Introduction to Nuclear Fusion

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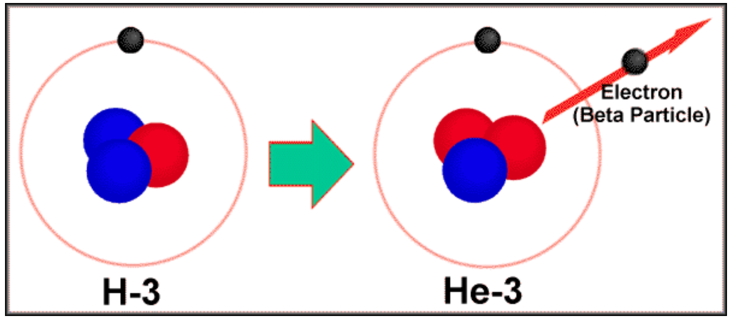
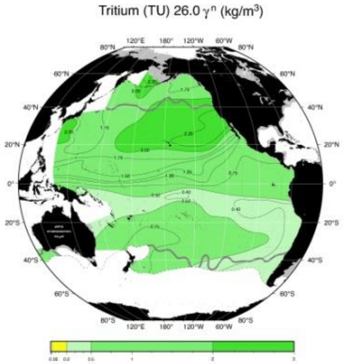
Tritium breeding

Tritium Breeding

- **Tritium**

  - The name is formed from the Greek word "tritos‟ meaning "third".
  - Total steady state atmospheric and oceanic quantity produced by cosmic radiation ~ 50 kg





- **Tritium production by heavy water reactors (HWR)**

  - extracted from the coolant and moderator of HWR $n + {}_1^2H \rightarrow {}_1^3H$
  - Tritium could also be produced by placing lithium into control and shim rods of fission reactors.

http://lhs2.lps.org/staff/sputnam/chem_notes/UnitII_Radioactivity.htm *http://www-pord.ucsd.edu/whp_atlas/pacific/maps/tritum/pac2600_tritium_final.jpg*

Tritium Breeding

- **Tritium Consumption in Fusion is huge:**
  55.8 kg per 1000 MW fusion power per year.

- **Total tritium to be received:**

- CANDU Reactors: 27 kg from over 40 years, ($30M/kg)
  Fission reactors: 2–3 kg/year ($84M-$130M/kg: ~억/g)

– Decay rate: 5.47 %/year (Half life: 12.3 year)

Korea WTRF

- Availability of **tritium supply** for fusion development beyond ITER first phase is an issue.
  Large power D-T facilities must breed their own tritium
  (this is why ITER's extended phase was planned to include the installation of a tritium breeding blanket).

→ FW/Blanket are necessary in the **near term** to allow continued development of D-T fusion

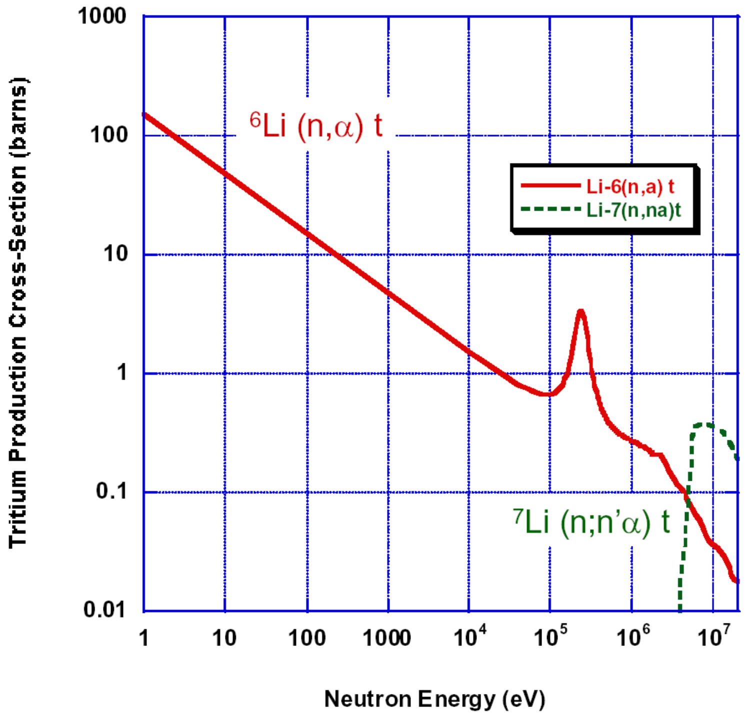
Neil B. Morley and Mohamed Abdou (UCLA), "Fusion Nuclear Technology Research and Opportunities for ITER Utilization", Fusion Power Associates Annual Meeting and Symposium, Washington D.C., October 11-12, 2005

Tritium Breeding

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

$$n + {}^6Li \rightarrow t + {}^4He + 4.78\,\text{MeV}$$ thermal and epithermal neutron energy range

$$n + {}^7Li \rightarrow t + {}^4He + n' - 2.47\,\text{MeV}$$ fast neutron energy range



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

$$d + t \rightarrow n + \alpha + 17.6\,\text{MeV}$$

Tritium Breeding

- **TBR (Tritium Breeding Ratio)**

- Ratio of total tritium production rate in blanket and tritium destruction rate in 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
$Li_{17}Pb_{83}$ (Lithium-lead eutectic)	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

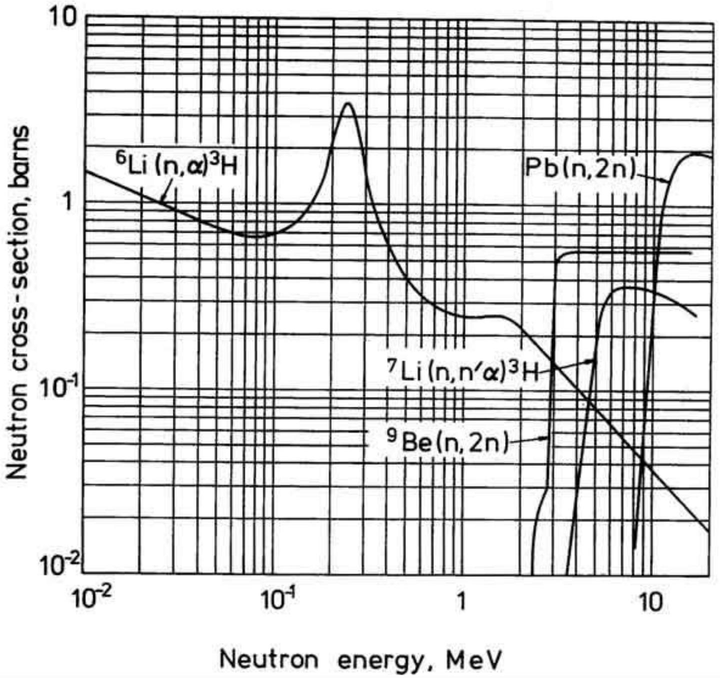
Tritium Breeding

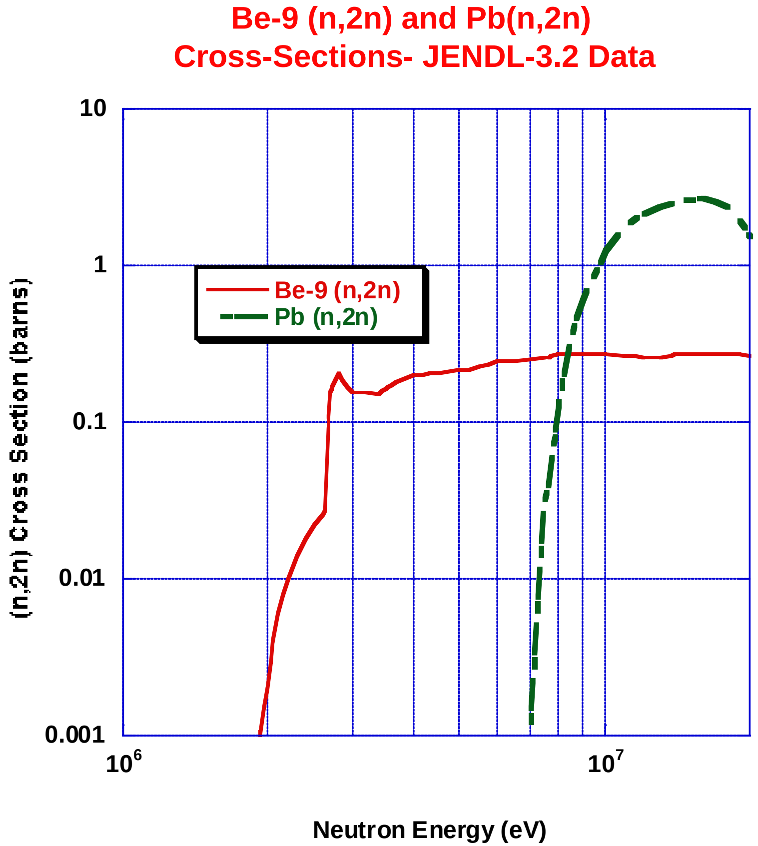
- **Neutron Multiplication**

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

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

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





Tritium Breeding

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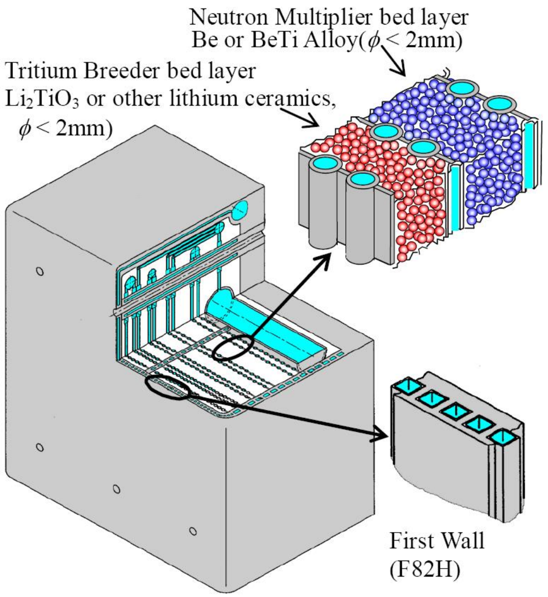
Material	Estimated Upper Limit Breeding Ratio, C_T
^{6}Li	1.1
Natural Li	0.9
^{9}Be + ^{6}Li (5%)	2.7
Pb + ^{6}Li (5%)	1.7



Japan DEMO 2001
solid blanket concept

Assuming materials encompassing the entire fusion core

Tritium Breeding

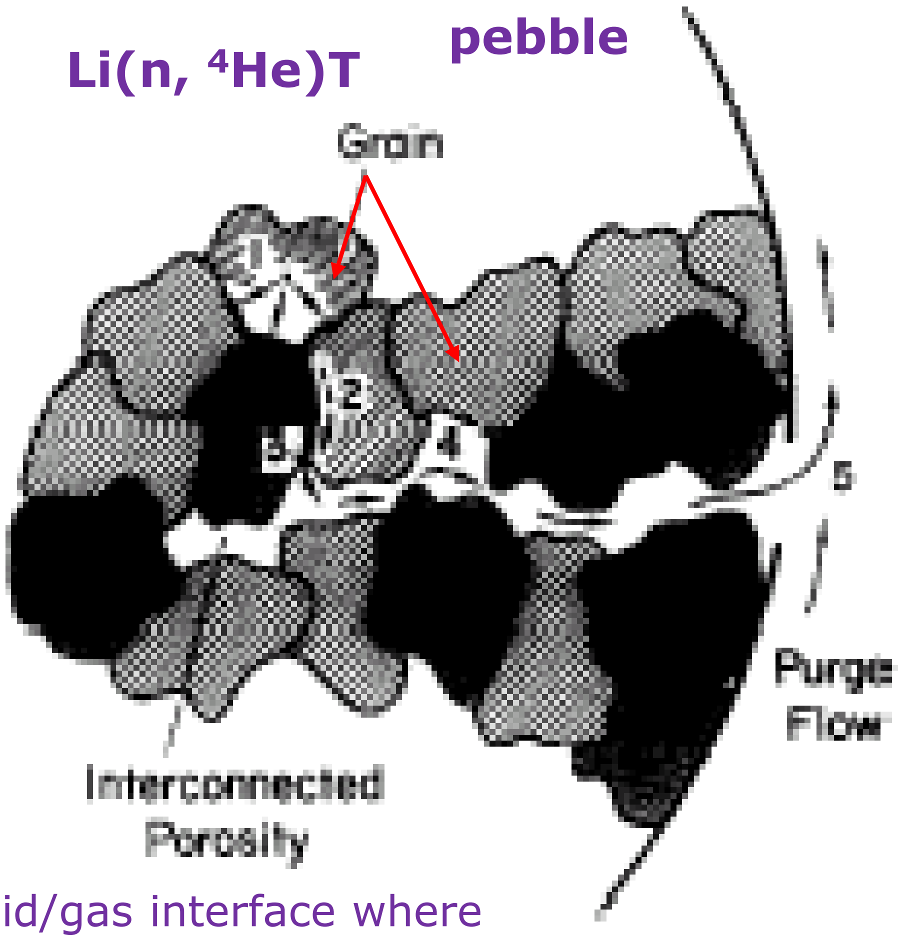
- **Solid Breeder Concepts**

- 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

Mechanisms of tritium transport

Li(n, ^{4}He)T

Breeder pebble



(solid/gas interface where adsorption/desorption occurs)

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

Tritium Breeding

- **Liquid Breeder Concepts**

Li	$Li_{17}Pb_{83}$ (Lithium-lead eutectic)	FLiBe ($LiF·BeF_2$) (Molten salt fluids)
Difficulty in T recovery (high dissolution of T)	Easy T recovery (low dissolution of T)	
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

MHD Pressure Drop

- Motion of a conductor in a magnetic field produces an EMF that can induce current in the liquid. This must be added to Ohm's law:

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{V} \times \mathbf{B}) \qquad \mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta \mathbf{j}$$

- Any induced current in the liquid results in an additional body force in the liquid that usually opposes the motion. This body force must be included in the Navier-Stokes equation of motion:

$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla)\mathbf{V} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{V} + \mathbf{g} + \frac{1}{\rho}\mathbf{j} \times \mathbf{B}$$

- For liquid metal coolant, this body force can have dramatic impact on the flow: e.g. enormous MHD drag, highly distorted velocity profiles, non-uniform flow distribution, modified or suppressed turbulent fluctuations

What is turbulence?

- Reynolds number: $Re = VL/\nu$ ← $(V^2/L) / (\nu V/L^2)$

$$\frac{\partial \mathbf{v}}{\partial t} = -(\mathbf{v}\cdot\nabla)\mathbf{v} + \nu\nabla^2\mathbf{v}$$

$(\mathbf{v}\cdot\nabla)\mathbf{v}$ ↑ V^2/L $\qquad$ $\nu\nabla^2\mathbf{v}$ ↑ $\nu V/L^2$

- When $Re \ll Re_{critical}$, flow = laminar

  When $Re \gg Re_{critical}$, flow = turbulent

MHD Pressure Drop

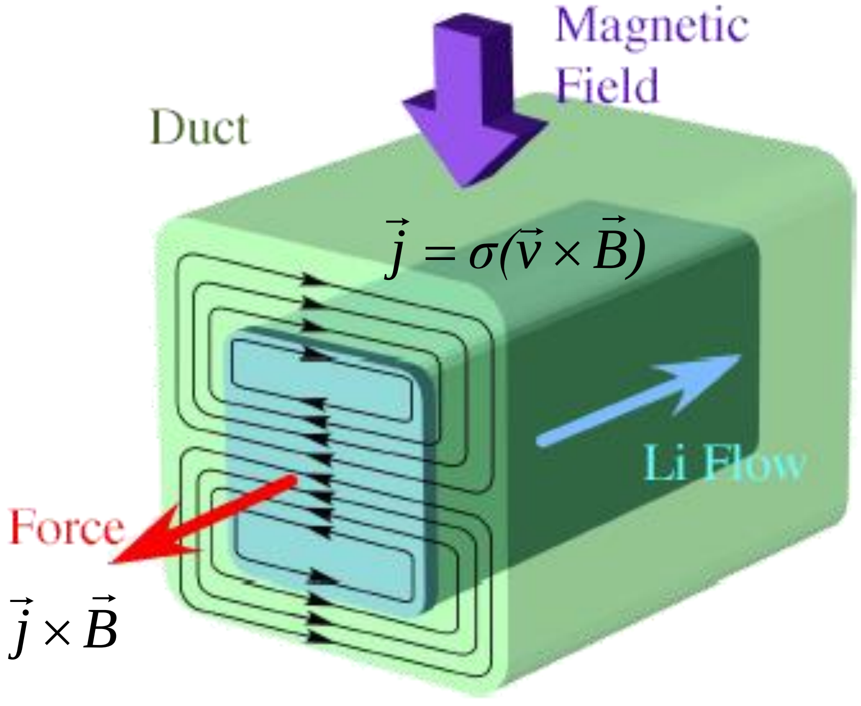
- **Main issue for flowing liquid metal in blankets**
  - Lorentz force resulting from liquid metal motion across the magnetic field generates MHD retarding force that is very high for electrically conducting ducts and complex geometry flow elements.

  - Thin wall MHD pressure drop

$$\nabla p = \vec{j} \times \vec{B}$$

$$\Delta p_{MHD} = LjB \approx L\sigma v B^2 \underbrace{\frac{\sigma_w t_w}{\sigma a}}_{c}$$

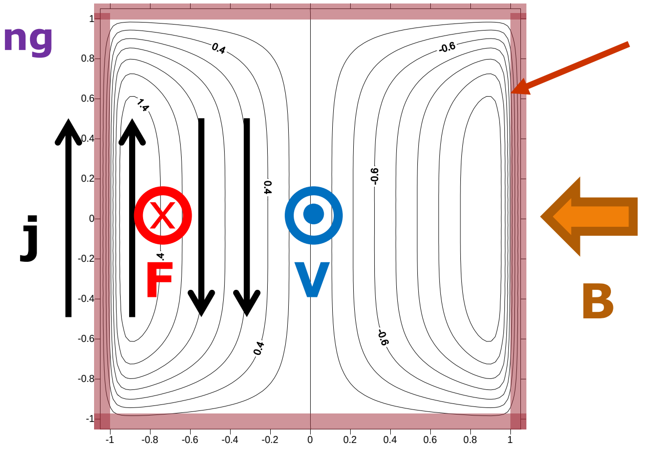
p: pressure
L: flow length
j: current density
B: magnetic induction
v: velocity
σ: conductivity (liquid metal or wall)
a,t: duct size, wall thickness



MHD Pressure Drop

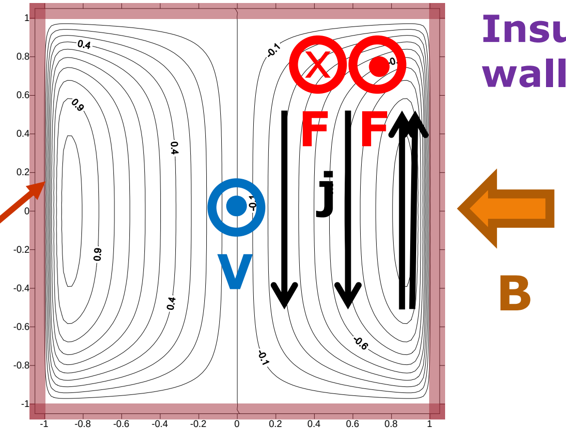
- **A perfectly insulated "WALL" can eliminate the MHD pressure drop. But is it practical?**

Conducting walls



Lines of current enter the low resistance wall – leads to very high induced current and high pressure drop

All current must close in the liquid near the wall – net drag from jxB force is zero

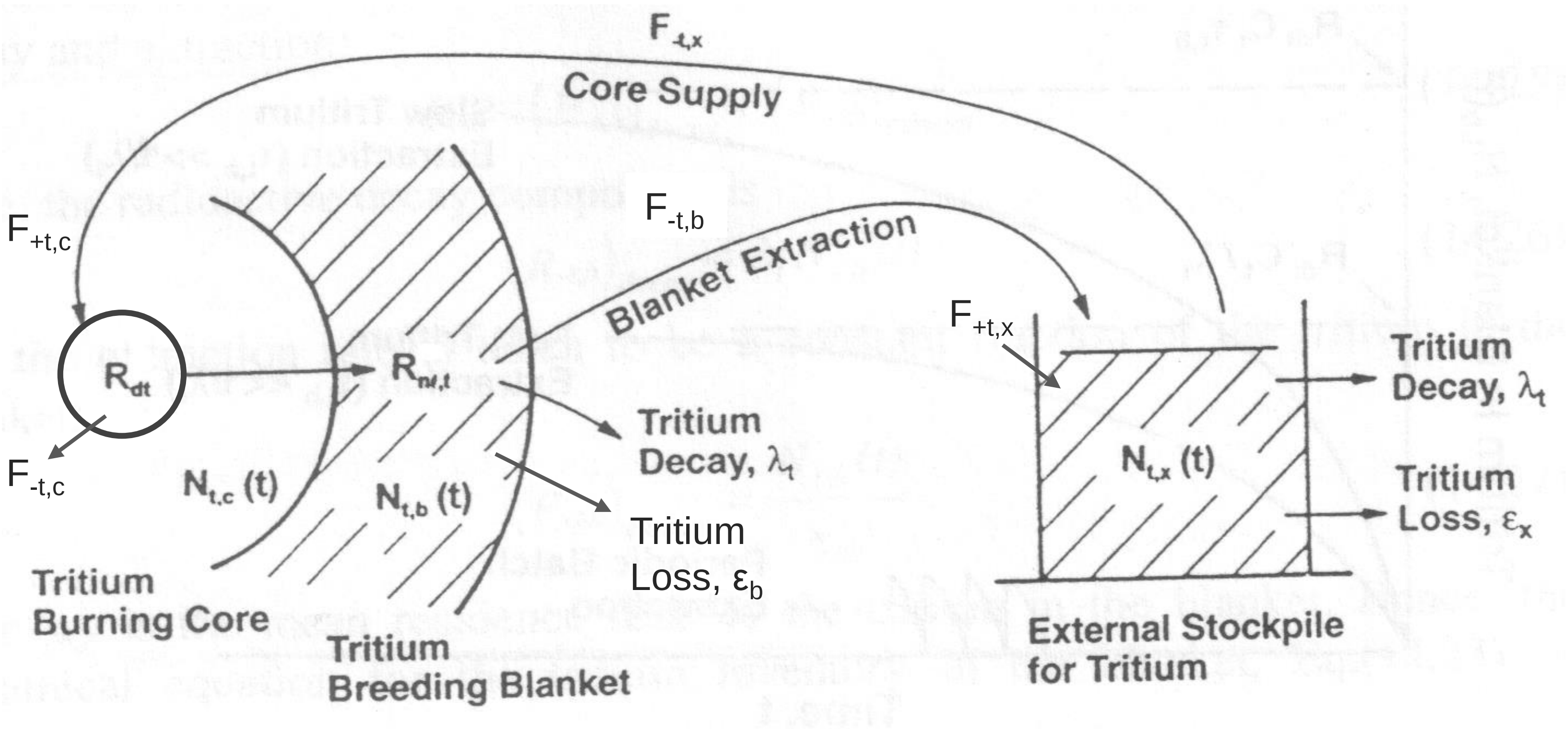


Insulated walls

- Net JxB body force $\nabla p = c\sigma v B^2$ where $c = (t_w \sigma_w)/(a\ \sigma)$
- For high magnetic field and high speed (self-cooled liquid metal concepts in inboard region) the pressure drop is large.
- The resulting stresses on the wall exceed the allowable stress for candidate structural materials

- Perfect insulators make the net MHD body force zero.
- But insulator coating crack tolerance is very low ($\sim 10^{-7}$).
  - It appears impossible to develop practical insulators under fusion environment conditions with large temperature, stress, and radiation gradients.
- Self-healing coatings have been proposed but none has yet been found (research is on-going).

Tritium Fuel Dynamics

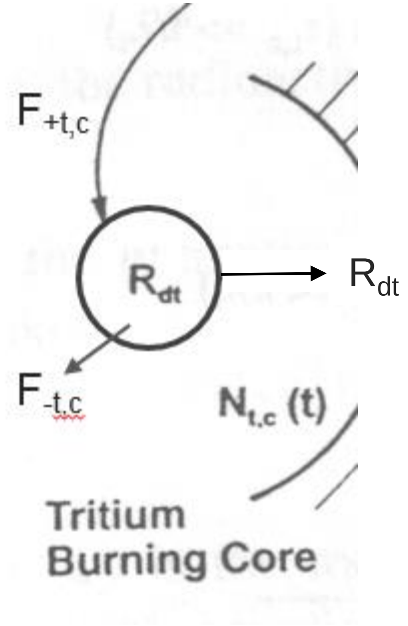


A. A. Harms et al, "Principles of Fusion Energy", World Scientific (2000)

Tritium Fuel Dynamics

$$\frac{dN_{t,c}}{dt} = F_{+t,c} - F_{-t,c} - R_{dt} = f_t F_{+t,c} - R_{dt} = 0$$

f_t: respective burn fraction of tritium



Steady state

$$F_{+t,c} = \frac{R_{dt}}{f_t}$$

Tritium decay neglected due to shorter time scale

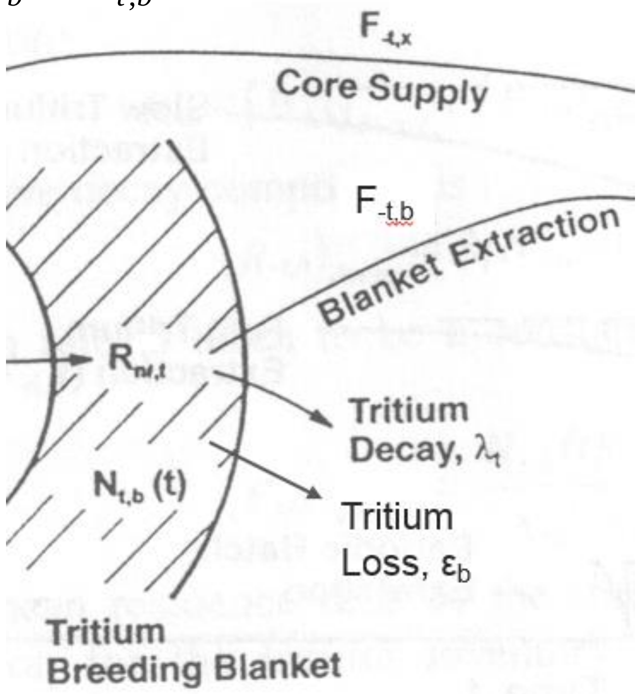
A. A. Harms et al, "Principles of Fusion Energy", World Scientific (2000)

Tritium Fuel Dynamics

$$\frac{dN_{t,b}}{dt} = F_{+t,b} - F_{-t,b} - \lambda_t N_{t,b} - \varepsilon_b N_{t,b}$$

$$= C_t R_{dt} - \frac{N_{t,b}}{\tau_{t,b}} - \lambda_t N_{t,b} - \varepsilon_b N_{t,b} \quad \leftarrow \quad \frac{1}{\tau_b} = \frac{1}{\tau_{t,b}} + \lambda_t + \varepsilon_b$$

$$= C_t R_{dt} - \frac{N_{t,b}}{\tau_b}$$



$C_t = \frac{R_{nl,t}}{R_{dt}}$: Tritium breeding ratio

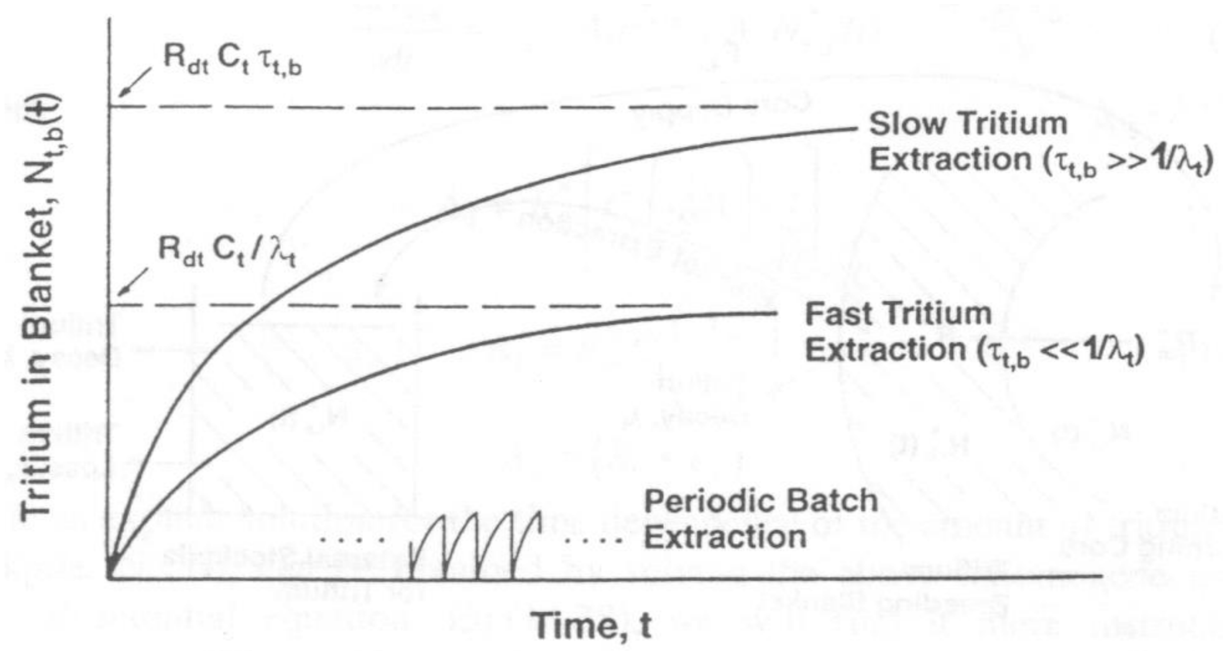
$\tau_{t,b}$: Mean residence time of the tritium in the blanket

A. A. Harms et al, "Principles of Fusion Energy", World Scientific (2000)

Tritium Fuel Dynamics

$$\frac{dN_{t,b}}{dt} = C_t R_{dt} - \frac{N_{t,b}}{\tau_b} \qquad N_{t,b}(0) = 0 \qquad \frac{1}{\tau_b} = \frac{1}{\tau_{t,b}} + \lambda_t + \varepsilon_b$$

$$N_{t,b} = Ae^{-\frac{t}{\tau_b}} + B = C_t R_{dt} \tau_b \left(1 - e^{-\frac{t}{\tau_b}}\right)$$



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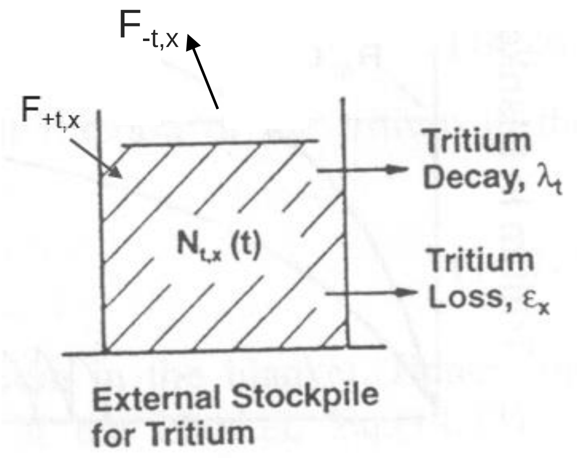
Tritium Fuel Dynamics



$$\frac{dN_{t,x}}{dt} = F_{+t,x} - F_{-t,x} - \lambda_t N_{t,x} - \varepsilon_x N_{t,x}$$

$$= \frac{N_{t,b}}{\tau_{t,b}} - \frac{R_{dt}}{f_t} - \lambda_t N_{t,x} - \varepsilon_x N_{t,x}$$

$$= \frac{C_t R_{dt} \tau_b}{\tau_{t,b}} \left(1 - e^{-\frac{t}{\tau_b}}\right) - \frac{R_{dt}}{f_t} - (\lambda_t + \varepsilon_x) N_{t,x}$$

$$= A_0 - A_1 e^{-\frac{t}{\tau_b}} - A_2 N_{t,x}$$

$$F_{-t,b} = \frac{N_{t,b}}{\tau_{t,b}}$$

$$F_{-t,x} = F_{+t,c} = \frac{R_{dt}}{f_t}$$

$$N_{t,b} = C_t R_{dt} \tau_b \left(1 - e^{-\frac{t}{\tau_b}}\right)$$

$$A_0 = R_{dt}\left[C_t\left(\frac{\tau_b}{\tau_{t,b}}\right) - \frac{1}{f_t}\right], \quad A_1 = R_{dt} C_t \left(\frac{\tau_b}{\tau_{t,b}}\right), \quad A_2 = \lambda_t + \varepsilon_x$$

A. A. Harms et al, "Principles of Fusion Energy", World Scientific (2000)

Tritium Fuel Dynamics

$$\frac{dN_{t,x}}{dt} = A_0 - A_1 e^{-\frac{t}{\tau_b}} - A_2 N_{t,x} \qquad N_{t,x}(0) = N_{t,0}$$

$$N_{t,x} = c_1 e^{-A_2 t} + c_2 e^{-\frac{t}{\tau_b}} + c_3$$

$$= \left(N_{t,0} - \frac{A_1}{\frac{1}{\tau_b} - A_2} - \frac{A_0}{A_2} \right) e^{-A_2 t} + \left(\frac{A_1}{\frac{1}{\tau_b} - A_2} \right) e^{-\frac{t}{\tau_b}} + \frac{A_0}{A_2}$$

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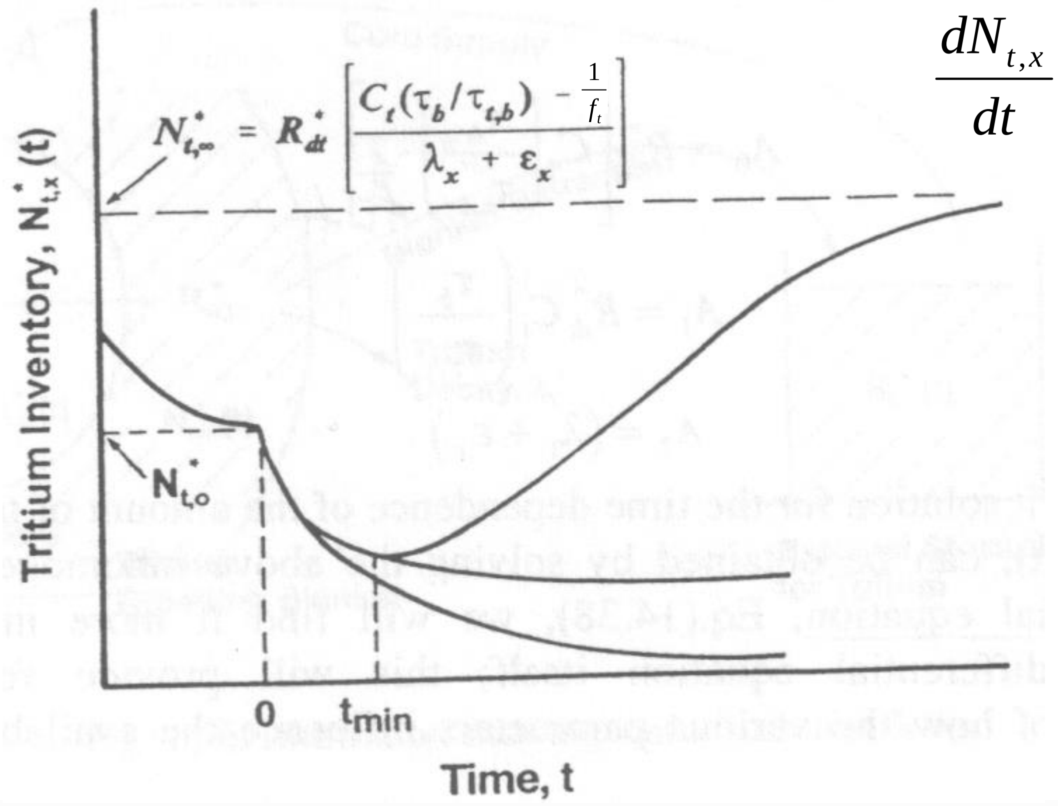
Tritium Fuel Dynamics

$$N_{t,x} = \left(N_{t,0} - \frac{A_1}{\frac{1}{\tau_b} - A_2} - \frac{A_0}{A_2} \right) e^{-A_2 t} + \left(\frac{A_1}{\frac{1}{\tau_b} - A_2} \right) e^{-\frac{t}{\tau_b}} + \frac{A_0}{A_2}$$



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$$A_0 = R_{dt}\left[C_t \left(\frac{\tau_b}{\tau_{t,b}} \right) - \frac{1}{f_t} \right]$$

$$A_1 = R_{dt} C_t \left(\frac{\tau_b}{\tau_{t,b}} \right)$$

$$A_2 = \lambda_t + \varepsilon_x$$

A. A. Harms et al, "Principles of Fusion Energy", World Scientific (2000)