Fusion Reactor Technology I
(459.760, 3 Credits)

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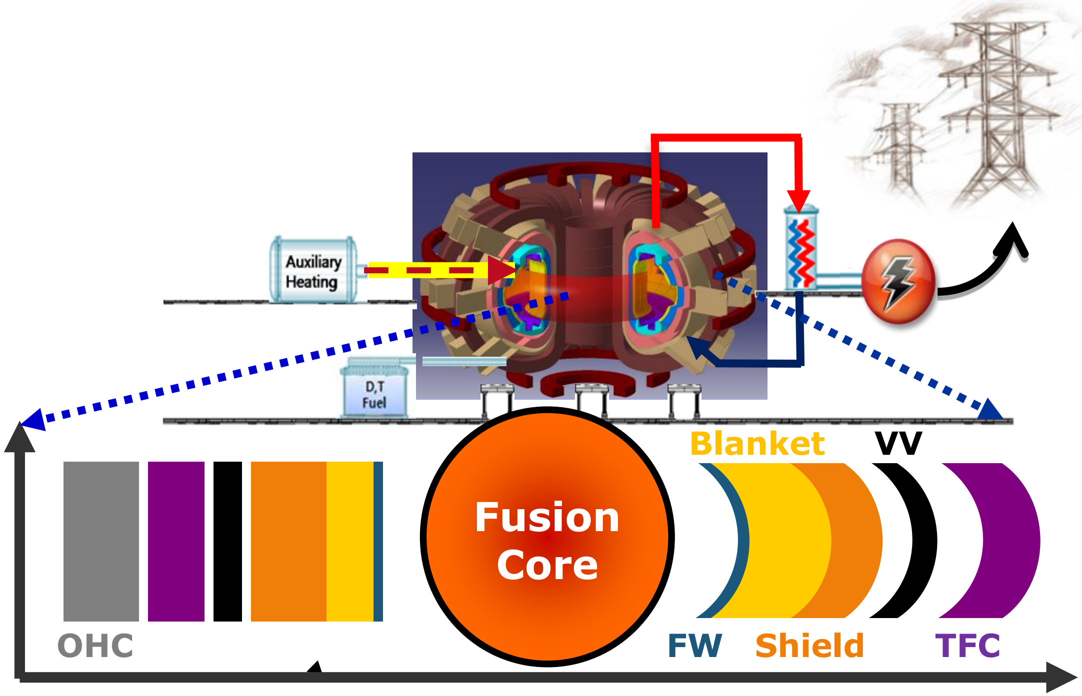
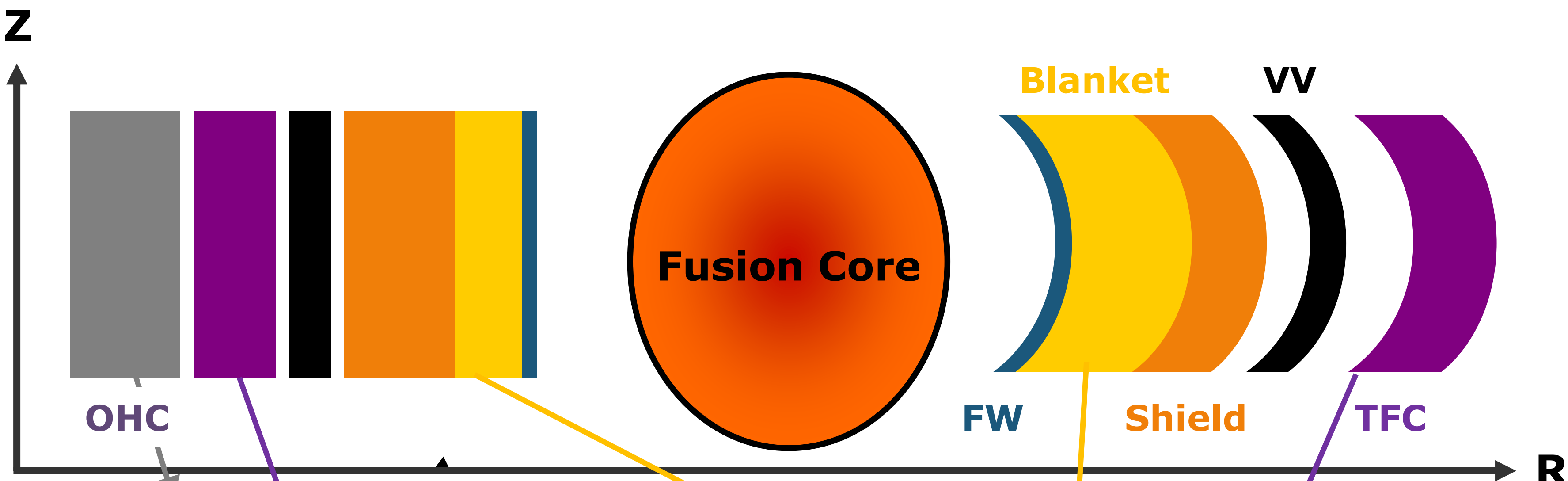
Contents

Radial Build in Fusion Reactors



Radial Build in Fusion Reactors



Volt second requirement, Operation scenario, Stresses, Current density, Voltage, Temperature, etc

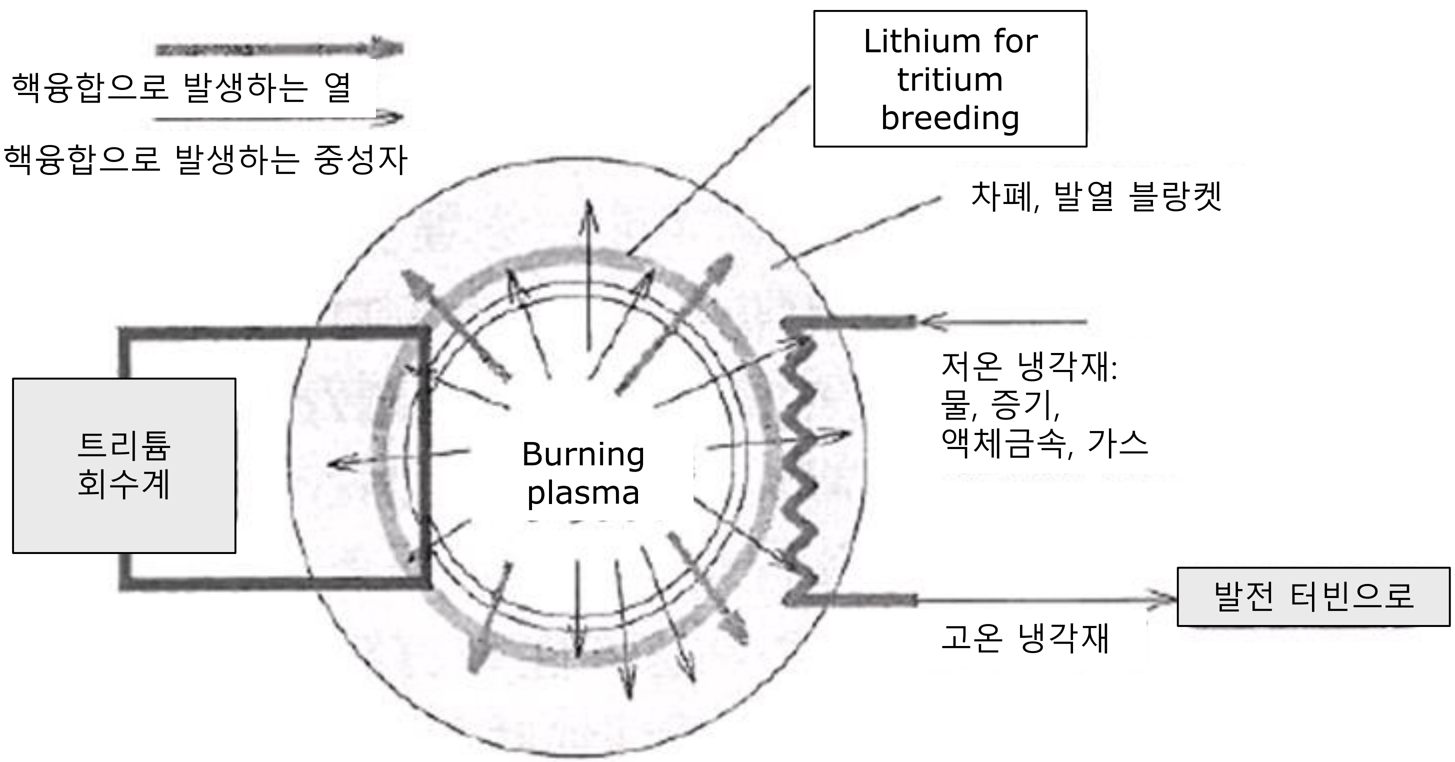
Neutron wall load, Shield & lifetime fluence requirement, T breeding ratio, etc

Max. TF field, Operation scenario, Stresses, Current density, Voltage, Temperature, etc

Toroidal field ripple requirement, Dose to insulator

2.2 토카막 핵융합로의 구성

- **에너지를 인출하기 위한 구조**
  - Concept of tritium breeding blanket



Blanket Functions

- **Power Extraction**

To recover energy from the emitted radiation and reaction products

- Convert kinetic energy of neutrons and secondary gamma rays into heat
- Absorbing plasma radiation on the first wall
- Extracting the heat (at high temperature, for energy conversion)

- **Tritium Breeding**

To breed tritium required in the D-T reactor core

- Tritium breeding, extraction, and control
- Having lithium in some form for tritium breeding

Blanket Functions

- **Physical Boundary for the Plasma**

To sustain a sufficiently clean plasma domain

- Physical boundary surrounding the plasma, inside the vacuum vessel
- Providing access for plasma heating, fueling
- Must be compatible with plasma operation
- Innovative blanket concepts can improve plasma stability and confinement.

- **Radiation Shielding of the Vacuum Vessel**

- To shield the surrounding structures and personnel

Blanket Concepts

- 증식재의 형태에 따라 고체 증식재와 액체 증식재로 나뉨.

Solid breeder	Liquid breeder
Li_2O, Li_2TiO_3, Li_2ZrO_3, Li_2SiO_4	Liquid lithium, Liquid metal, FLiBe (용융염: molten salt fluids)
화학적으로 안정 잠재적인 안정성 높음 구조재와의 양립성이 우수함	방사선 손상 경미 높은 TBR
중성자 조사에 의한 손상	화학적으로 활성 – 구조재 부식 액체리튬의 안정성 문제 MHD 압력 손실로 인한 유속 감소: 전기절연막 필요

Blanket Concepts

- **Solid Breeder Concepts**

- To have the lithium-containing tritium breeder as non-mobile and to reduce tritium inventory:
M.A. Abdou et al, 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 $Be_{12}Ti$) is possible
(Lead is not practical as a separate multiplier)
- Structure is typically Reduced Activation Ferritic Steel (RAFS).

Blanket Concepts

- **Liquid Breeder Concepts**

- Many liquid breeder concepts exist, all of which have key feasibility issues. Selection can not prudently be made before additional R&D and fusion testing results become available.

- Type of Liquid Breeder:

Two different classes of materials with markedly different issues.

a) Liquid Metal: Li, $Li_{17}Pb_{83}$

High conductivity, low Pr number

Dominant issues: MHD, chemical reactivity for Li, tritium permeation for LiPb

b) Molten Salt: Flibe ($(LiF)_n \cdot (BeF_2)$), Flinabe ($LiF-BeF_2-NaF$)

Low conductivity, high Pr number

Dominant issues: Melting point, chemistry, tritium control

HW1: What is Pr number and why is it important?
HW2: What are Flibe and Flinabe?

Blanket Concepts

- **Liquid Breeder Concepts**

- Type of cooling

a) Self-cooled

Liquid breeder circulated at high speed to serve as coolant.

Concepts: Li/V, Flibe/advanced ferritic, Flinabe/FS

b) Separately cooled

A separate coolant, typically helium, is used.

The breeder is circulated at low speed for tritium extraction.

Concepts: LiPb/He/FS, Li/He/FS

Blanket Concepts

- **Liquid Breeder Concepts**

- Type of cooling

c) Dual coolant

First Wall (highest heat flux region) and structure are cooled with a separate coolant (helium). The idea is to keep the temperature of the structure (ferritic steel) below 550ºC, and the interface temperature below 480ºC.

The liquid breeder is self-cooled; i.e., in the breeder region, the liquid serves as breeder and coolant. The temperature of the breeder can be kept higher than the structure temperature through design, leading to higher thermal efficiency.

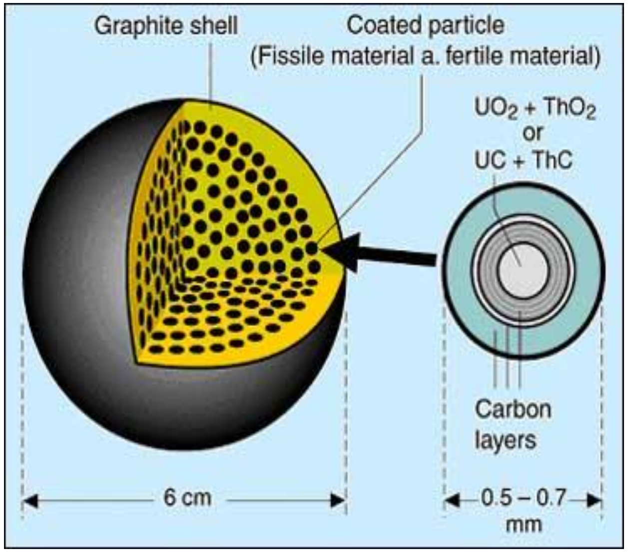
Blanket System

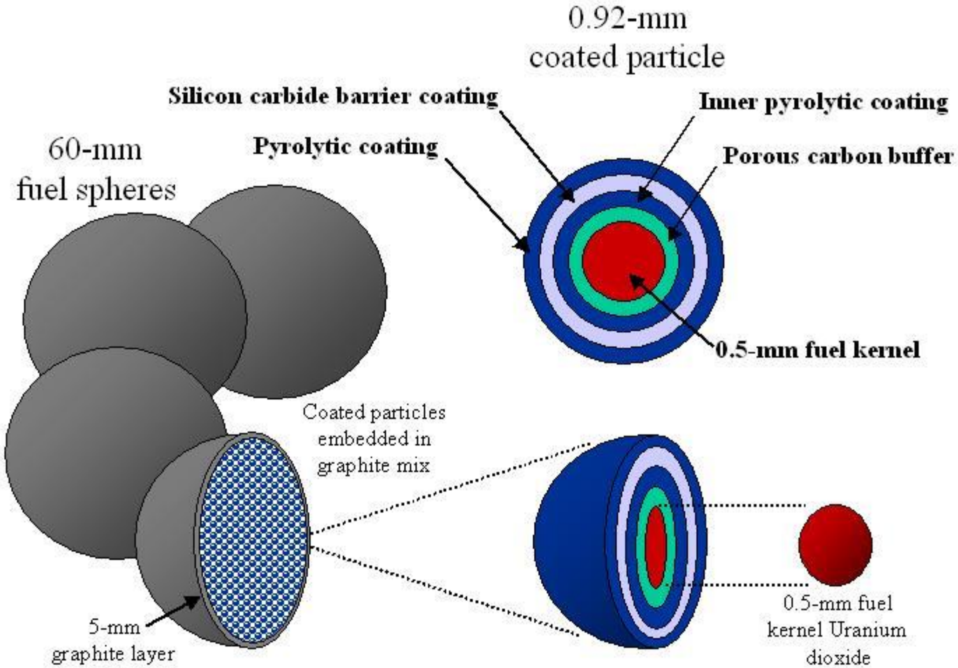
- Blanket system: 블랑켓 구조체, 냉각·발전계, 트리튬회수계,
  공학안전계로 구성
- 냉각·발전계: 경수로와 같은 구성.
  초임계압수를 이용할 경우 고온·고압(~290-540°C, 25 MPa)의
  1차 냉각수 이용, 블랑켓 냉각 및 직접 발전(45% 열효율) 또는
  증기발생기에서 1차 냉각수와의 열교환에 의해 발생시킨 증기로 발전
- 트리튬회수계: 저온흡착탑 이용, He gas 중 수소동위원소를 흡착 및 회수.
  흡착탑의 재생처리 시, 팔라듐 투과막을 통해 흡착탑 내의 잔류 헬륨을
  분리해서 순도를 높인 tritium을 연료순환계로 이송
- 공학안전계: 블랑켓 내부로의 냉각수 누출 발생(LOCA) 대비.
  냉각수 증발에 따른 과도한 내압상승에 의한 blanket 용기 파손을
  피하는 것을 목적으로 압력을 개방 및 압력억제 탱크 장비

Blanket Structure

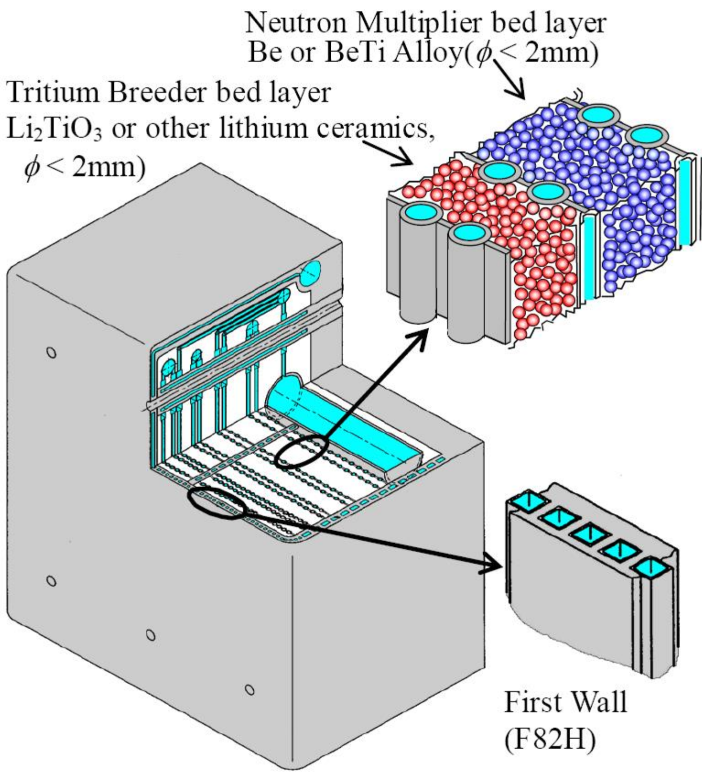
- 상자용 용기 속에 직경 1 mm 정도의 미소구 형상의 고체증식재 및 중성자 증배재 충전.
- Neutron multiplier: (*n*, *xn*)-type material
  고에너지 중성자와의 반응을 위해 플라즈마 근처에 배치
- Breeder: 증배재 후방에 배치. 반사된 중성자를 효과적으로 이용하기 위해
  증배재 전면에도 얇게 배치.
- Reflector: graphite 등 사용.
- 냉각관/냉각패널: 증식재, 증배재, 구조재와 중성자와의 반응에 의해 발생한
  열을 제거. 각 재료를 소정의 온도 범위로 유지.
  증배재로 Be 사용할 경우 고체증식재의 고온에서의 공존성 문제를
  피하기 위해 증식재층과 증배재층 간에 칸막이 설치.
  He gas로 tritum 이송
- First wall: 플라즈마에 면하므로 높은 열부하를 받음.
  내부에 냉각유로 설치
- 블랑켓용기: 제작성, 원격보존성 및 전자기력 절감을 고려한 소형 모듈방식

Blanket Structure

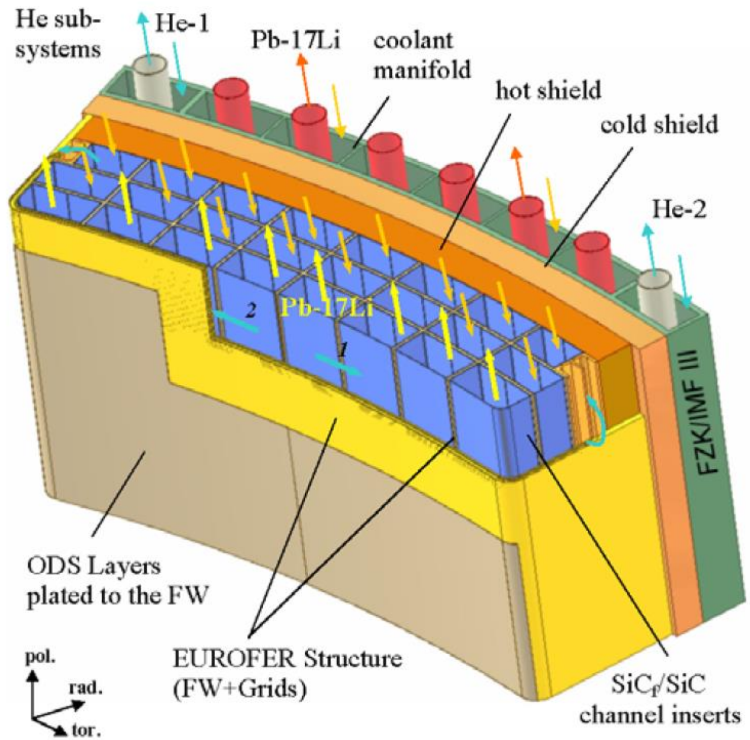




Blanket Structure



Japan DEMO 2001
solid blanket concept



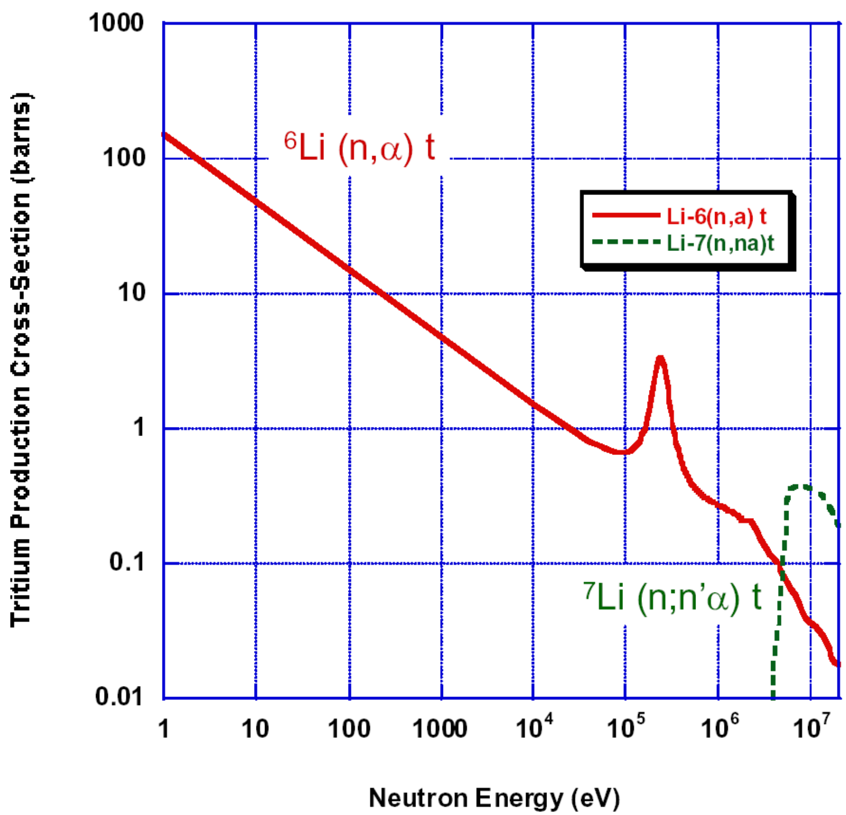
EU PPCS Model C
dual-coolant blanket concept

Tritium Breeding

- **Tritium production by neutron-induced reactions with natural lithium (^6Li:^7Li=7.5:92.5)**

$^6Li + n \rightarrow T + He + 4.78$ MeV: thermal and epithermal neutron energy range

$^7Li + n \rightarrow T + He + n' - 2.47$ MeV: fast neutron energy range



- The ^{7}Li(n,n'α)t reaction is a threshold reaction and requires an incident neutron energy in excess of 2.8 MeV.

Tritium Breeding

- **TBR (Tritium Breeding Ratio)**

- Ratio of total tritium production rate in blanket and tritium destruction rate in core
- Needed to be higher than 1 to compensate for tritium transport losses during extraction and transfer as well as for its decay before injection into the core

$$C_t = \frac{\int_{V_b}\int_{v_n} \sigma_{n6}(v_n) N_6 N_n(v_n) v_n dv_n d^3r + \int_{V_b}\int_{v_n} \sigma_{n7}(v_n) N_7 N_n(v_n) v_n dv_n d^3r}{\int_{V_c} N_d N_t <\sigma v>_{dt} d^3r}$$

N_6, N_7: ^{6}Li and ^{7}Li atom densities in the blanket volume V_b
σ_{n6}, σ_{n7}: corresponding microscopic neutron absorption cross sections
N_n: speed dependent neutron density
v_n: neutron speed
V_c: fusion core volume

Tritium Breeding

- **TBR (Tritium Breeding Ratio)**

- 상용 핵융합로 100 kg/yr (~400 g/day) 정도의 tritium 요구

$C_T = 55.7 P_f f_d$ (g/yr), P_f: 핵융합반응출력(MW), f_d: availability

Ex. P_f = 2500 MWt (전기출력 1000 MWe), f_d = 0.8 → 100 kg 소비

Cf. CANDU(중수로)에서의 tritium 생산량 ~2 kg/yr

Cf. Tritium available worldwide: ~20 kg (2006, Canada OPG)

(+Korea WTRF)

- ITER tritium credit: $30 M/kg

- Market value: $100M-$200 M/kg (1억/g)

- TBR = 1.08 이상 요구: 재료표면으로의 흡착, 방사성 붕괴분의 보충,
저장용 tritium의 확보, 차기 핵융합발전소 건설 대비

- TBR 계산: neutronics – 물질과 중성자와의 상호작용의 단면적(핵데이터)과
계산기법의 개발이 중요.
blanket의 복잡한 구조 고려해야 함 (3-D).

Tritium Breeding

- **TBR for Various Breeder Materials**

Material	Calculated Tritium Breeding Ratio, C_T
$Li_{17}Pb_{83}$	1.6
LiPb	1.4
FLIBE	1.1
$LiAlO_2$	0.9
Li_2O	1.3
Li_2SiO_4	0.9
Li_2ZrO_3	1.0

- In a "typical" blanket 1 cm thick with 10% volume fraction of 316 SS, preceded by a 1 cm steel front-wall and backed by a 100 cm thick shield → Use of the various solid breeders generally requires an added neutron multiplier

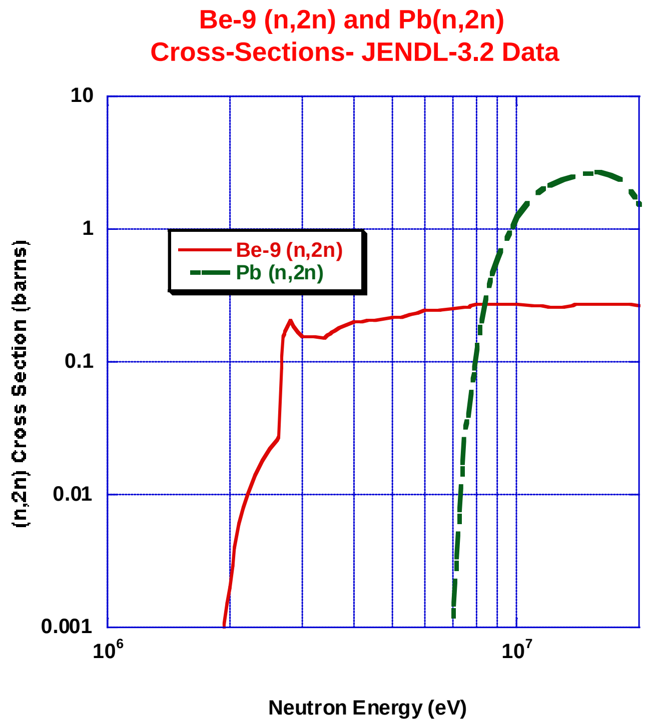
Tritium Breeding

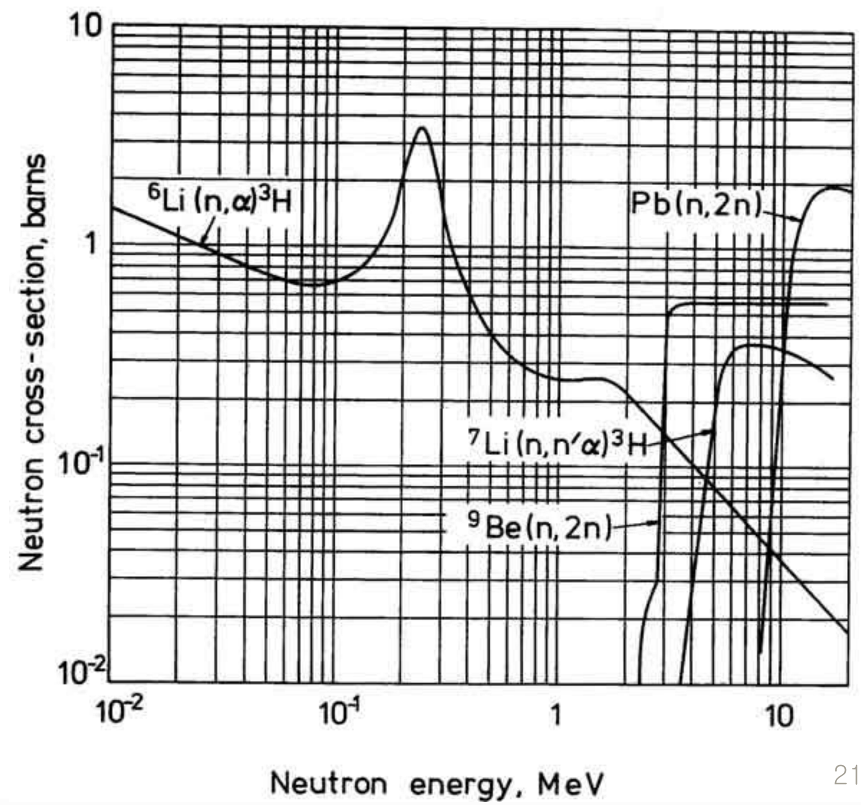
- **Neutron Multiplication**

- Adequate tritium breeding may be obtained if a neutron multiplier such as ^{9}Be or Pb is added.

$^{9}Be + n \rightarrow 2n + 2He - 2.5\ MeV$

$^{A}Pb + n \rightarrow 2n + {}^{A-1}Pb - 7\ MeV$





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Material	Estimated Upper Limit Breeding Ratio, C_T
^{6}Li	1.1
Natural Li	0.9
^{9}Be + ^{6}Li (5%)	2.7
Pb + ^{6}Li (5%)	1.7

Assuming materials encompassing the entire fusion core

Tritium Breeding

- **Solid Breeder Concepts**

- 리튬세라믹스에 대한 tritium 용해도, 흡착량, 구조재료와의 반응성, tritium 확산계수 등의 설계 데이터베이스 필요
- 중성자 조사에 의해 생성된 tritium은 결정립 내에서의 확산, 표면이탈반응 등을 통해 sweep gas 중에 방출됨.
- 온도를 높여 확산 속도를 빠르게 하고, sweep gas에 H_2 첨가해서 표면반응을 빠르게 함.
(tritium 회수에 필요한 체류시간을 1일 이내로 줄임).
- Sweep gas로부터의 tritium 회수법:
HT gas의 흡착, HTO의 cold trap, 흡착

Tritium Breeding

- **Liquid Breeder Concepts**

Li	$Li_{17}Pb_{83}$ (Lithium-lead eutectic)	FLiBe ($LiF \cdot BeF_2$) (Molten salt fluids)
tritium 회수 어려움: 수소동위체의 용해도가 큼	tritium 회수 쉬움: tritium 용해도가 매우 작음	
tritium의 구조재료를 통한 투과누출이 작음: tritium이 Li 중에 모임	tritium의 투과누출이 큼: 구조재로의 세라믹 코팅막 등의 투과장벽이 필요	FLiBe 중의 tritium 화학형 TF나 T_2에 의해 구조재의 부식 증가 또는 tritium 추가누출 증대
		화학적으로 안정하고 고온 사용이 가능