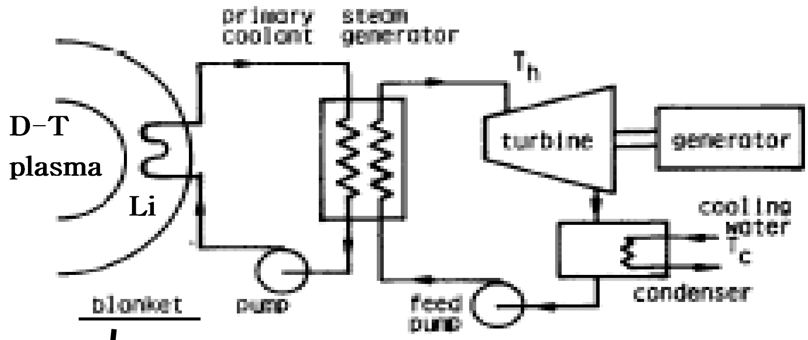
Chapter 6. Fusion Reactor Blanket

Reading assignments: **Harms Chap. 13, Stacey Chap. 10**
Dolan, Chap. 26



Breeding T + Moderating n --> Heat removal by coolant

Fusion reactor core: $D + T \Rightarrow \alpha(3.5) + n(14.1)$

Blanket region: $\hookrightarrow \; n + \begin{pmatrix} ^6Li \\ ^7Li \end{pmatrix} \Rightarrow T + \alpha + \begin{pmatrix} 4.78 \\ n - 2.47 \end{pmatrix}$

T breeding Ratio (TBR): $c_t \equiv \dfrac{total\ production\ rate\ in\ blanket}{destruction\ rate\ in\ core} > 1.05$

for a self-sustaining reactor

1. Blanket design considerations

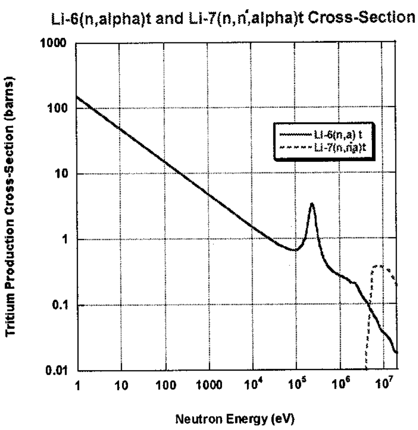
- Material limitations (structural, breeding, coolant materials)
- Heat removal (heat transfer, coolant tube stresses, pressure drop, pumping power, coolant channel configuration)
- Neutronics for breeding, energy multiplication, radiation attenuation
- Environment (^3T, structural activation, fire & hazards) and economics (resources, cost)
- Ease of disassembly, repair, maintenance

2. Blanket materials

A. Tritium breeding materials

: some form of Li-containing material

for $\underline{^6\text{Li}}$ $(thermal\ n,\ \alpha)\,^3\text{T}$ and
(7.5%) $\underline{^7\text{Li}}$ $(fast\ n,\ n',\ \alpha)\,^3T$
(92.5%)



1) Breeding requirement

- TBR C_t : > 1.05 to compensate for transport losses and its decay
  Depends on the blanket thickness and the structural material sizes
- Fusion consumption: 55.8 kg / GW year
- Production & cost in fission reactors
  CANDU: 27 kg/40 years, $30M/kg (2004)
  Fission reactors: few kg/year, $200M/kg

2) Some tritium breeding materials

a. Liquid

Li ($T_m \approx 450$ K, $T_b \approx 1600$ K, High κ, $C_t \lesssim 1.4$, **High** air/water reaction, Reactive, MHD effects)

Compatibility with Li due to corrosion & mass transfer problem:

Path A: 316 S.S. up to $T \lesssim 770$ K

Path B: Ni(Fe-Ni-Cr) alloy at much lower than 770 K

Path C: Refractory & reactive metals (Mo, V, Nb, Ti) up to 1100 K

$Li_{17}Pb_{83}$ eutectic ($T_m \approx 505$ K, High κ, **$C_t \lesssim 1.6$**, Moderate air/water reaction, **Corrosive,** ^3T permeation, MHD effects, n multiplier & γ shield of Pb)

FLiBe ($(LiF)_n$-BeF_2) molten salt (**$T_m \approx 637$ K**, **Low** κ, High C_p, **$C_t \lesssim 1.07$**, **No** air/water reaction,
Good chemical stability and resistance to radiation damages,
Compatability with Mo, Nb, Ni alloys up to $T \lesssim 970$ K
316 S.S. up to $T \lesssim 920$ K)

b. Solid

Li-Pb mixture (**$C_t \lesssim 1.6$**, Moderate air/water reaction),

Li_2O ($T_m \approx 1700$ K, $C_t \lesssim 1.4$, **Low** air/water reaction)

Li ceramics: Li_2SiO_3, Li_4SiO_4, Li_2ZrO_3, $LiAlO_2$, Li_2TiO_3
($T_m \approx 1500 \sim 1900$ K, **$0.9 \lesssim C_t \lesssim 1$**, **No** air/water reaction)

Non-mobile breeder avoiding problems of reaction, corrosion and MHD
Low κ, Less corrosive, $T_{operat.} \approx 670 \sim 950$ K, ^3T is removed by He gas
Periodic reloading, Difficulty in recycling (waste issue), ^3T permeation
Coolant: He or water

B. Neutron multipliers

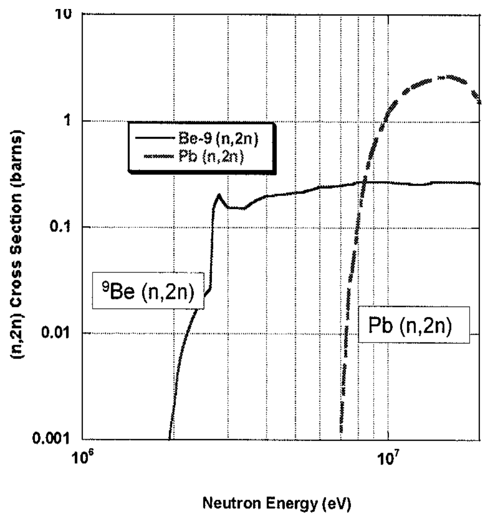
: (n, 2n) reaction materials
with low threshold to increase the supply of neutrons to blanket

Beryllium (Be, $Be_{12}Ti$)

High cross section, Resource limitation,
High α production, Highly toxic

Lead (in LiPb)

Low (n, 2n) cross section



C. Coolants

1) Liquid metals: Li (Na , K), Li-Pb eutectic

High κ and C_p ⇒ Carrying high heat fluxes at high T & low P.
Reactive, corrosive, high T_m ⇒ Compatibility problem
MHD effects by magnetic fields on pressure drop and heat transfer
Needs high pumping power, High stresses due to high P
Compatible with V and Nb alloys up to 1100 K

2) He gas

Inert & non-radioactive, unaffected by $\bar{B}$, easy extraction of ^3T
Well developed technology from HTGR
Low κ & C_p ⇒ Needs high flow rates, large ducts, high pumping power
Flow vel. 30~100 m/s, T≈800~1300 K, P≈5~10 MPa
Impurities in He coming from trace materials (O_2, N_2, H_2, H_2O, CO_2, ...), breeding materials, steam generator, seals, ...
⇒ Compatability problems (corrosion, embrittlement, ...)
Compatible with S.S. at He outlet T ≲725 K ⇒ Low thermal efficiency

3) Molten salts: FLIBE, Heat transfer salt (KNO_3-$NaNO_3$-$NaNO_2$)

Low T_b and vapor pressure ⇒ Low P operation
Little MHD effects, but chemical breakdown & increased corrosion by induced voltage

4) Water (boiling or pressurized)

Good heat transfer properties and low required pumping power
Well developed technology from BWR & PWR
Good neutron moderator
Requires high P and low outlet T (low thermal efficiency)
(e.g., PWR: ~14 MPa, ~600 K, ≲36%)
Hazardous reaction with Li, Difficult ^3T removal.

D. Structural materials

Limited by material failures (melting, evaporation, corrosion, embrittlement, swelling, creep, etc caused by heat, neutron radiation, and reaction with breeding and coolant materials) and by activation by 14.1-MeV neurons

Key issues include thermal stress capacity, coolant compatibility, waste disposal, and radiation damage effects

Potential structural materials (Stacy, Table 10.2.5)

Material Class	Alloys	Principal Advantages	Principal Disadvantages
Austenitic stainless steels	316, 20% CW	Large data base Fabrication experience	Poor thermophysical properties Large swelling High activation
	PCA[a]	Lower swelling than 316 High irradiated ductility	Poor thermophysical properties High activation
Ferritic stainless steels	HT-9 9CR-1Mo	Large unirradiated data base Low swelling and radiation creep	Ferromagnetic Ductile–brittle transition temperature increased by irradiation Low creep strength
Titanium alloys	Ti-64 Ti-6242 Ti-5621	Fabrication experience Potentially low activation	Lack of irradiation data base Hydrogen embrittlement Excessive tritium inventory
Nickel alloys	Inconel 625 PE-16 Inconel 718	Low swelling and creep High temperature capability	High activation Susceptible to radiation embrittlement
Vanadium alloys	V-15Cr-5Ti V-10Cr-3Ti	Radiation damage resistant Corrosion resistant to lithium High-temperature operation Good thermophysical properties Low activation	Little fabrication experience H_2O compatibility uncertain Not compatible with helium coolants
Niobium alloys	Nb-1ZR FS-85 Nb-753	High-temperature operation Desirable thermophysical properties Good liquid metal compatibility	Little fabrication experience H_2O compatibility uncertain Not compatible with helium coolants High activation

[a]Primary candidate alloy, an alloy under development.

Commercial alloys (Ti alloys, Ni base superalloys, refractory alloys, etc) are shown to be unacceptable for fusion for various technical reasons.

The ferritic/martensitic S.S is the reference structural materials for DEMO.

V alloy and SiC are long-term R & D materials for commercial reactor.

The three leading candidates are ferritic/martensitic S.S., V alloy, SiC/SiC based on safety, waste disposal, and performance consideration.

Structural Material	**Coolant/Tritium Breeding Material**					
	Li/Li	He/PbLi	H_2O/PbLi	He/Li ceramic	H_2O/Li ceramic	FLiBe/FLiBe
Ferritic steel		■	■	■	■	■
V alloy	■					
SiC/SiC		■		■		■

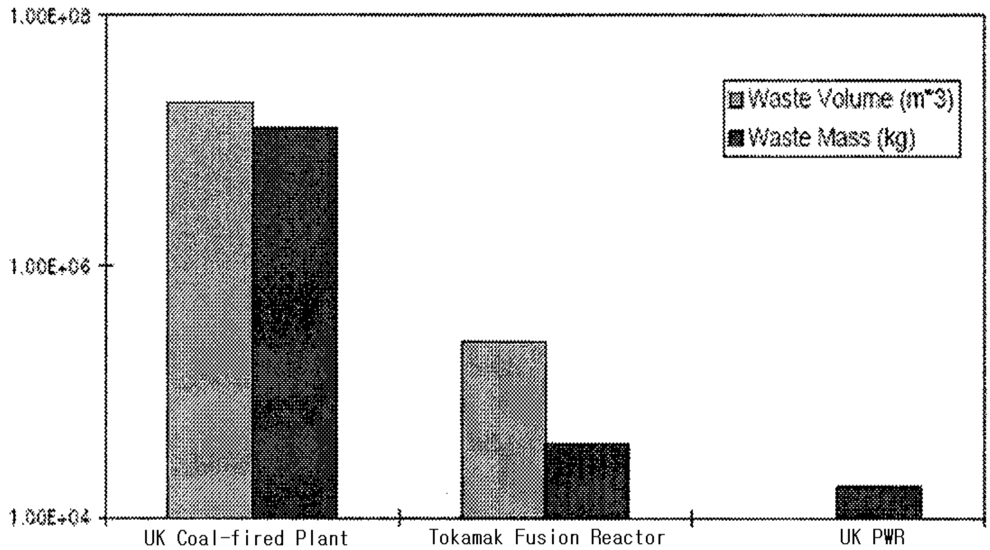
From Y.H. Kim, KAERI (2004)

Maximum operating temperature (in K) limited by structural strength or by compatibility of coolant and structure

Working fluid / Coolant	**S.S.**	**V alloy**
Liquid Li	770	1070
He	970	< 620
FLiBe	920	< 570
Water (H_2O)	~670	< 570

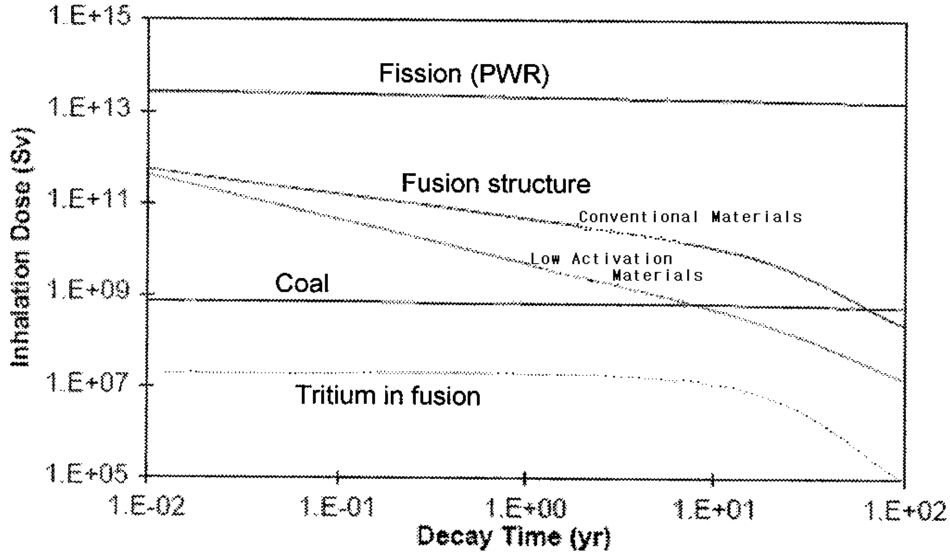
Comparison of waste masses & volumes from power plants of same capacity

(From "A Study of the Environmental Impact of Fusion" (AERE R 13708))



Comparison of radiotoxicities of waste based on inhalation dose for 100 years

(From "A Study of the Environmental Impact of Fusion" (AERE R 13708))



E. Neutron Reflectors (graphite, etc.)

for economical use of neutrons for ^{3}T breeding

Notes)

Other materials considered in blanket design

i) MHD insulators for concepts with self-cooled liquid metals

ii) Thermal insulators only in some concepts with dual coolants

iii) Tritium permeation barriers in some concepts

3. Blanket designs

A. Liquid breeder concepts

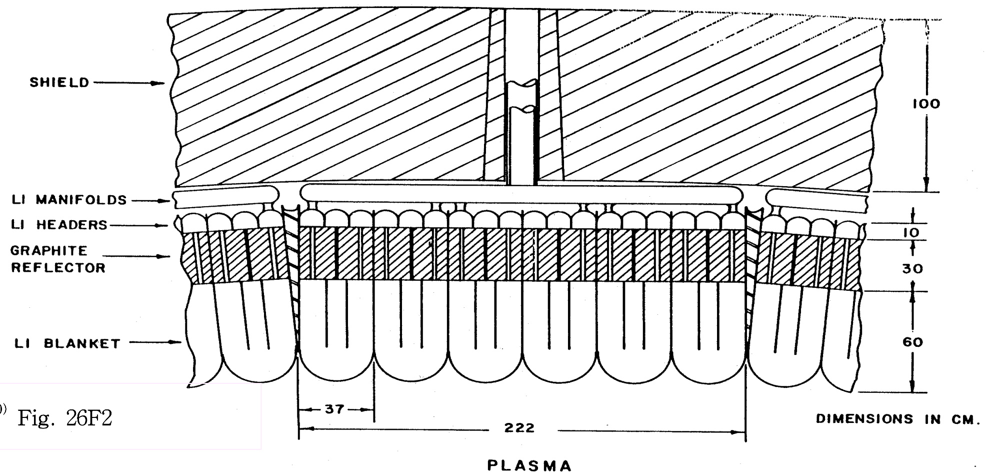
* Self-cooled: high speed circulation to also serve as coolant

* Separately cooled: low speed circulation only for ^3T extraction and a separate coolant (e.g., He)

* Dual coolant: self-cooled breeding zone and FW & structures cooling by separate coolant (He, ...)

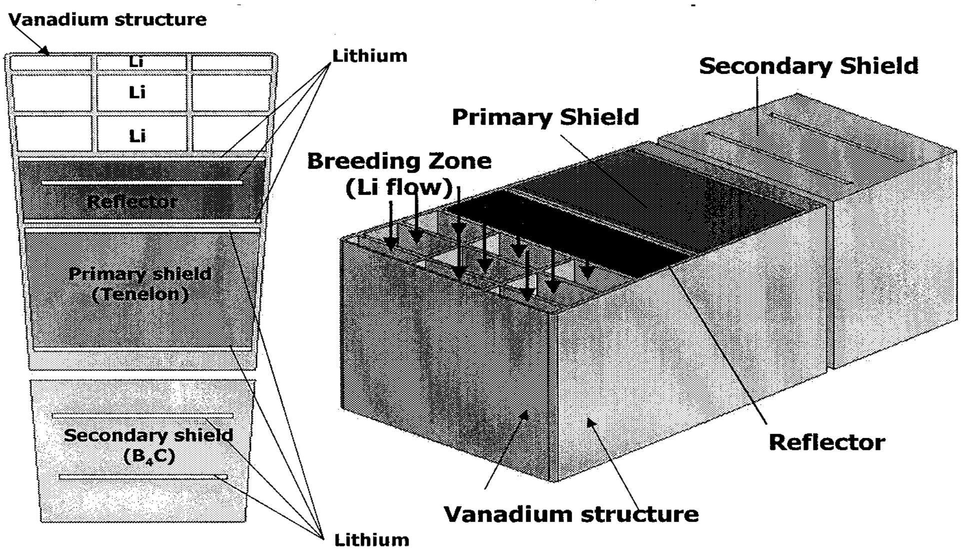
1) Li self-cooled blanket (UWMAK, 1976)

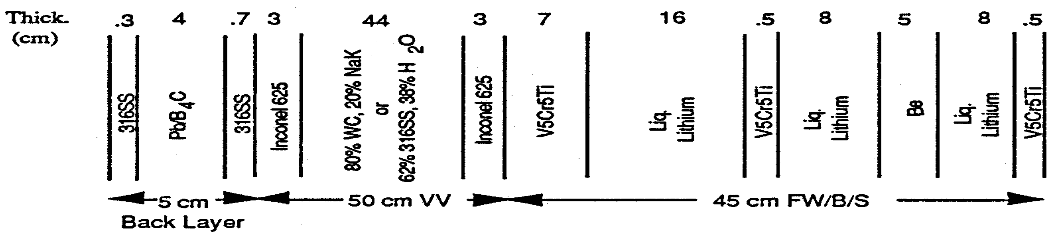
Li Breeder, Li Coolant, C Reflector, TZM Structure



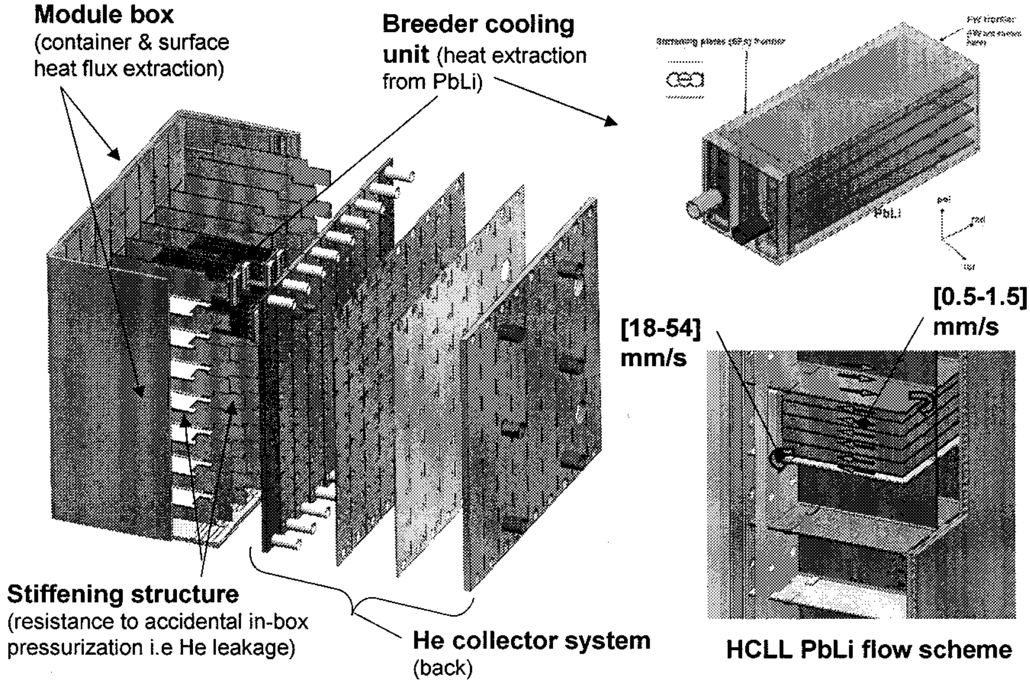
Dolan[10] Fig. 26F2

2) Li/V(V_5Cr_5Ti) self-cooled blanket (ITER, USA)



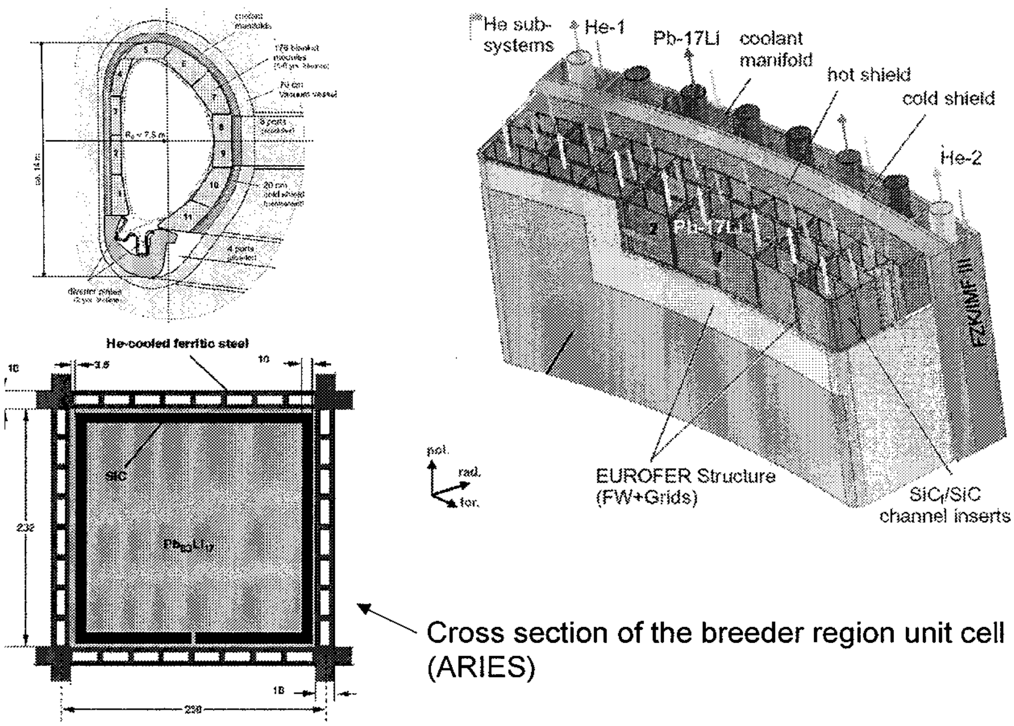


3) He-Cooled Lead Lithium (HCLL) blanket (DEMO, EU)



HCLL PbLi flow scheme

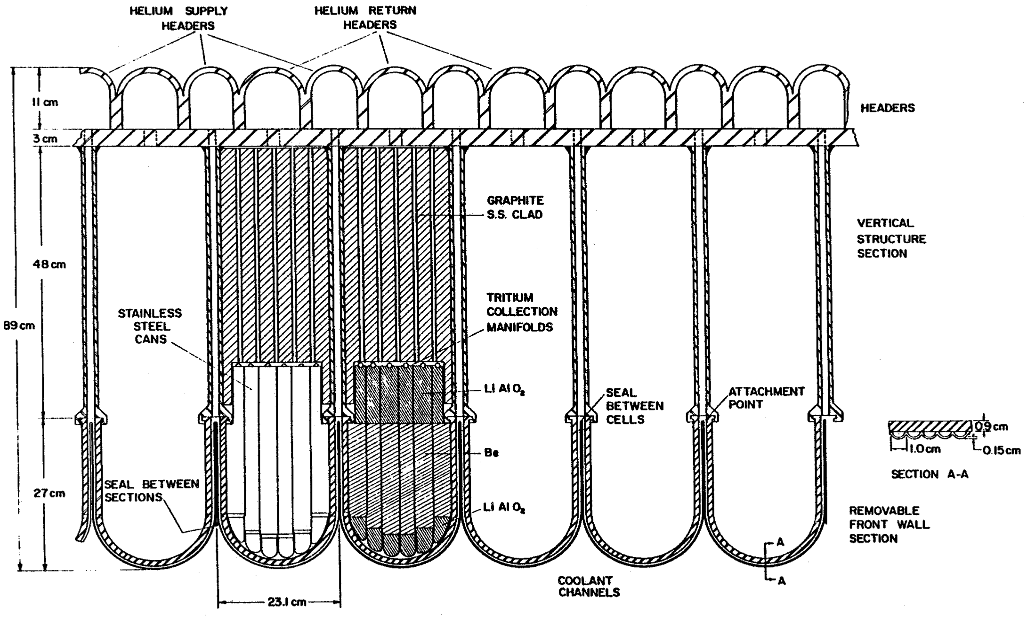
4) Dual coolant concept design (ARIES, USA & USA)



Cross section of the breeder region unit cell (ARIES)

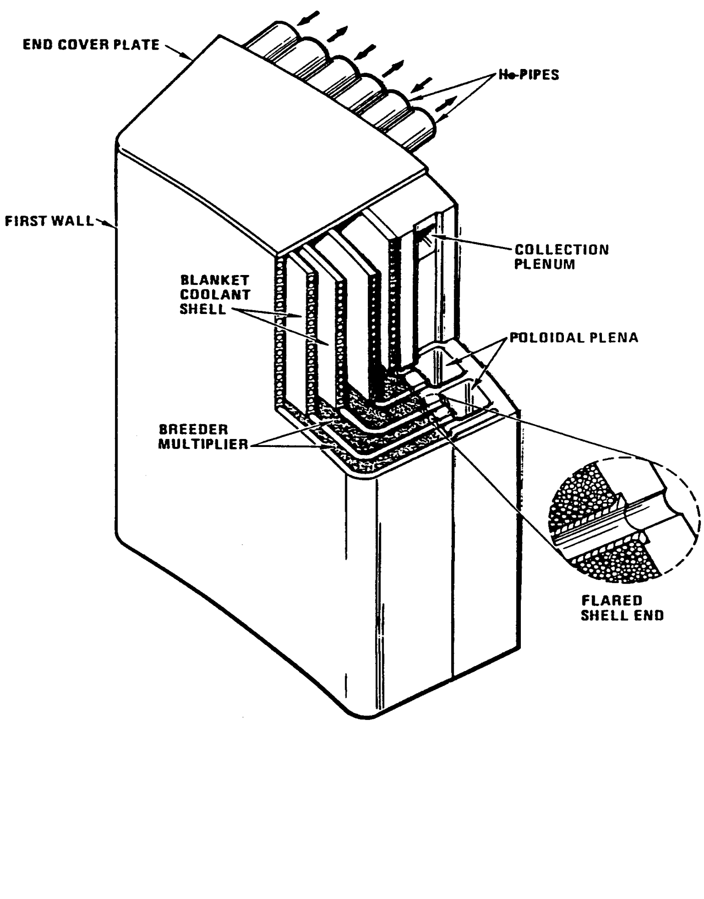
B. Solid breeder concepts

1) He-cooled solid breeder blanket (UWMAK-II, 1974)

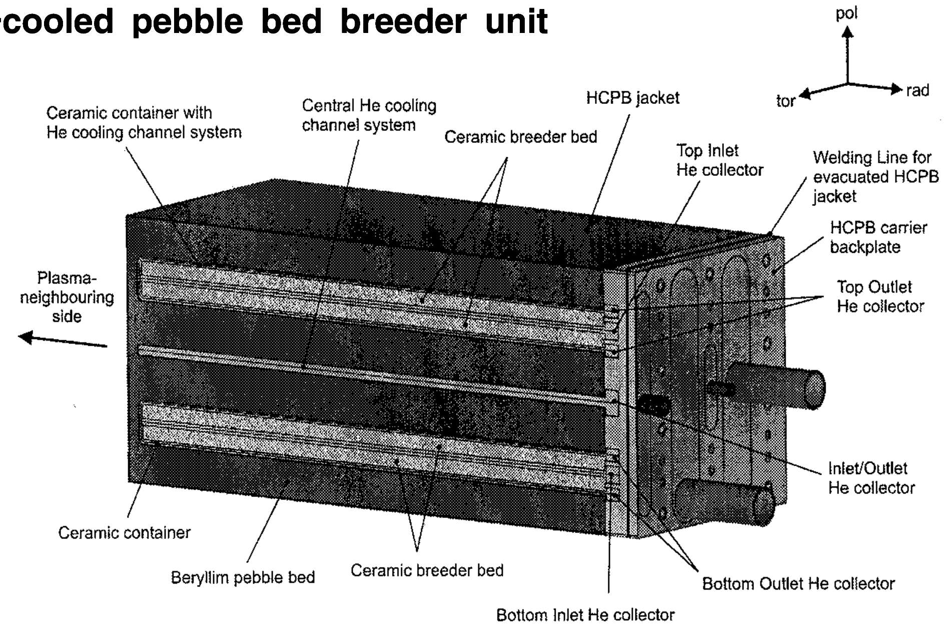


2) Nested-shell He-cooled solid breeder blanket (ARIES-I, 1991)

Sphere-pac Li_2ZrO_3 Breeder, He Coolant at 10 MPa,
Sphere-pac Be Multiplier, SiC Structure

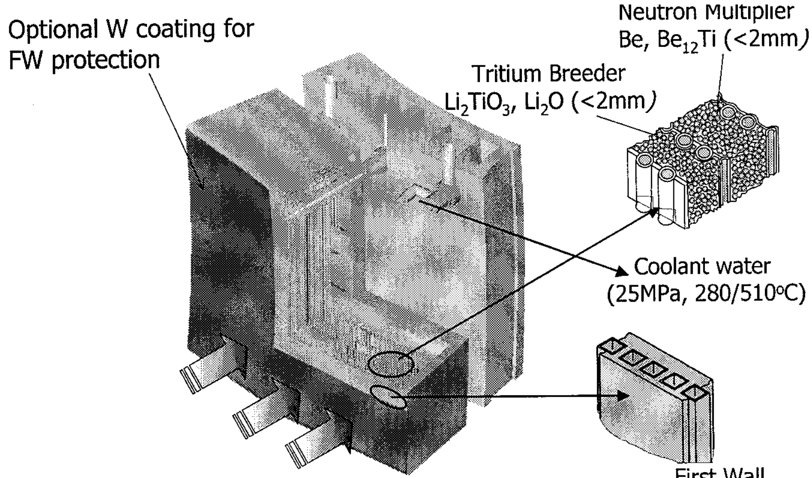


3) He-cooled pebble bed breeder unit

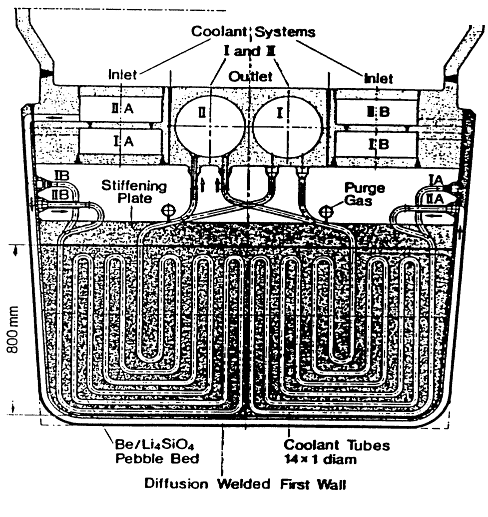


4) Water-cooled solid breeder blanket

Japan

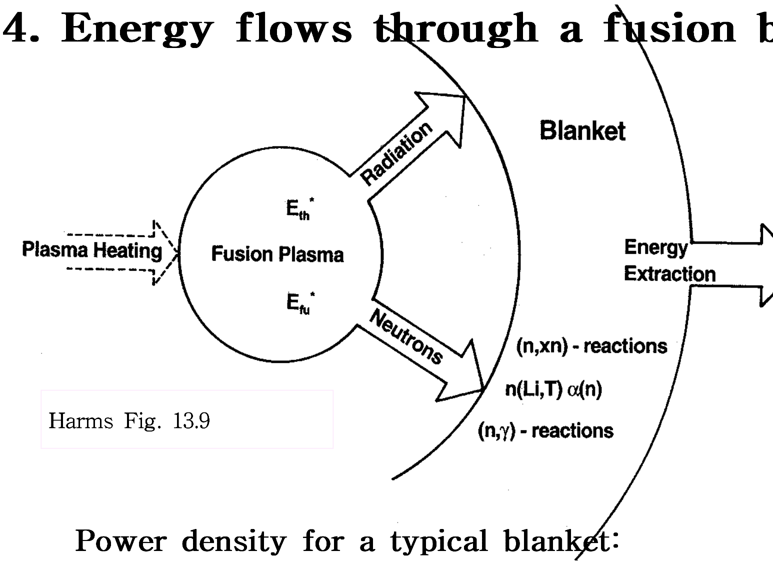


Surface Heat Flux:1 MW/m²
Neutron Wall Load: 5 MW/m²(1.5×10¹⁵n/cm²s)



Germany

4. Energy flows through a fusion blanket

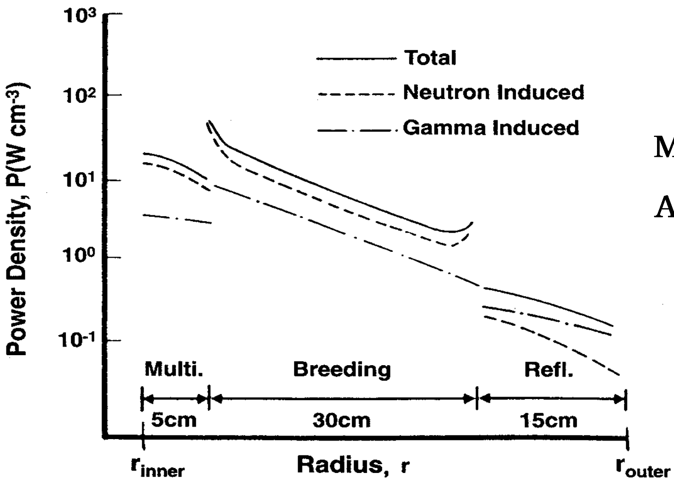


Harms Fig. 13.9

$E_b^* = b(f_n E_{fu}^* + E_{rad}^*) + \sum_l E_{nl}^*$

E_{nl}^* is the l-type neutron-induced reaction energy

Power density for a typical blanket:
(Be multiplier, $LiAlO_2$ breeder, H_2O coolant, C reflector)



Maximum: ~80MW/m^3

Average: ~15MW/m^3

(cf) Fission reactor $\leq$ 80MW/m^3

Harms Fig. 13.8

Energy removed from the blanket:

$$E_b^* = b(f_n E_{fu}^* + E_{rad}^*) + \sum_l E_{nl}^*$$
$$= M_b f_n E_{fu}^* + b E_{rad}^*$$

where b is the blanket coverage factor depending on the specific blanket geometry and the blanket multiplication factor M_b is

$$M_b = \frac{b f_n E_{fu}^* + \sum_l E_{nl}^*}{f_n E_{fu}^*}$$

$$= b + \frac{Q_{n6}\int_{V_b} n_n n_6 < \sigma_{n6} v_n > d^3 r + Q_{n7}\int_{V_b} n_n n_7 < \sigma_{n7} v_n > d^3 r}{f_{n,DT}\, Q_{DT}\int_{V_c} n_D n_T < \sigma v >_{DT}\, d^3 r}$$

For pure fusion blankets w/o fissionable materials, $1.3 \leq M_b \leq 1.8$