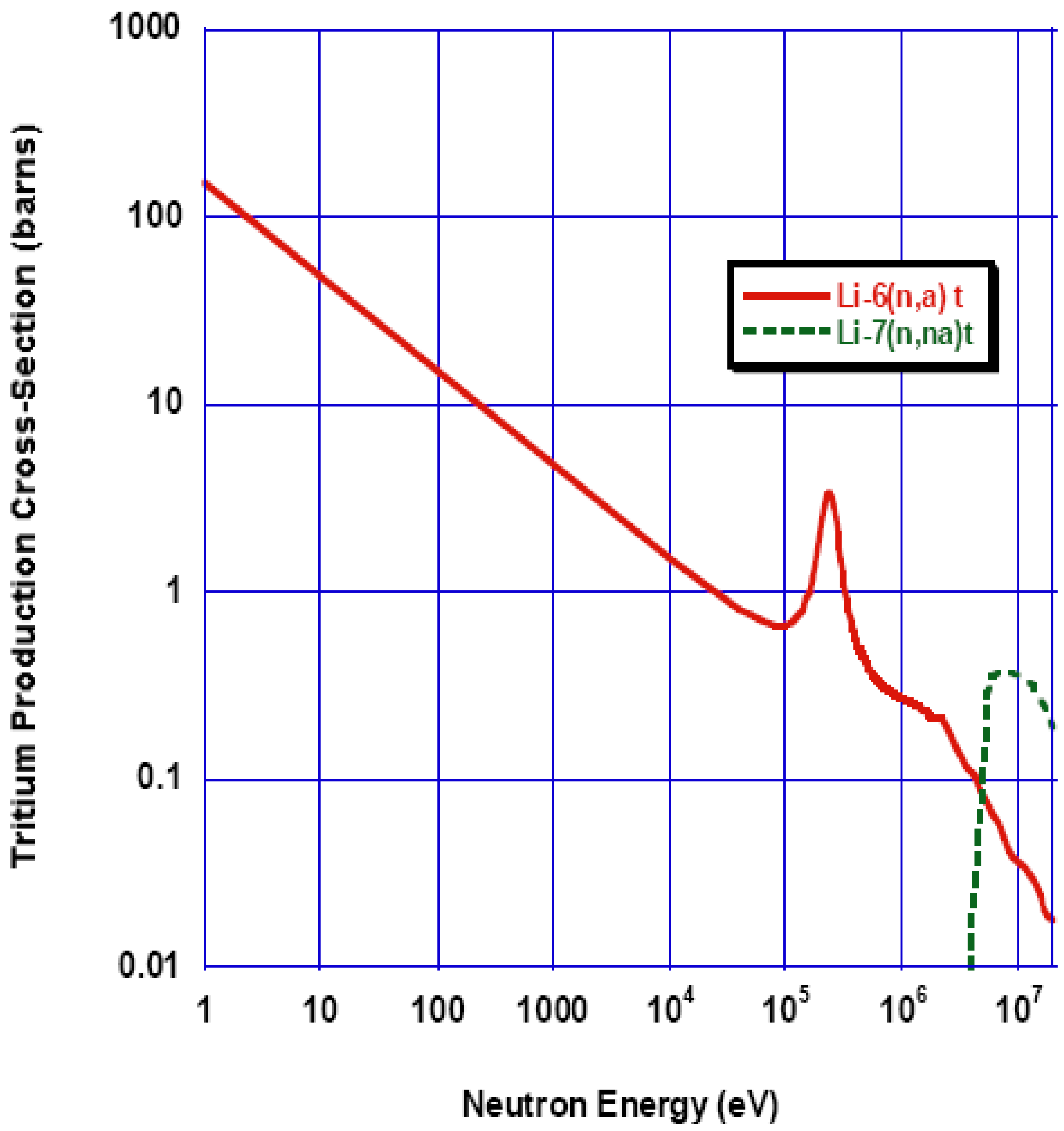
↓

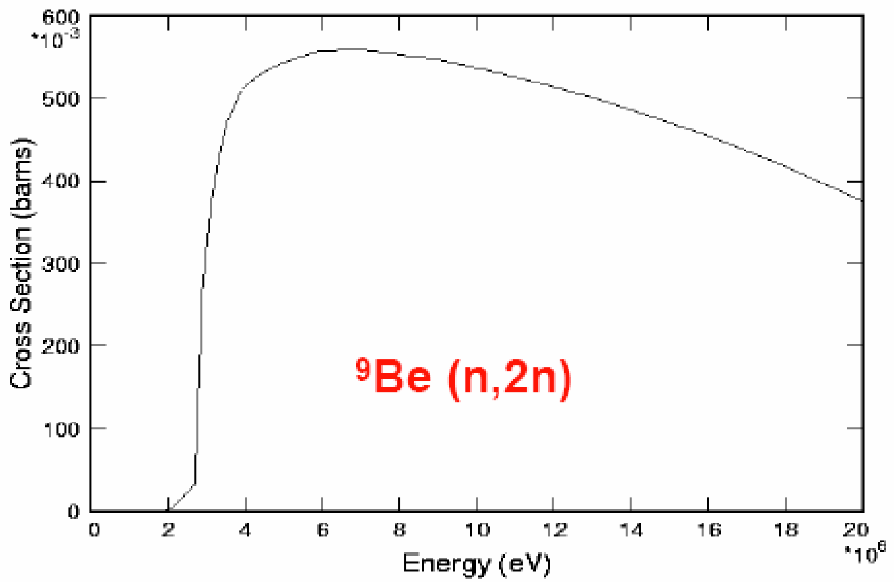
3. **Coolant**
   – Li, LiPb – Molten Salt – Helium – Water

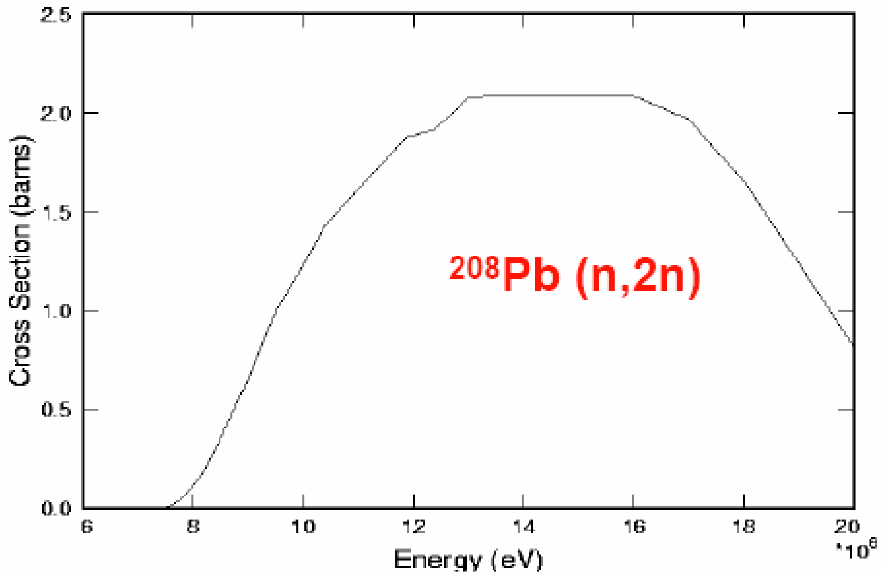
→ **GEN IV Reactors**

4. **Structural Material** → **High-temperature, low activation**
   - Ferritic Steel (accepted worldwide as the reference for DEMO)
   - Long-term: Vanadium alloy (compatible with Li) and SiC/SiC

Cross Sections of Breeder and Multiplier Materials







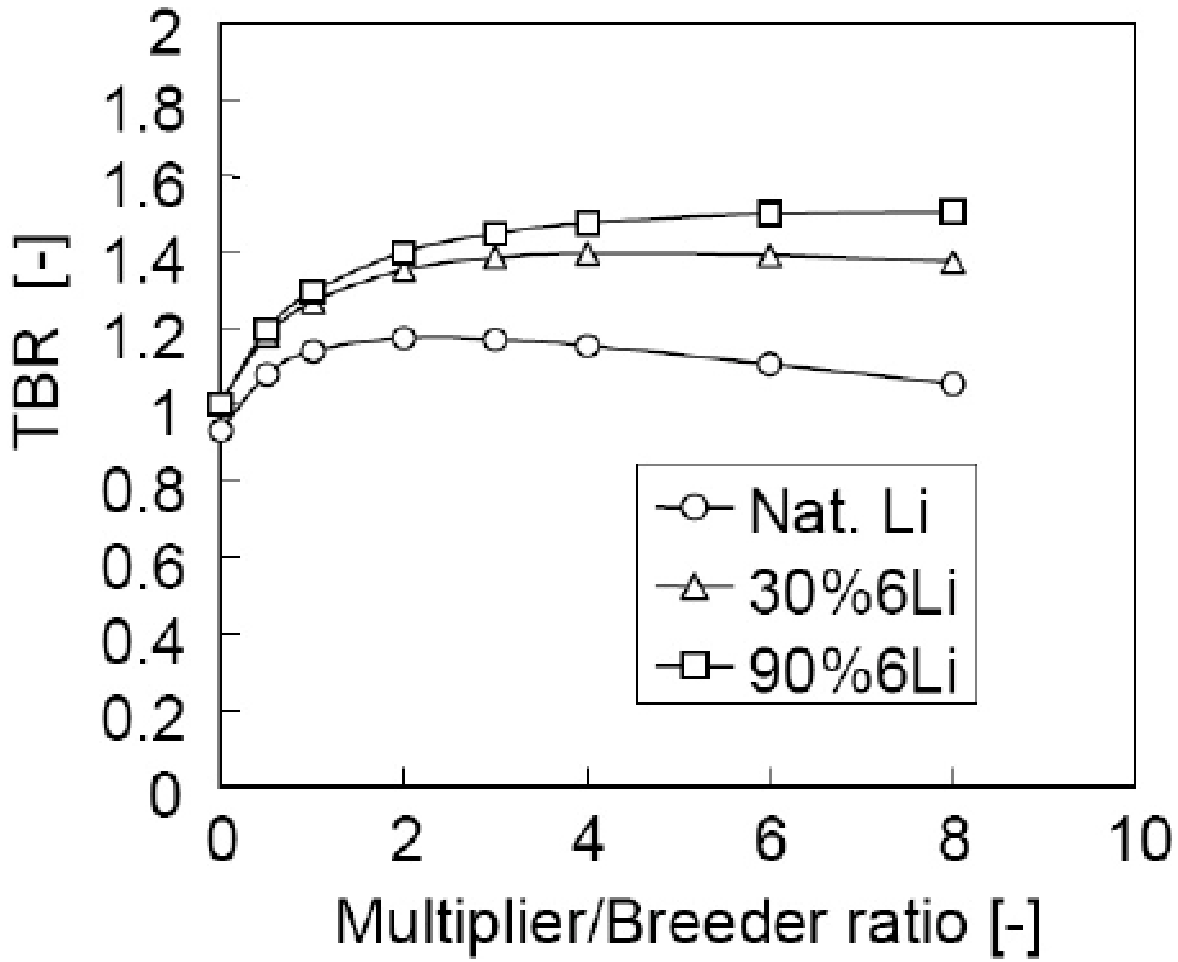
Selection of Breeding Blanket Materials

Approximate TBR with no structure

$LiAlO_2$	1.0
Li_2TiO_3	1.0
Li_2ZrO_3	1.0
Li_4SiO_4	1.0
Li_2O	1.4
Flibe	1.1
Flibe 90% ^{6}L	1.3
PbLi17	1.4
PbLi17 90% ^{6}Li	1.7
Li	1.8

May need multiplier or ^{6}Li enrichment !

TBR vs. multiplier / breeder ratio



$Be_{12}Ti$ / Li_2TiO_3

Selection of Coolant

- **Water**
  - ✓ **simple, reliable, and inexpensive**
  - ✓ **tritium removal, corrosion, compatibility (lithium ceramics, LiPb, or hot Be)**
- **Helium**
  - ✓ **HTGR experience, nonradioactive**
  - ✓ **easy tritium extraction, unaffected by B**
  - ✓ **high pressure, high flow rates, high pumping power, many tubes and welds**
  - ✓ **neutron streaming, impurities → corrosion, possible He shortage**
- **Liquid metals – pumping across B, fire**
- **Flowing Li2O – radiation stability, heat transfer, clogging**
- **Molten salts – chemical stability & corrosion**

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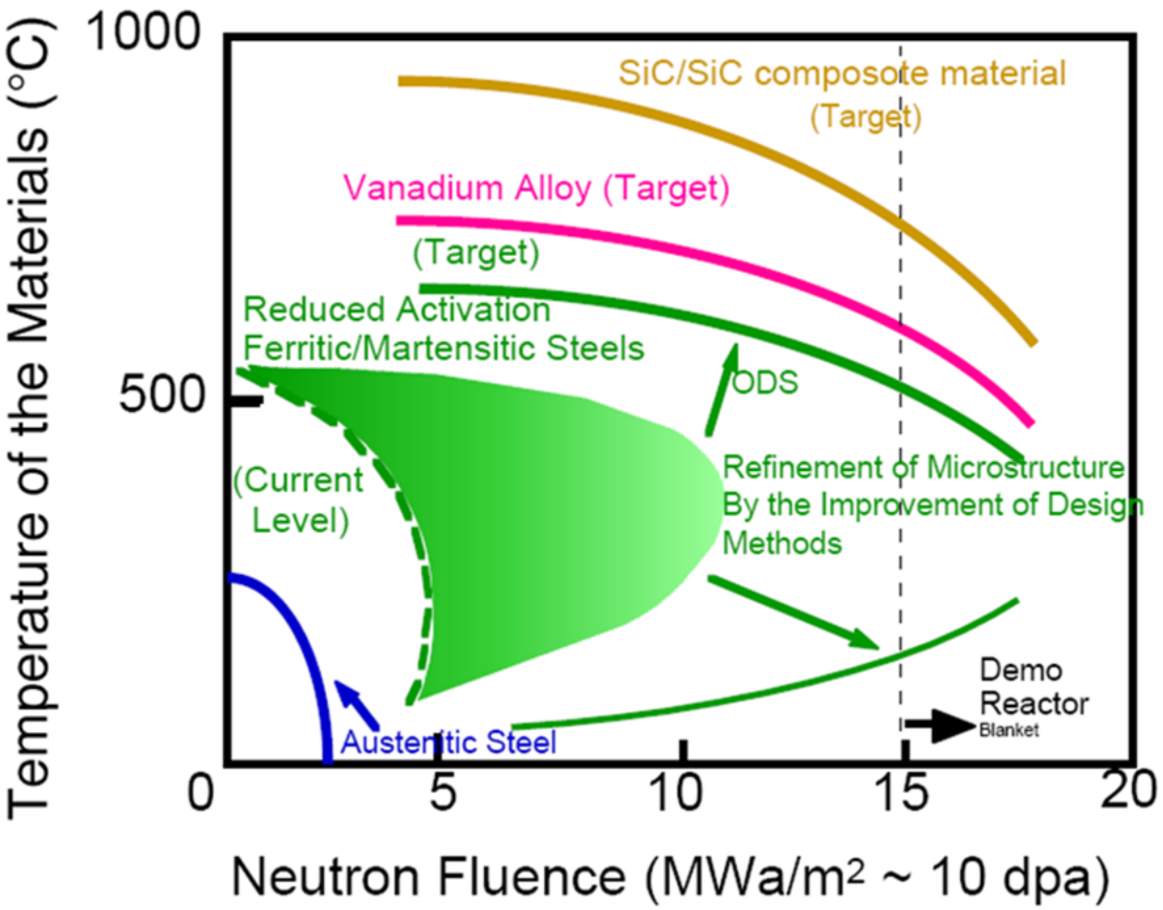
Structural Materials Development for Fusion Reactors

	ITER	DEMO	Reactor
Fusion Power	0.5 GW	2.5 – 5 GW	2.5 - 5 GW
Heat flux (first wall) (divertor)	0.1-0.3 MW/m^2 ~ 10 MW/m^2	0.5 MW/m^2 ~15-20 MW/m^2	0.5 MW/m^2 ~20 MW/m^2
Neutron Load (FirstWall)	0.78 MW/m^2	< 2 MW/m^2	~ 2 MW/m^2
Integrated Neutron Load (First Wall)	0.07MW.year/m^2 (3 years operation)	5 - 8 MW.year/m^2	10 - 15 MW.year/m^2
Displacement per atom (dpa)	< 3 dpa	50 - 80 dpa	100 - 150 dpa
	Increasing Materials challenge		
Transmutation product rates at first wall	~10 appm Helium / dpa ~45 appm H / dpa		



DEMO Structural Material Selection: RAFM Steels

For the experimental 'Reduced Activation Ferritic Martensitic' steels: -

→Ta replaces Nb,

→ V replaces Ti

→Cr replaces Mn … up to a point… nothing much replaces Mo.

F82H (Japan): Fe - 7.7%Cr – 2%W - 0.2%V - 0.04%Ta - 0.09%C

Eurofer (EU): Fe - 8.9%Cr – 1%W - 0.2%V - 0.14%Ta - 0.12%C

There are also "Oxide Dispersion Strengthened" (ODS) variants -

Nanoscale Y_2O_3 particles:

- act as He, H sinks and improve defect rate,
- strengthen,
- reduce creep.

Currently only small experimental batches made

Advanced Reduced-Activation Alloy (ARAA) : KAERI
Ti-RAFM : KIMM

Advanced Radiation Resistant Oxide Dispersion Strengthened Steel (ARROS) consisting of a Fe-10Cr-1Mo system with Mn, V, Ni, Zr, Ti, and Y2O3 as minor elements

Shielding Materials

- Protect magnet coils
  - superconductor
  - copper stabilizer
  - insulation
- Reduce activation
- Protect people
- Neutrons and gammas attenuation ~ 10^{-7}

Shielding Requirements – ARIES CS
Radiation Limits, 40 full-power years

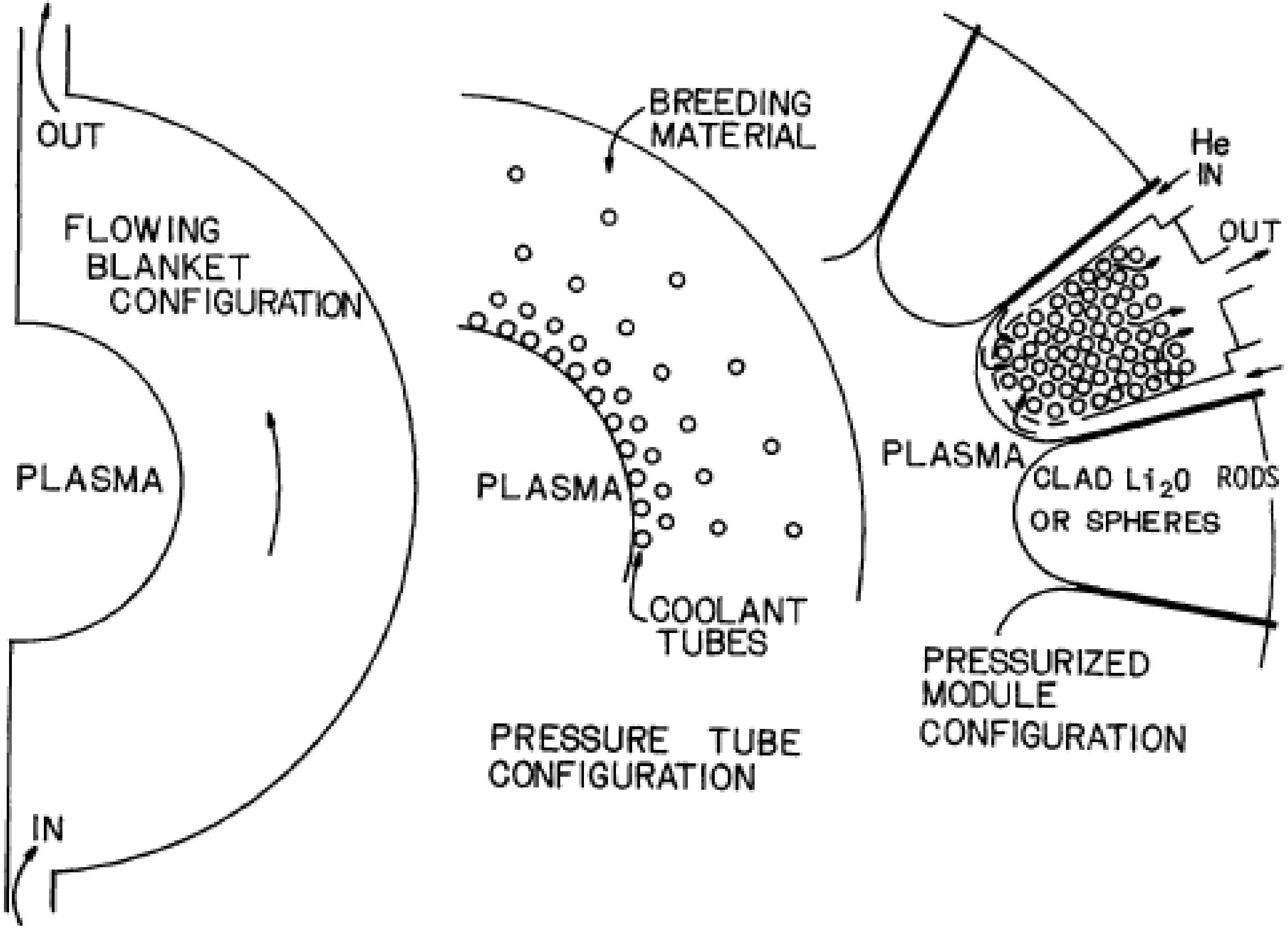
Fast neutron fluence to coils	< 10^{19}	/cm^2
Nuclear heating in Nb_3Sn coils	< 2	mW/cm^3
Dose to coil insulator	< 10^{11}	rad
Copper stabililzer displacements per atom	< $6x10^{-3}$	dpa

(El-Guebaly FST 2008)

- **WC is used for both neutrons and gammas**
- **ARIES CS: double-walled vacuum vessel**

(RAFM steel structure, borated steel filler, and water)

Coolant Flow Configurations



Coolant Channel Design Issues

- Temperature distribution
  - ✓ Maximum coolant T_{out}
  - ✓ Cool first wall
  - ✓ Hot breeder for tritium removal
  - ✓ Avoid hot spots
  - ✓ Compatibility limits
- Pumping power
- Stresses from gravity, pressure, temperature gradients
- Thermal expansion allowance
- Avoid creep, fatigue, corrosion

Coolant Channel Design Issues

- Neutronics
  - ✓ Low void fraction
  - ✓ Small structure fraction
  - ✓ Avoid long-lived radioisotope generation
  - ✓ Avoid neutron streaming
- Tritium removal and inventory
- Materials
  - ✓ abundant, inexpensive, noncorrosive
  - ✓ easily fabricated & joined
- High reliability
- Easy maintenance

Design Compromises

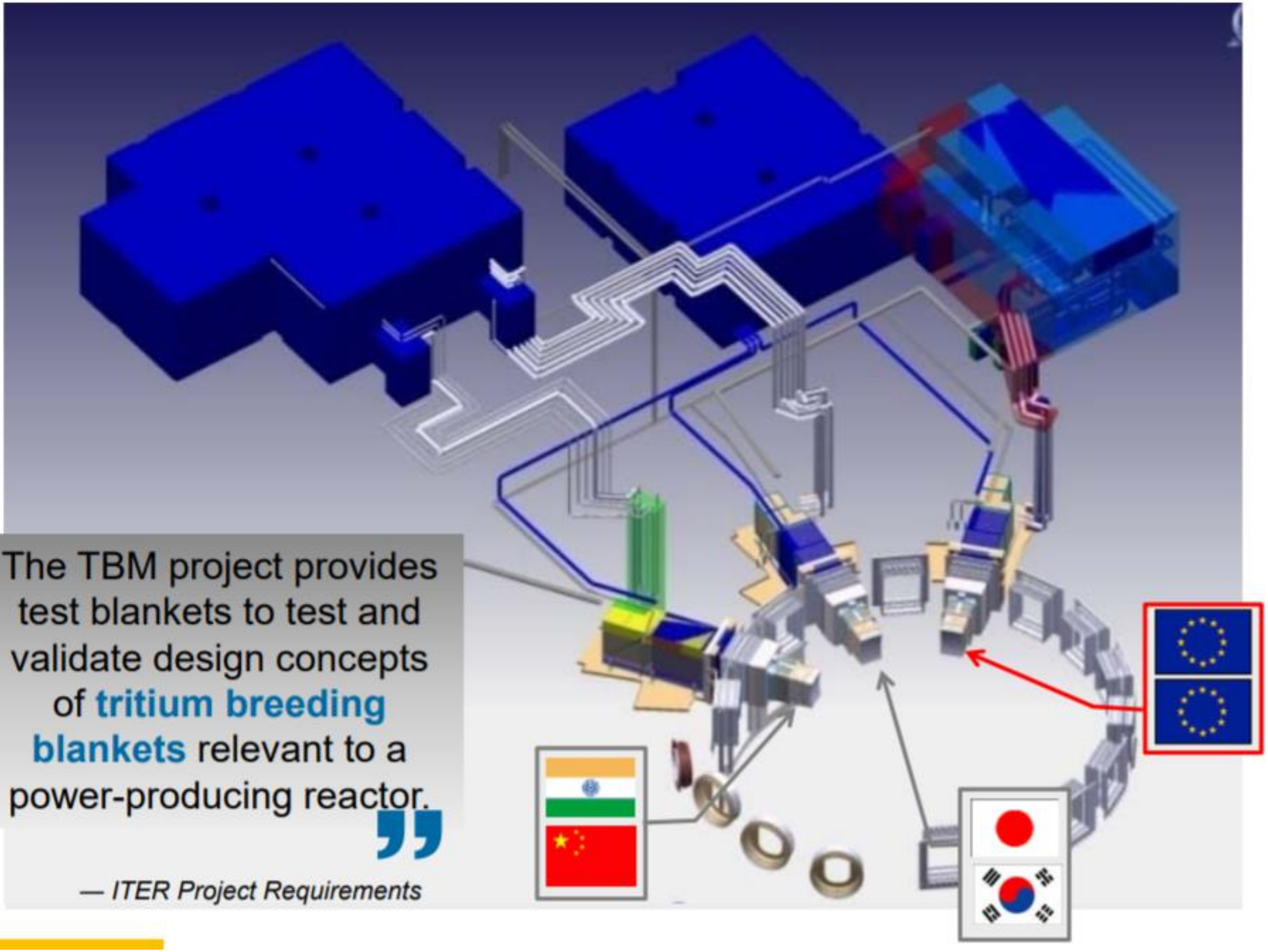
- **High T_{out} good thermal conversion efficiency, but poor strength and compatibility.**
- **Large coolant ΔT → lower flow rates and pumping powers, but exacerbates thermal stress.**
- **High He pressures decrease the required velocities, but increase duct stresses.**
- **Thin tubes have high hoop stresses, and thick tubes have high thermal stresses.**
- **Large He tube diameters decrease the number of tubes and welds needed, but they increase hoop stress and neutron streaming .**

Concept studies on breeding blankets in the world

Blanket type	WCLL	HCLL	HCCB	WCCB	LLCB	DCLL	Molten Salt	Li-V	HCCB	SCLL	Li Evap.
Structural material	RAFM	RAFM	RAFM	RAFM	RAFM	RAFM + ODS	Ferritic Steel	V alloy (+ insulation)	SiCf/SiC	SiCf/SiC	W alloy
Breeder	Pb-16Li (liquid)	Pb-16Li (Liquid)	Li_4SiO_4, Li_2TiO_3 (pebbles)	Li_2TiO_3 (pebbles)	Pb-16Li (liquid) + Li_2TiO_3 (pebbles)	Pb-16Li (liquid)	FLiBe (liquid)	Li (nat.)	Li_2TiO_3, Li_2O (pebbles)	Pb-16Li (liquid)	Li (nat.)
Neutron Multiplier			Be (pebbles)	Be (pebbles)			Be (pebbles)		Be (pebbles)		
Coolant	H_2O (15 MPa)	He (8 MPa)	He (8 MPa)	Supercritical H_2O (25 MPa)	He (8 MPa)	He (8 MPa) + Pb-16Li	FLiBe (liquid)	Li (nat.)	He (10 MPa)	Pb-16Li	Li (nat.) evap.
T coolant	265 - 325	300 - 500	300 - 500	290 - 520	325 - 500	300 - 480 (He) 460 - 700 (PbLi)	450 - 550	330 - 610	600 - 900	765 - 1100	1100 - 1200
T Structural material	265 - 550	300 - 550	300 - 550	290 - 550	300 - 550	300 - 550	max. 550	330 - 700	700 - 1150	765 - 1000	max. 1300
Reactor concept studies & R&D	PPCS-A	PPCS-AB	PPCS-B	SSTR	DEMO-S	ARIES-ST APEX PPCS-C	FFHR-2	ARIES-RS	DREAM A-SSTR2	ARIES-AT TAURO	APEX-EVOLVE

From Y. Poitevin et al (2015)

ITER TBM Programs (2008)



> The TBM project provides test blankets to test and validate design concepts of **tritium breeding blankets** relevant to a power-producing reactor.
>
> — *ITER Project Requirements*

ITER TBM Program Status

Blanket type	WCLL	HCLL	HCCB	WCCB	LLCB
Structural material	RAFM	RAFM	RAFM	RAFM	RAFM
Breeder	Pb-16Li (liquid)	Pb-16Li (Liquid)	Li_4SiO_4, Li_2TiO_3 (pebbles)	Li_2TiO_3 (pebbles)	Pb-16Li (liquid) + Li_2TiO_3 (pebbles)
Neutron Multiplier			Be (pebbles)	Be (pebbles)	
Coolant	H_2O (15 MPa)	He (8 MPa)	He (8 MPa)	Supercritical H_2O (25 MPa)	He (8 MPa)
T coolant	265 - 325	300 - 500	300 - 500	290 - 520	325 - 500
T Structural material	265 - 550	300 - 550	300 - 550	290 - 550	300 - 550
TBM Leaders					

Port No. (PM)	TBM Leader 1 (TL)	TBM Leader 2 (TL)
16 (PM : EU)	HCLL (EU) (Helium Cooled Lithium Lead)	HCPB (EU) (Helium Cooled Pebble Bed)
18 (PM : JA)	WCCB (JA) (Water Cooled Ceramic Breeder)	HCCR (KO) (Helium Cooled Ceramic Reflector)
2 (PM : CN)	HCCB (CN) (Helium Cooled Ceramic Breeder)	LLCB (IN) (Lithium Lead Ceramic Breeder)

2018: TBM ports from Three to Two
Four models can be tested simultaneously

Reasonable proposal in this case may be

Equatorial Port #16:
Water-Cooled Lithium-Lead (WCLL)
Helium-Cooled Solid-Breeder (HCSB, 1st TBS)

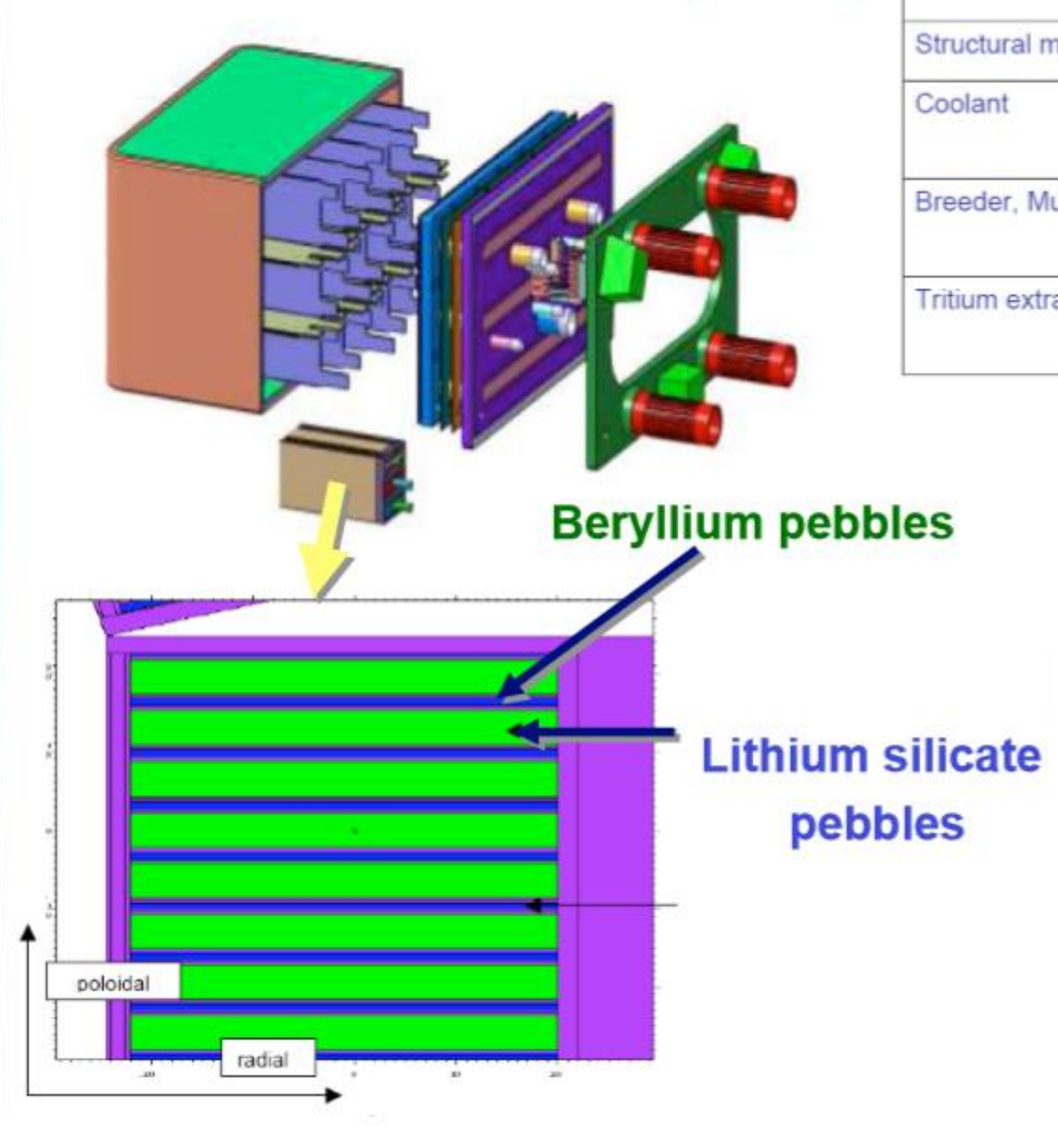
Equatorial Port #18:
Water-Cooled Ceramic Breeder (WCCB)
Helium-Cooled Solid-Breeder (HCCB, 2nd TBS)

EU Blanket for DEMO

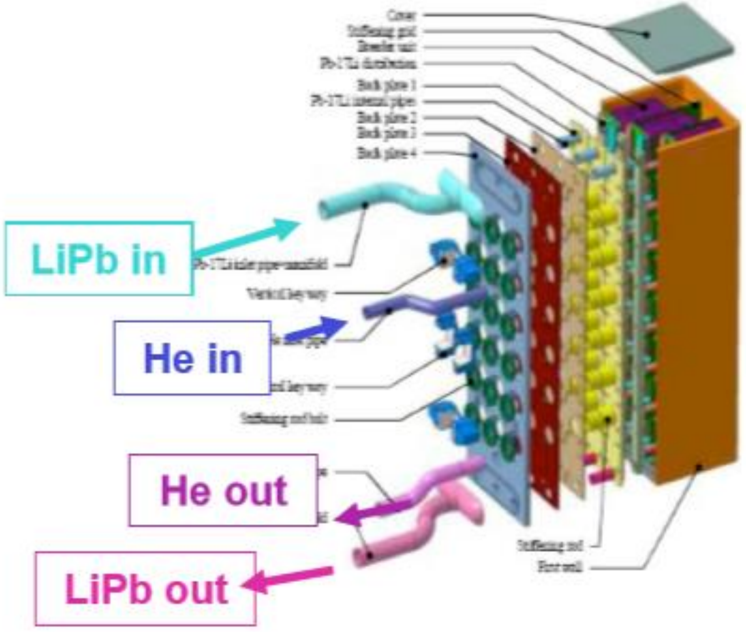
		Model A	Model B	Model AB	Model C	Model D
blanket	Structural material	Eurofer	Eurofer	Eurofer	Eurofer	SiC/SiC
	Coolant	Water	Helium	Helium	LiPb/He	LiPb
	Coolant T in/out (°C)	285 / 325	300 / 500	300 / 500	480 / 700 300 / 480	700 / 1100
	Breeder	LiPb	Li_4SiO_4	LiPb	LiPb	LiPb
	TBR	1.06	1.12	1.13	1.15	1.12
divertor	Structural material	CuCrZr	W alloy	W alloy	W alloy	SiC/SiC
	Armour material	W	W	W	W	W
	Coolant	Water	Helium	Helium	Helium	LiPb
	Coolant T in/out (°C)	140 / 170	540 / 720	540 / 720	540 / 720	600 / 990

EU Test Blanket Model

Helium-cooled Pebble-Bed (HCPB)



	HCPB	HCLL
Structural material	RAFM steel (EUROFER)	RAFM steel (EUROFER)
Coolant	Helium, 8 MPa, 300/500°C	Helium, 8 MPa, 300/500°C
Breeder, Multiplier	Solid breeder (pebble beds) Li_2TiO_3/Li_4SiO_4, Be/$Be_{12}Ti$	Liquid breeder Pb-15.7Li
Tritium extraction	Low pressure He loop (~1 bar)	Slowly re-circulating PbLi (geodesic pressure)



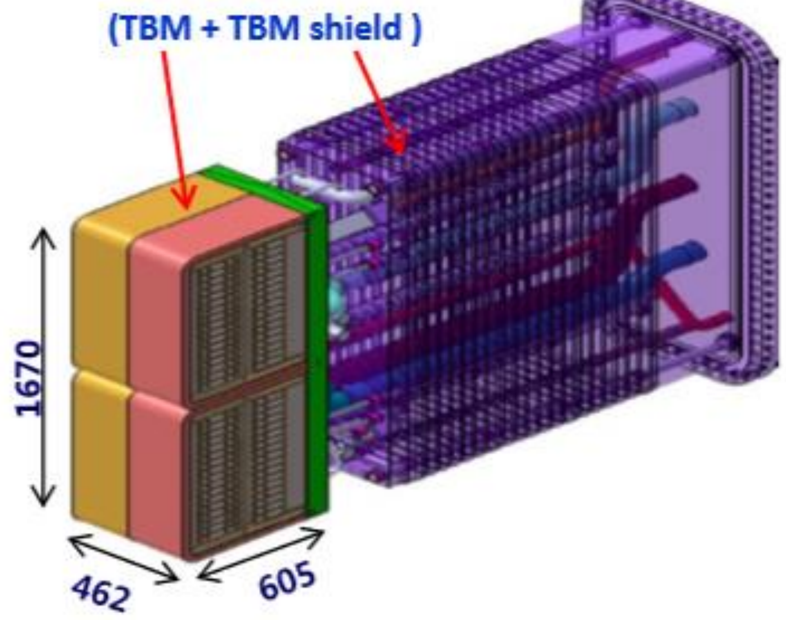
Helium-cooled Lithium Lead (HCLL)

KO Test Blanket Model

- **KO Helium Cooled Ceramic Reflector (HCCR) TBM**
  (DEMO-relevant breeding breeder concept)

Parameter	Values
FW heat flux	0.3 MW/m²
Neutron wall load	0.78 MW/m²
Thermal Power	**0.98 MW**
Structural material	**KO-RAFM (ARAA) (< 550°C), 0.01% Zr Improved creep and impact resistances**
Breeder	**Li_2TiO_3 (< 920°C), 80 kg 70% enrichment Li-6**
Multiplier	**Be (< 650°C)**
Reflector	**Graphite (<1200°C) Reduce the Be Multiplier up to 50%**
Size	**1670(P) x 462(T) x 605(R) (mm)**
Coolant	8 MPa He, 1.14 kg/s (Nominal) 300°C inlet / 500°C outlet
Purge gas	He with 0.1 % H_2
TBM-shield	316L(N)-IG Block/Cooling Channels ITER FW/BLK-PHTS (40°C, 4 MPa)

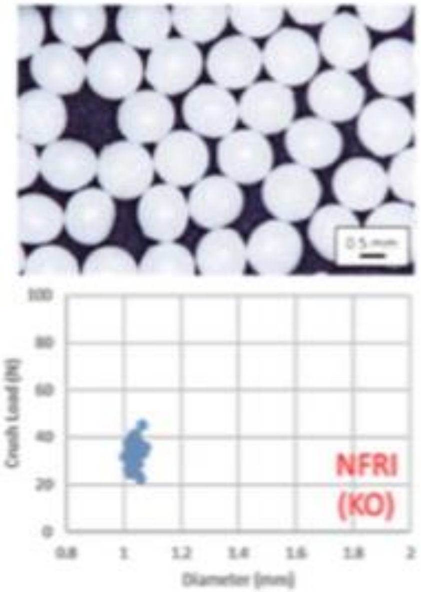
TBM-set



ARAA (Advanced Reduced Activation Alloy) Product

KO TBM Development Progress

- **Mass production of Ceramic Pebble Breeder**
  - **Li_2TiO_3 Pebble (dia. ~ 1 mm)**
  - Relative Density of Pebble : 85%
  - Capacity of Mass Production Equipment : **50 kg/y**



- **HeSS (Helium Cooling Supply System)**
  - **Evaluation of component lifetime**
  - Build-up know-how for ITER TBM operation
  - Evaluation Test loop built for circulator

- **Purge gas loop (Full Scale) under building-up**