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Estimation of Tritium Recovery from a Molten Salt Blanket of FFHR

Dept. Applied Quantum Physics and Nuclear Engineering, Kyushu University

Satoshi FUKADA

1. Background study :

Characteristics of Flibe as a self-cooled blanket

- Advantages

(1) liquid blanket, low reactivity with air or water

(2) low MHD effect

(3) TBR >1 with addition of Be and low tritium solubility

⟶ FFHR or HYLIFE-II

- Disadvantages

(1) less Flibe-facing structural materials under neutron irradiation

(2) unknown tritium behavior or recovery in Flibe is not studied.

(3) possibly high tritium leak to the environment

(4) issues of Be safety ⟶ JUPITER-II

___ Relating to this study

Design activities in NIFS Collaboration

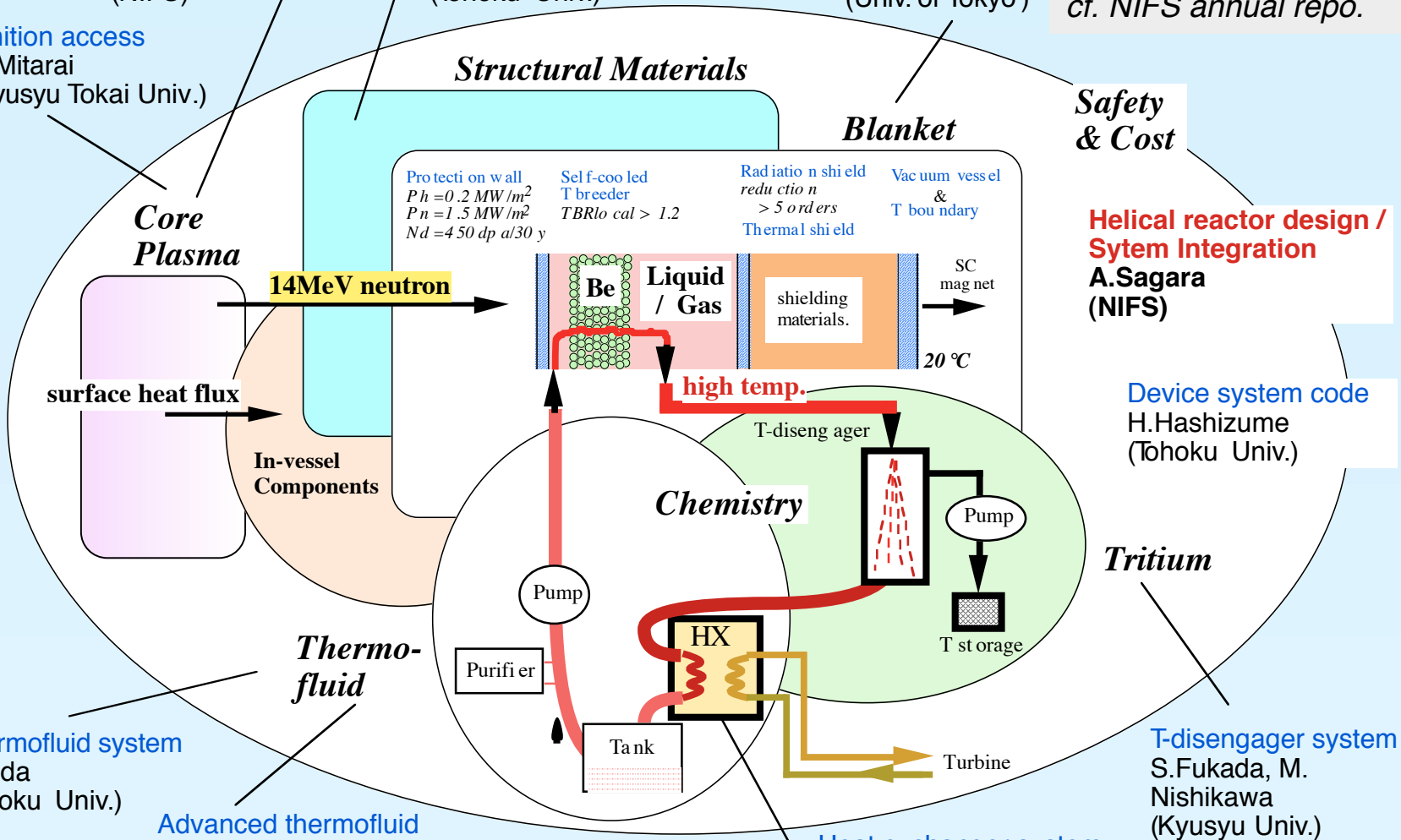
Helical core plasma
K.Yamazaki
(NIFS)

Thermo-mechanical analysis
T.Yamamoto, H.Matsui
(Tohoku Univ.)

Blanket system
S,Tanaka
(Univ. of Tokyo)

Now, on going
cf. NIFS annual repo.

Ignition access
O.Mitarai
(Kyusyu Tokai Univ.)



Helical reactor design / Sytem Integration
A.Sagara
(NIFS)

Device system code
H.Hashizume
(Tohoku Univ.)

Thermofluid system
S.Toda
(Tohoku Univ.)

Advanced thermofluid
T.Kunugi
(Kyoto Univ.)

Heat exchanger system
A.Shimizu
(Kyusyu Univ.)

T-disengager system
S.Fukada, M. Nishikawa
(Kyusyu Univ.)

May 21, 2001, A.Sagaar

1. Background study :

Tritium recovery from Flibe relating to the things

(1) Physical Properties (Underlined properties are not available or not reliable)

- Tritium solubility (TF or T_2)
- Tritium diffusivity , permeation coefficient or mass-transfer coefficient
- Viscosity, thermal diffusivity or heat-transfer coefficient
- Phase diagram, vapor pressure, free energy change of fluoride formation

Estimated from H_2, D_2 or other data

(2) Affecting factors

- Chemical forms of tritium in Flibe , T_2, TF or T_2O, or Flibe purification
- REDOX control condition, change from TF to T_2
- Corrosive HF or TF in Flibe
- Isotopic effect and coexistent components

to use purified Flibe and REDOX control by Be

1. Background study : Necessary conditions imposed on apparatus of tritium recovery from Flibe

- All tritium generated in a blanket is recovered
- Very low tritium leak to the environment
- Simple apparatus and easy to operate
- Operation over melting temperature
- High operation safety and material compatible with HF

  $M+nHF \Rightarrow MF_n+(n/2)H_2$
- Operated under low water vapor condition

  $BeF_2+2H_2O \neq Be(OH)_2+2HF$, $LiF+H_2O \neq LiOH+HF$

→ Permeation window, He-Flibe counter-current column, Vacuum disengager

2. Design study :

Design of tritium-recovery apparatus for FFHR

Assumptions

- Based on FFHR design
- Steady-state operation
- Tritium generated in a blanket is transferred by Flibe and is recovered by a tritium recovery apparatus.
- No isotope effect in properties
- No decomposition of Flibe by VxB
- We focused on whether or not tritium can be recovered by a realistic scale of apparatus.

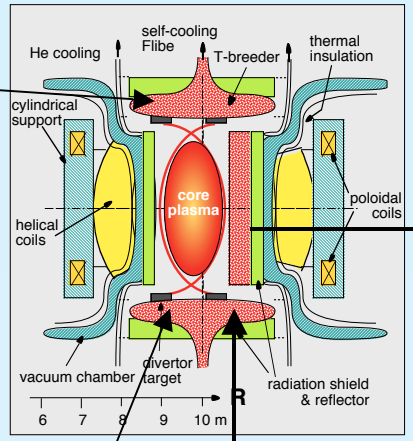
Table 1 FFHR parameters on tritium recovery

Fusion power	1GWt
Tritium generation rate	190g-T/day
Coolant	LiF(64%)-BeF_2(36%)
Coolant flow rate in blanket	2.3m^3/s
Colant inlet temperature	470℃
Coolant outlet temperature	570℃
Tritium leak rate	10 Ci/day
Major radius	10 m
Neutron wall loading	1.7 MW/m^2
TBR	>1.2

What is the rate-determining step of tritium recovery

2. Design study : Flow of Flibe and tritium

Flibe blanket



Tritium generation rate **(1 GWt)**

190 g-T/day = 1.8 MCi/day

x_{in} ($= K_H p_{in}$ or $= K_S p_{in}^{0.5}$)

Tritium leak rate $\sim K_p A_{in} p_{in}^{0.5}$

570C

Bypass ratio □

Tritium recovery system

Tritium recovery system

Tritium storage

Be pebbles

pump

470C

Flibe flow rate **2.3m³/s**

Tritium permeation barrier

x_{out} ($= K_H p_{out}$ or $= K_S p_{out}^{0.5}$)

Tritium leak rate $\sim K_p A_{out} p_{out}^{0.5}$

Tritium permeation barrier

Heat exchanger

Tritium leak rate to the environment **~10 Ci/day**

$K_p A_{in} p_{in}^{0.5} + K_p A_{out} p_{out}^{0.5}$ + others

2. Design study : Evaluation of tritium leak

- If there is **no barrier for tritium leak**,

  Q_{leak}= 2x10^{-3}mol-T/s = 5 MCi/day ⟶ huge tritium leak

  (A=10^{2}m^2, p_{T2}=10^{3}Pa, K_p=3.15x10^{-11}mol/msPa$^{0.5}$ (ferrite) , t=5mm)

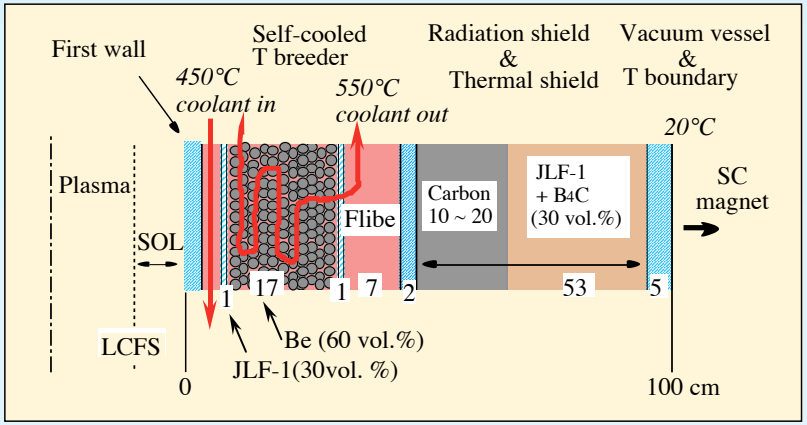
  impossible to lower the tritium leak rate, < 10^{-8} Pa

- If the heat exchanger or the tritium recovery system is **surrounded by a stagnant Flibe (or Flinak) layer (barrier)**,

  Q_{leak}= 6x10^{-10}mol-T/s = 1.6Ci/day ⟶ allowable tritium leak

  (A=10^{2}m^2, p_{T2}=10^{3}Pa, D_T=5x10^{-9}m^2/s,
  K_H=3.2x10^{-7}mol/m^{3}Pa, t=50cm)

- Other reliable tritium barrier with a factor of 10^6 is OK, if available (e.g. alumina)



2. Design study : Material balance of tritium in Flibe

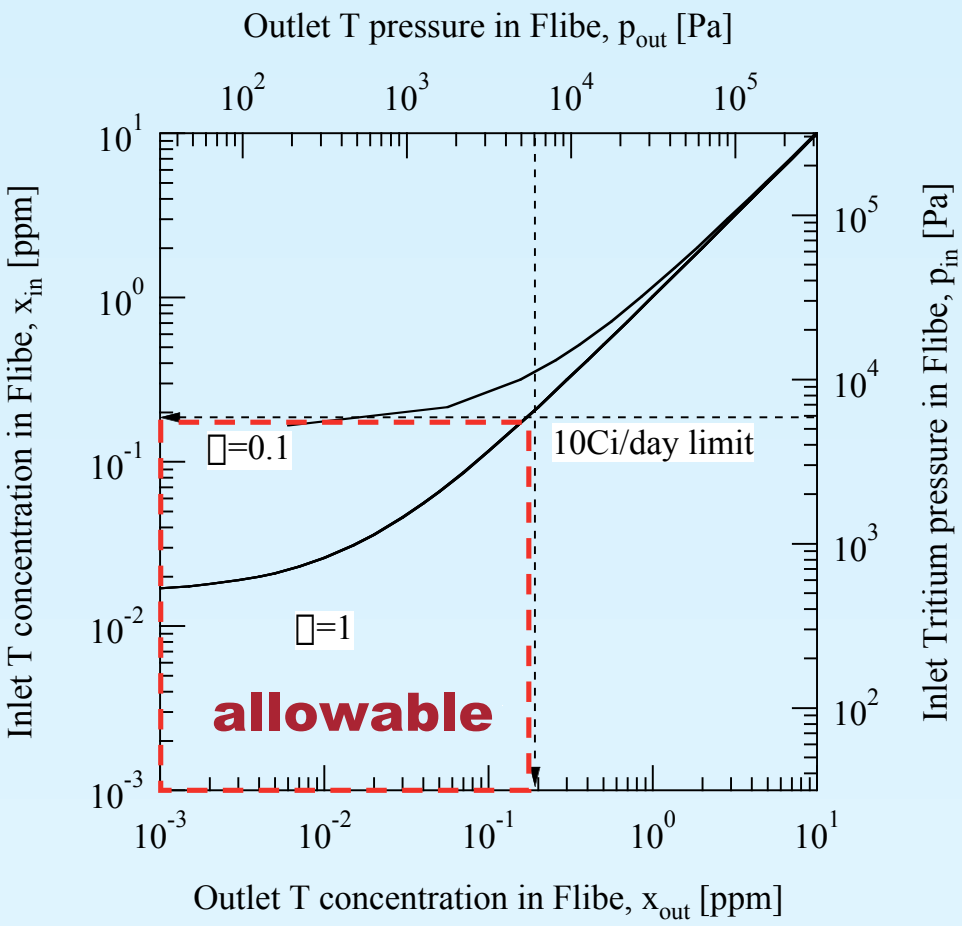


Fig. 2 Relation between c_{in} and c_{out}

$$Q_T = \square W_{Flibe} C_{Flibe} (x_{T,in} \square x^{b}_{T,out})$$

$$x_{T,out} = \square x^{b}_{T,out} + (1 \square \square) x_{T,in}$$

$$p_{T,in} = K_H x_{T,in}$$

$$p_{T,out} = K_H x_{T,out}$$

$$Q_{leak} = K_p A p^{0.5}_{T,in} + K_p A p^{0.5}_{T,out}$$

Necessary conditions

Q_T=1.8MCi/day

Q_{leak}<10Ci/day

Design of economic apparatus

□=0.1 is possible

if 50cm shield is present

Permeation window

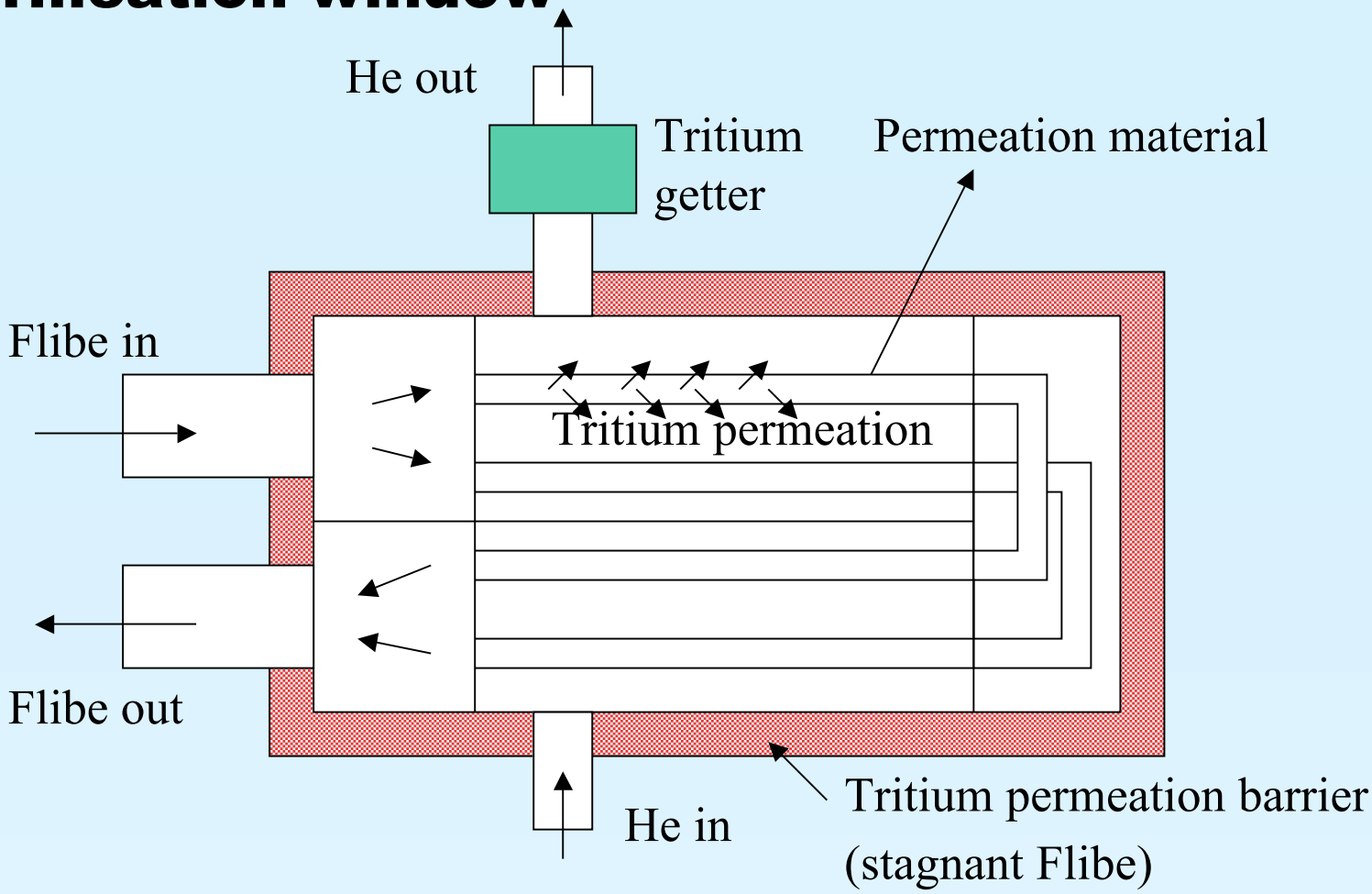


Fig. 3 Permeation window system

2. Design study : Tritium transfer process in Flibe-facing material

Processes include

(1) Tritium (TF or T_2) generation rate in Flibe

(2) Tritium (TF or T_2) diffusion in Flibe

(3) Tritium (TF or T_2) solution in Flibe

(4) Tritium migration from Flibe surface to metal surface (impurity layer)

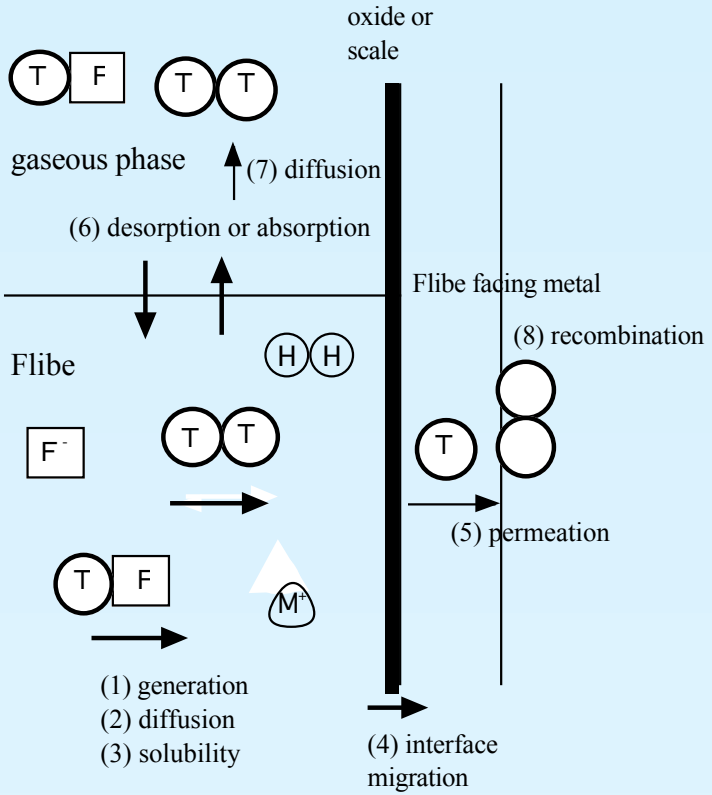
(5) Tritium (T) permeation through metal

(6) Desorption or absorption of tritium (TF or T_2) from Flibe

(7) Tritium (TF or T_2) diffusion in gas

(8) Tritium recombination on metal surface

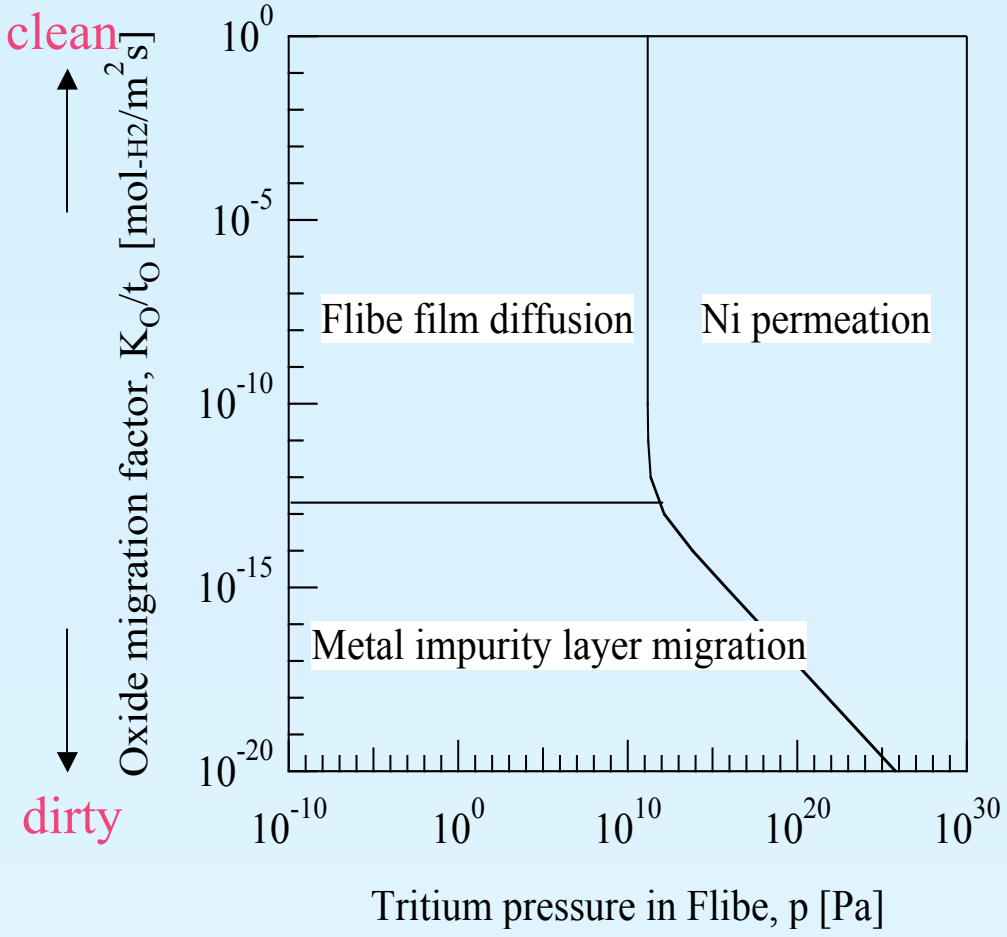
( ) unique to Flibe



If H_2 or H_2O coexists in Flibe, HT or HTO is also present.

Fig. 4 Mass transfer processes from Flibe to gas phase

2. Design study : Rate-determining step of permeation window



$$j = 2k_M\left(c_{F,B} - c_{F,1}\right) \quad \text{Fluid Flibe film}$$

$$= \frac{2K_O}{t_O}\left(p_1 - p_2\right) \quad \text{Impurity migration}$$

$$= \frac{K_p}{t_p}\left(\sqrt{p_2} - \sqrt{p_3}\right) \quad \text{Permeation}$$

$$= 2k_d c_{S,3}^2$$

Fig. 5 Rate-determining step of the overall tritium permeation

2. Design study :

Design equations of permeation window

- Permeation material : Ni, or ferritic steel
- Upstream side : (purified) Flibe
- Downstream side : He purge
- Overall resistance of mass-transfer of tritium permeation

$$\left(\frac{1}{k_{L,0}H_{T_2}}\right)^{1/2} = \left(\frac{1}{k_L H_{T_2}}\right)^{1/2} + \left(\frac{t_s}{K_p}\frac{\left(p_{1,in}^{0.5}-p_2^{0.5}\right)-\left(p_{1,out}^{0.5}-p_2^{0.5}\right)}{\ln\left(\frac{p_{1,in}^{0.5}-p_2^{0.5}}{p_{1,out}^{0.5}-p_2^{0.5}}\right)}\right)^{1/2}$$

Diffusion in Flibe Permeation through wall

$$\frac{k_L d}{D_L} = 0.023\left(\frac{\rho_L d v}{\mu_L}\right)^{0.8}\left(\frac{\mu_L}{\rho_L D_T}\right)^{1/3}\left(\frac{\mu_{L,b}}{\mu_{L,w}}\right)^{0.14}$$

- Tritium generated in blanket, Q_T, is all recovered by permeation window.

$$Q_T = A\,k_{L,0}\frac{\left(c_{1,in}-H_{T_2}p_2\right)-\left(c_{1,out}-H_{T_2}p_2\right)}{\ln\left(\frac{c_{1,in}-H_{T_2}p_2}{c_{1,out}-H_{T_2}p_2}\right)}$$

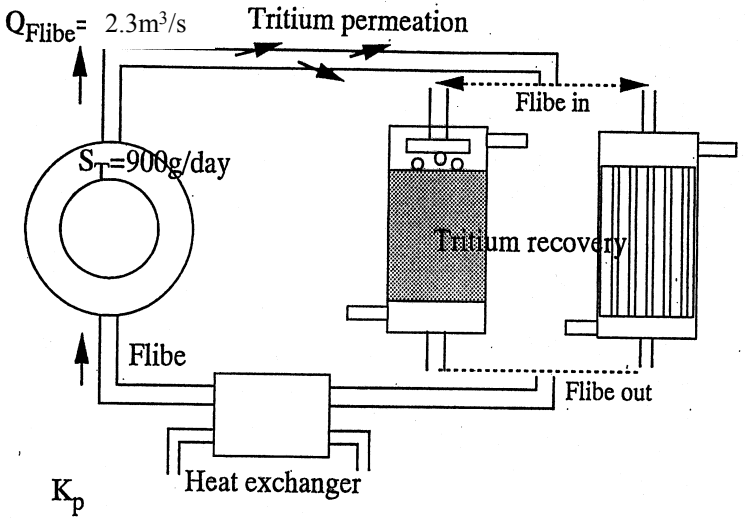


Fig. 5 Permeation window tritium recovery system

2. Design study :

Estimation of permeation window area

- Tritium recovery is easy at high tritium pressure (concentration)

  ⇨high tritium leak
- Tritium recovery is difficult at low tritium pressure (concentration)

  ⇨large apparatus
- Operation at around x_T=0.2 ppm satisfies 10Ci/day limit and 190g/day recovery
- Resistances of Flibe-film diffusion is controlling and permeation gives a small effect

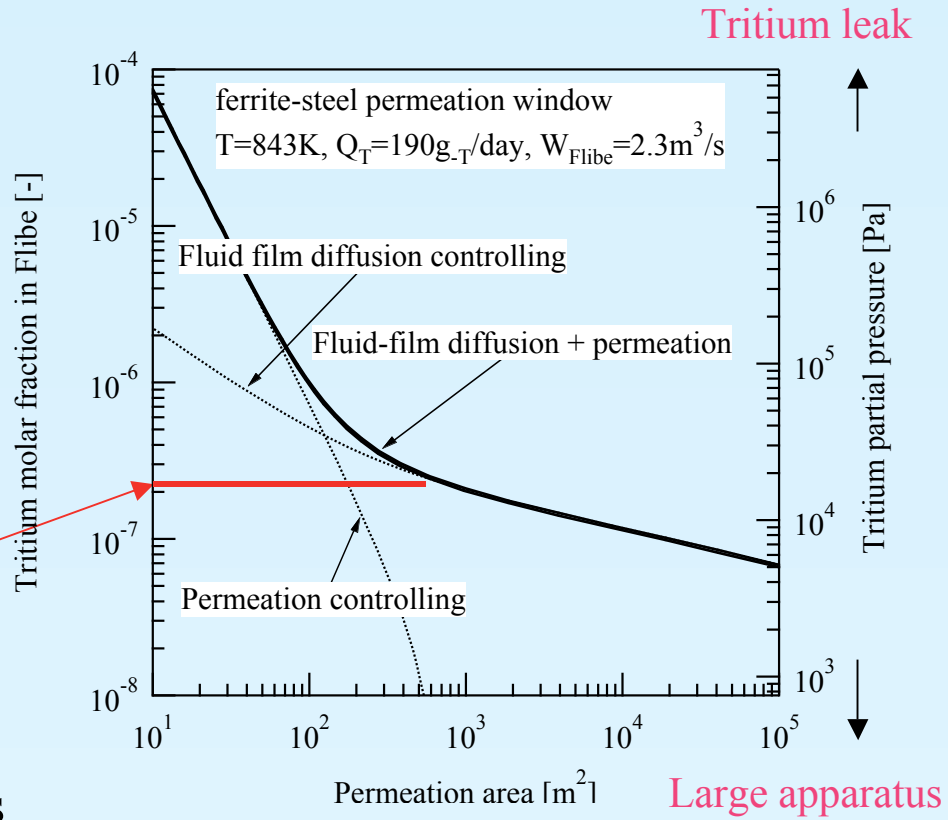


Fig. 6 Permeation window area

(□=1, t=1mm)

Counter-current extraction tower

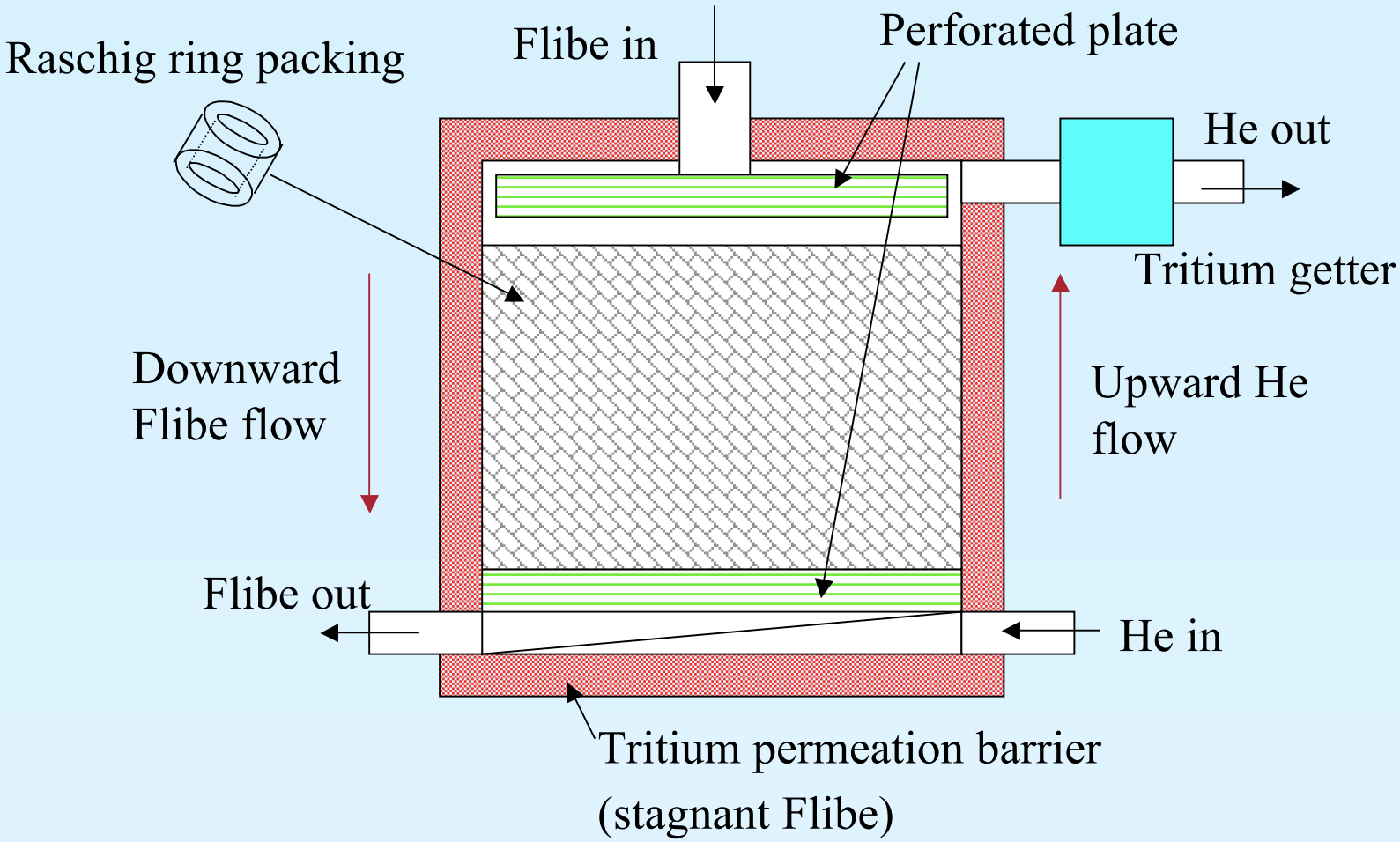


Fig. 8 Flibe-He counter-current extraction tower

2. Design study :

Design equations for He extraction tower

- Material balance equation

$$Ldy = Gdx$$

$$k_L a_v \Omega_s \left(y - y_i\right)dz = k_G a_V c_t \left(x - x_i\right)dz$$

- Gas-phase height transfer unit

$$H_G = \frac{G}{k_G a_V c_t} = 3.07 \frac{G^{0.32}}{L^{0.51}} \left(\frac{\Omega_G}{D_G}\right)^{\frac{2}{3}}$$

- Flibe-phase height transfer unit

$$H_L = \frac{L}{k_L a_V \Omega_S} = \frac{1}{430} \left(\frac{L}{\Omega_L}\right)^{0.22} \left(\frac{\Omega_L}{D_L}\right)^{0.5}$$

- Concentration profile (Solution)

$$\frac{y}{y_{in}} = \frac{\exp\left(1 - \frac{K_C L}{G}\right)\left(\frac{z}{H_{0,L}}\right) - \frac{K_C L}{G}}{\exp\left(1 - \frac{K_C L}{G}\right)\left(\frac{h}{H_{0,L}}\right) - \frac{K_C L}{G}}$$

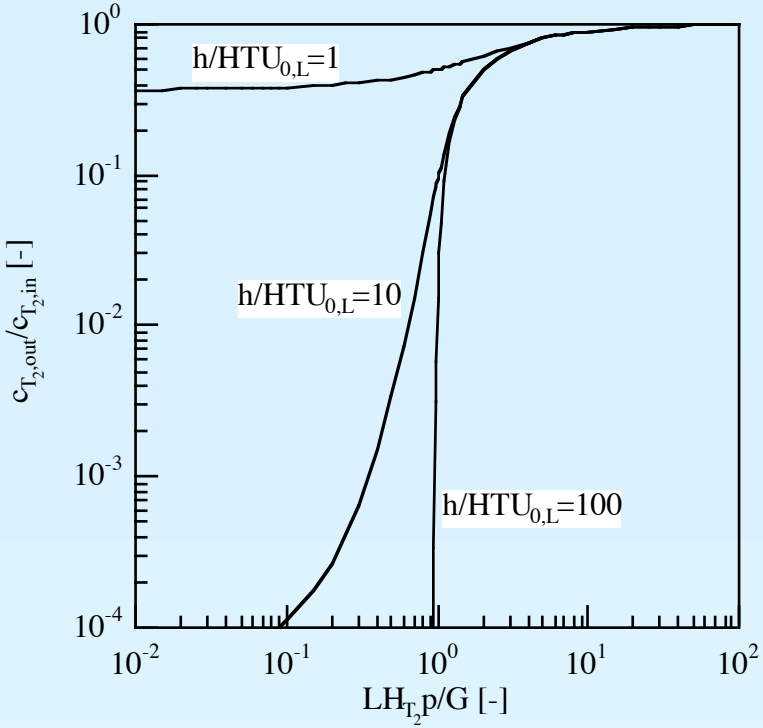


Fig. 9 Concentration change in extraction tower

Rate-determining step is liquid phase diffusion.

2. Design study :

Tritium concentration in He extraction tower

- Tritium concentration in He almost increases logarithmically.
- Tritium concentration in Flibe almost decreases logarithmically.
- 10^5 of DF for Flibe-tritium system is possible by 5 m extraction tower.
- 190 g/day tritium can be recovered by one extraction tower.
- Values of H_L are unsure because they are not determined by Flibe experiment but by water-hydrogen system.
- $\underline{(HTU)_L} >> \underline{(HTU)_G}$

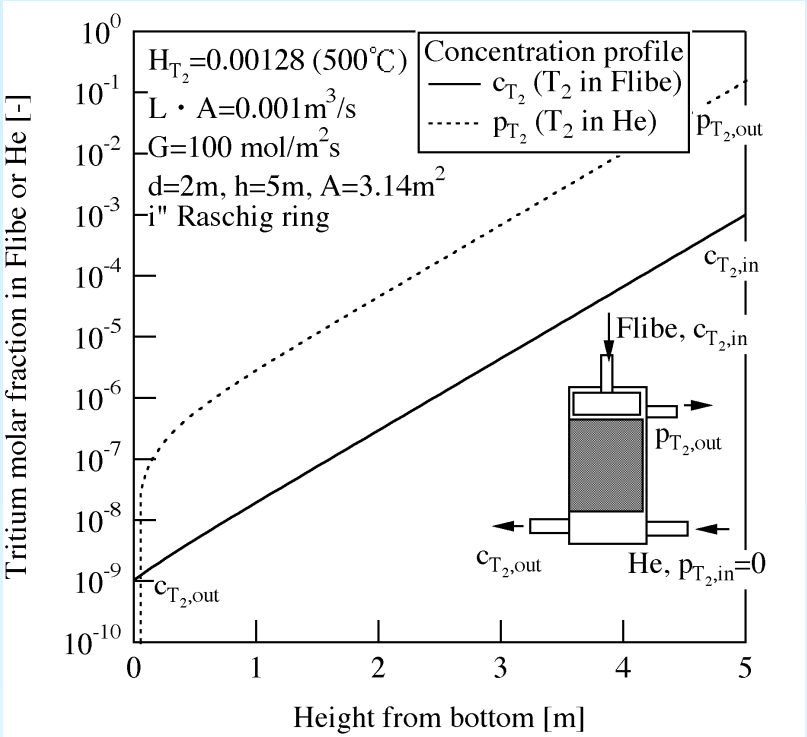


Fig. 10 Tritium concentration in He extraction tower

(□=0.1)

2. Design study : Analysis of vacuum disengager

Assumptions

- Flibe drops free fall from the top and dissolved tritium is desorbed by a vacuum pump.
- d_p=2mm, h=10m, □=0.1
- Surface recombination resistance is ignored.
- Drop formation energy ～1.4kW
- Pumping power for perforation ～ 160kW

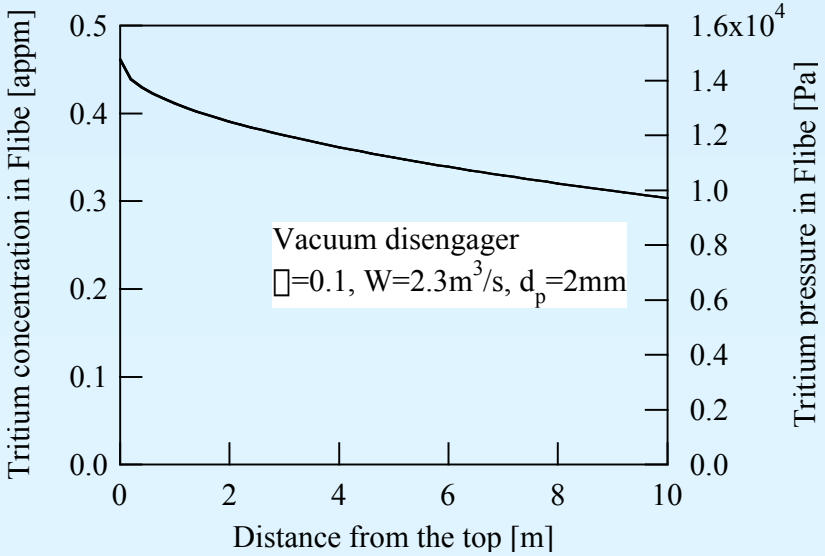
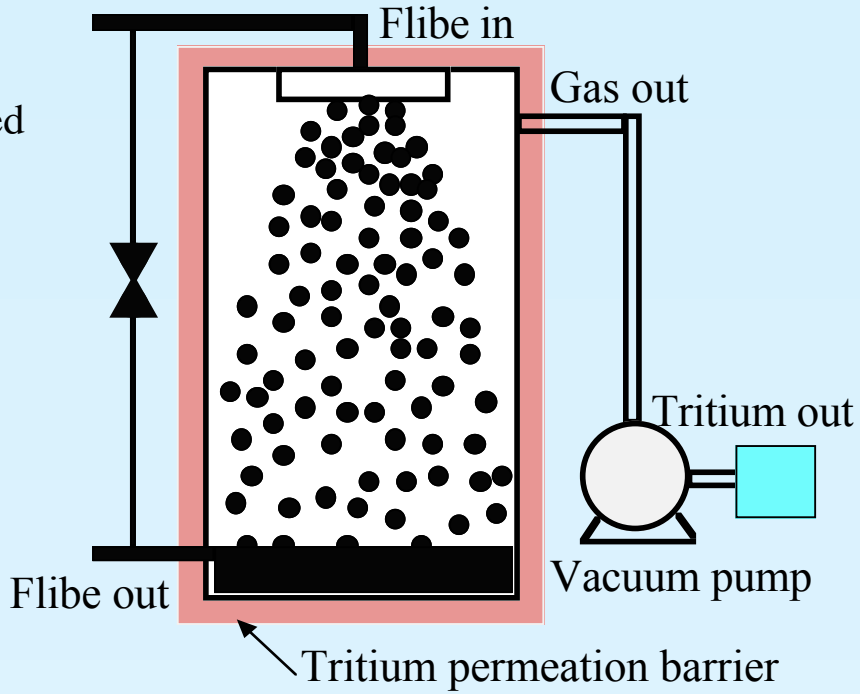


Fig.11 Concentration profile in disengager



$$\frac{x_{T,out}}{x_{T,in}} = \frac{6}{\square^2} \square \frac{1}{n^2} \exp(\square \frac{4Dn^2\square^2 t}{d^2})$$

$$t = \sqrt{2h/g}$$

$$Q_T = \square W_{Flibe} c_{Flibe} \left(x_{T,in} \square x_{T,out} \right)$$

2. Design study : Conclusions from design study

- Need a tritium barrier to control tritium leak below 10Ci/day
- As long as the tritium leak rate is lower than the permissible level (e.g. by stagnant Flibe), arranging the tritium recovery system in a by-pass line is effective.
- In that case, the recovery systems of the permeation window, extraction column and vacuum disengager are a realistic-scale apparatus.
- Diffusion in fluid Flibe is the rate-determining step in the permeation window and He-Flibe counter-current column.
- In order to raise the accuracy of the design, the mass-transfer coefficient from Flibe to extraction gas should be clearly determined.

2. Design study :

On Flinabe as a blanket material ($LiF\text{-}NaF\text{-}BeF_2$)

advantages

- Low melting point (=240C?), low operation temperature
- TBR>1 may be possible with addition of Be.
- Other physical properties may be similar to Flibe

disadvantages

- Activation of Na (formation of ^{22}Na or ^{24}Na)
- There are no data available on tritium mass-transport

→ More data are necessary for the design of the tritium recovery system