A design for recovery of tritium from Flibe loop in FFHR-2

Satoshi FUKADA
Dept. of Advanced Energy Engineering Science, Kyushu University
sfukada@aees.kyushu-u.ac.jp
and JUPITER-II group

Keywords: tritium recovery, Flibe, helical fusion reactor, tritium extraction tower

Advantages and disadvantages of Flibe ($2LiF+BeF_2$) for its application to self-cooled blanket

- **Advantages of Flibe**

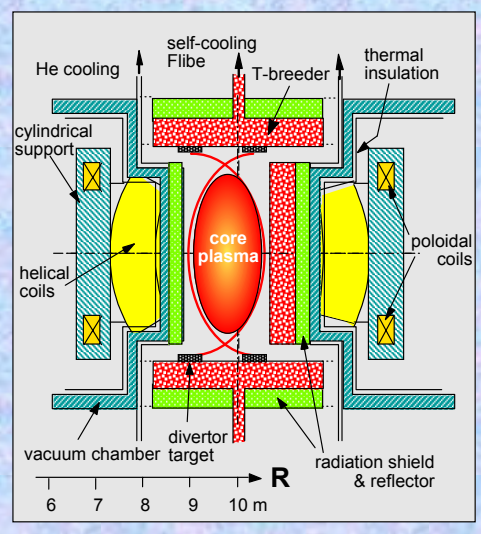
  stable, high TBR when Be is used, low electric conductivity, low tritium solubility

- **Disadvantages of Flibe**

  high melting temperature (456°C), generation of TF, high tritium leak

A concept of helical-type fusion reactor, *e.g.*, FFHR-2 adopts a self-cooled Flibe blanket concept

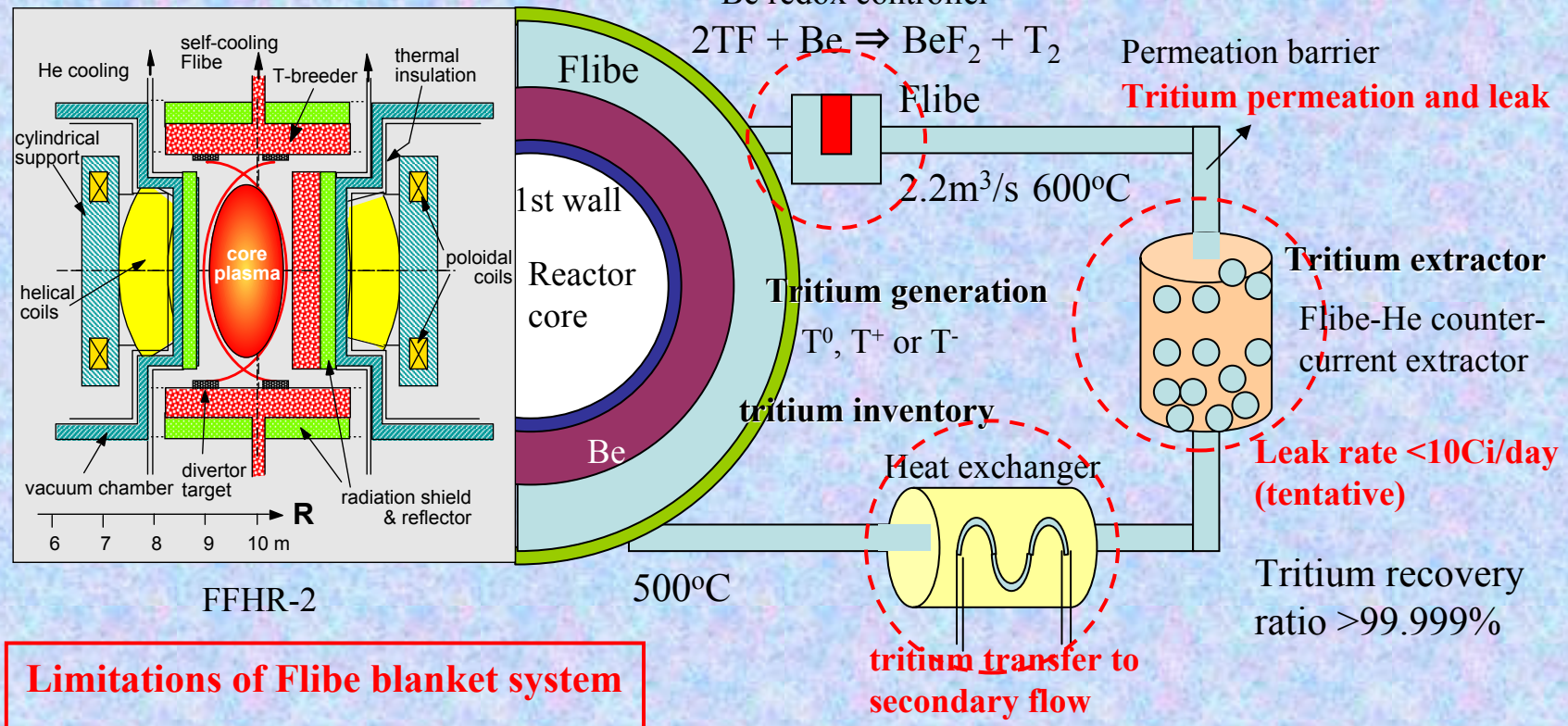
- To develop measures to solve TF control, material corrosion and tritium permeation
- Investigate high tritium recovery apparatus
- Apply the result to FFHR-2 design



Overall tritium material balance in FFHR-2 Flibe system

1GW LiF+n ⇒TF+He

T Generation rate 150g/day, 1.6MCi/day



FFHR-2

Limitations of Flibe blanket system

- Transformation of TF to T_2
- High tritium recovery
- Control of tritium leak

⇒

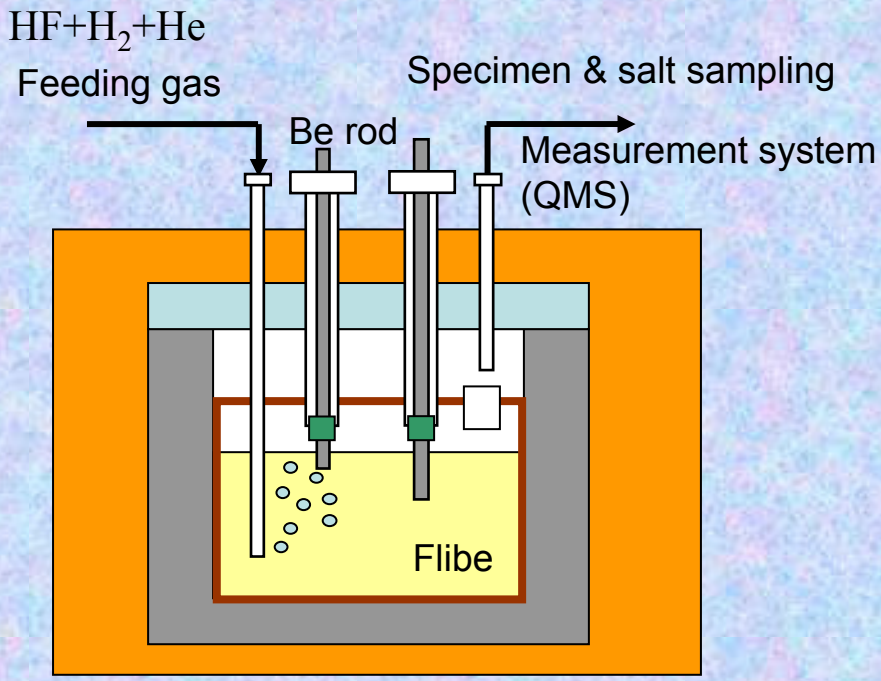
Analysis of redox control
Tritium (H) permeation through Flibe
Flibe-He extraction tower analysis

Design parameters for FFHR Flibe-tritium system

Fusion power	1GWt
Tritium generation rate in Flibe blanket	190g/day (1.8MCi/day)
Target value of tritium leak to the environment	10Ci/day
Flibe flow rate	$2.2m^3/s$
Inlet temperature	500C
Outlet temperature	600C
Flibe velocity	5m/s
Tritium concentration in Flibe at outlet of blanket	$5.2x10^{-10}$wfr (990Pa)
Duct diameter	0.74m
Duct area (blanket-(TR)-(HX)-pump-blanket)	$40m^2$
Heat exchange area	$700m^2$
Heat exchanger length	10m
Heat transfer coefficient	$1x10^4W/m^2K$
Duct thickness	5mm
Tritium diffusion coefficient in Flibe	$5x10^{-9}m^2/s$ (estimated)
Tritium solubility in Flibe as T_2	$5.3x10^{-13}$wtfr.Pa
Tritium permeability through sus316	$9.7x10^{-11}g/msPa^{0.5}$

Handling Flibe pot in glove box for investigating transformation of TF to T_2

Glove-box for tritium + Be handling (INL)



Flibe pot

Purification:
$BeO+HF=BeF_2+H_2O$(removed) Redox control: $Be+HF(TF)=BeF_2+H_2(T_2)$

Experimental apparatus for redox control set up in INL
(JUPITER-II task 1-1-A experiment)

Redox control of tritium in self-cooled Flibe blanket

Reduction-Oxidation condition

$LiF + n \Rightarrow TF + He$ $\quad$ $Be + 2TF = BeF_2 + T_2$

- TF (or HF) material balance

$$M_{Flibe}\frac{dx_{TF}}{dt} = Q_T - 2V_{Flibe}k_{BeF_2}\left(x_{Be}x_{TF} - \frac{x_{BeF_2}x_{T_2}}{K_{BeF_2}x_{TF}}\right)$$

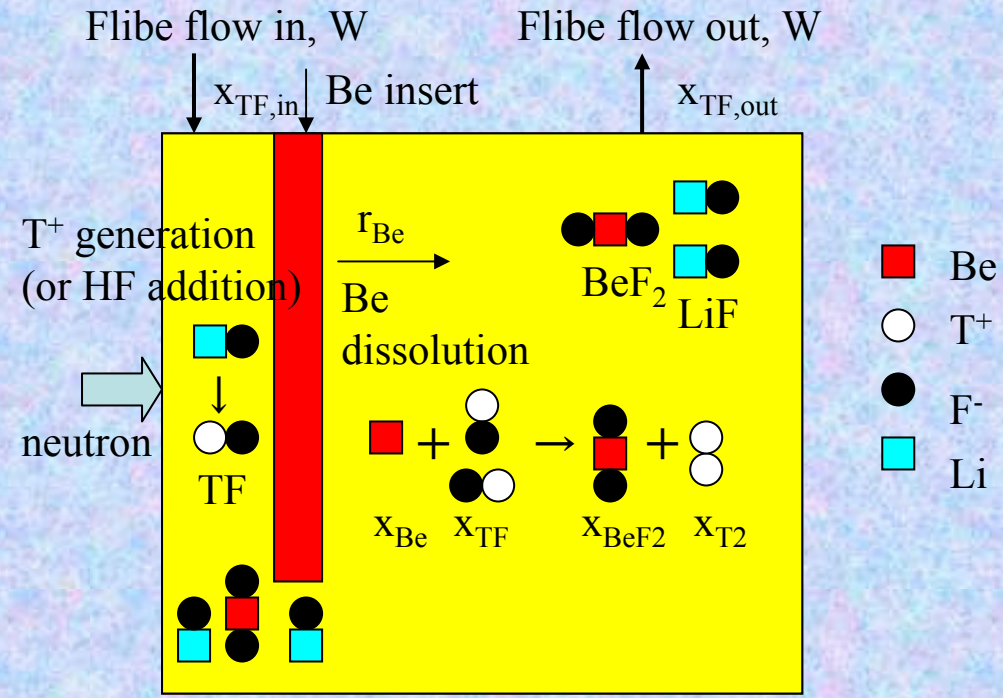
$$+W\left(x_{TF,in} - x_{TF,out}\right) - 2V_{Flibe}k_{FeF_2}\left(x_{Fe}x_{TF}^2 - \frac{x_{FeF_2}x_{T_2}}{K_{FeF_2}}\right)$$

- Material balance of Be dissolved

$$M_{Flibe}\frac{dx_{Be}}{dt} = r_{Be} - V_{Flibe}k_{BeF_2}\left(x_{Be}x_{TF} - \frac{x_{BeF_2}x_{T_2}}{K_{BeF_2}x_{TF}}\right)$$

- Metallic impurity material balance

$$M_{Flibe}\frac{dx_{Fe}}{dt} = -V_{Flibe}k_{FeF_2}\left(x_{Fe}x_{TF}^2 - \frac{x_{FeF_2}x_{T_2}}{K_{FeF_2}}\right)$$



Blanket and Flibe pot

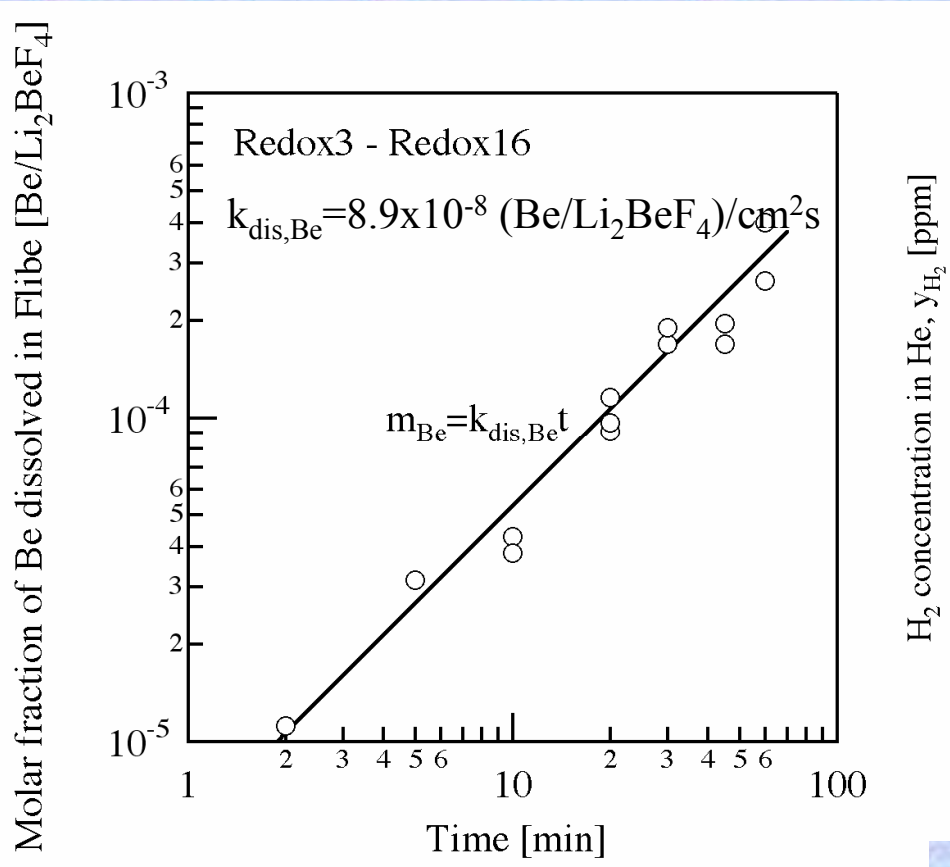
k_{BeF2} and r_{Be} were determined by experiment

Reaction-rate constant, Be dissolution rate

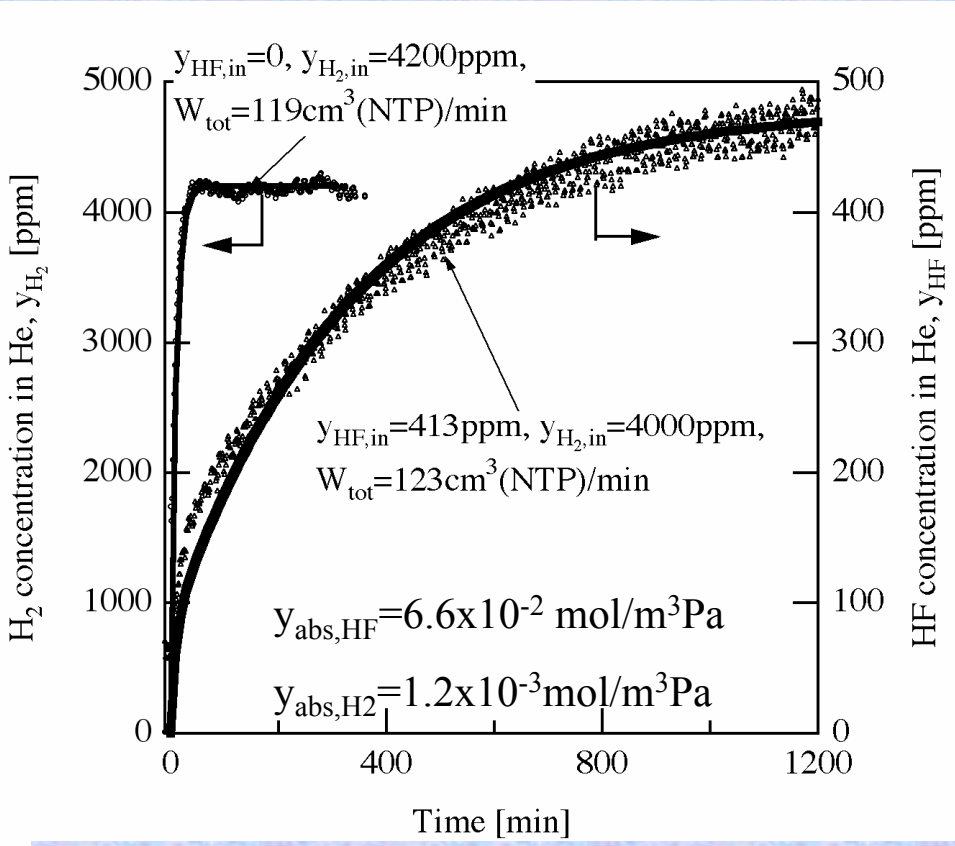
Assumptions: Complete mixing in Flibe blanket, 1st-order reaction

To determine dissolution of Be, HF and H_2 in Flibe

- Dissolution rate of Be in Flibe, $m_{Be}=k_{dis,Be}A_{Be}t$
- Dissolution rate of HF (TF) and H_2 (T_2) in Flibe, $r_{HF}=k_{HF}(y_{HF}-y_{HF,sat})A_{Be}$



Be dissolution rate



HF and H_2 dissolution curves

Experiment (marks) and numerical model (line) were consistent.

Transformation of HF(TF) to $T_2(H_2)$ by a Be rod inserted in Flibe

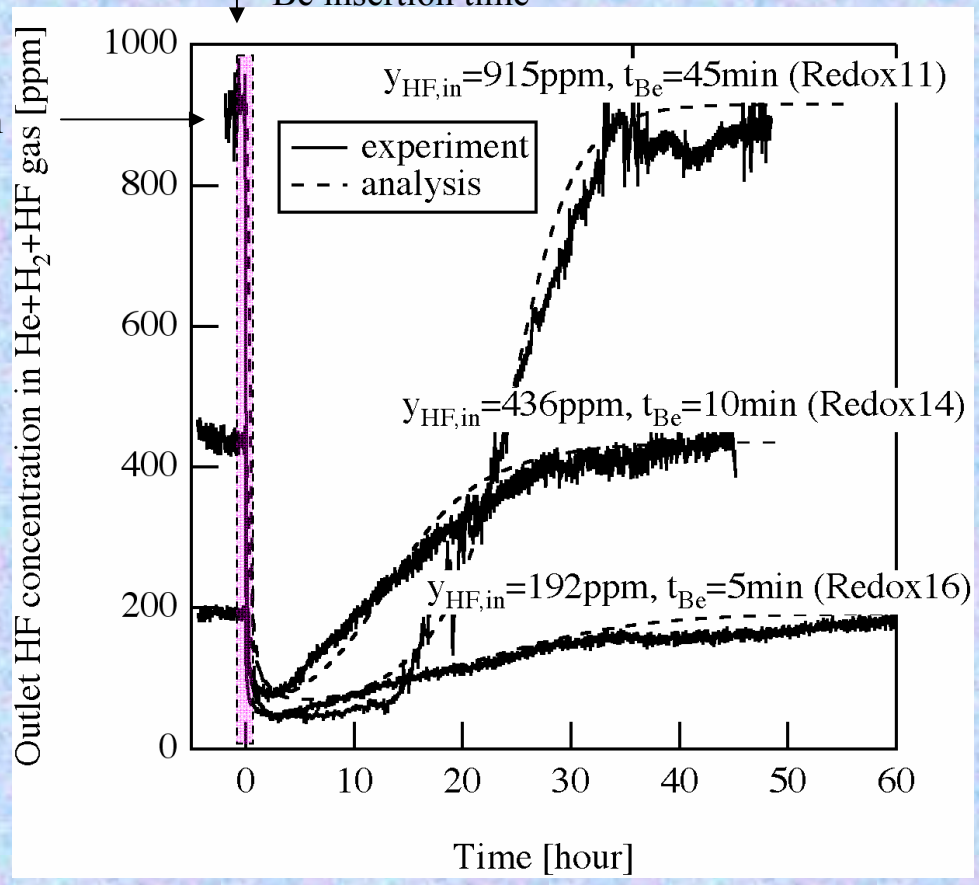
generation — Flow in and out

$$M_{Flibe}\frac{dx_{TF}}{dt} = Q_T - 2V_{Flibe}k_{BeF_2}\left(x_{Be}x_{TF} - \frac{x_{BeF_2}x_{T_2}}{K_{BeF_2}x_{TF}}\right) + W\left(x_{TF,in} - x_{TF,out}\right) - 2V_{Flibe}k_{FeF_2}\left(x_{Fe}x_{TF}^2 - \frac{x_{FeF_2}x_{T_2}}{K_{FeF_2}}\right)$$

Transformation by Be — Transformation by Fe

Be insertion time

HF supply condition



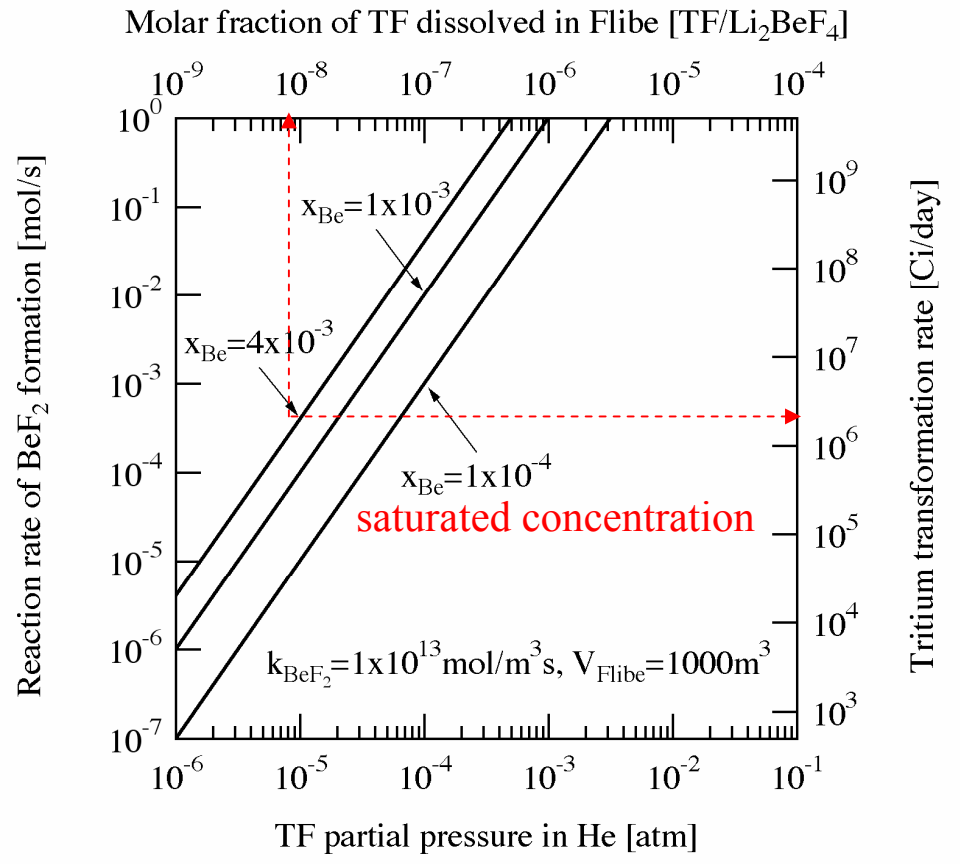
$HF \rightarrow H_2$ conversion

$Be + 2HF = BeF_2 + H_2$

$Fe + 2HF = FeF_2 + H_2$

experiment of Flibe Redox control by Be

Concentration of Be and TF to attain steady-state transformation of TF to T_2 in FFHR-2 fusion reactor

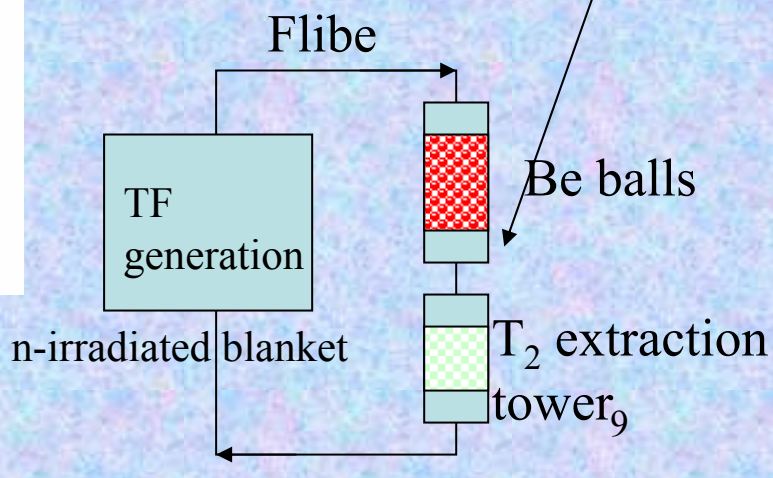


TF concentration in Flibe blanket

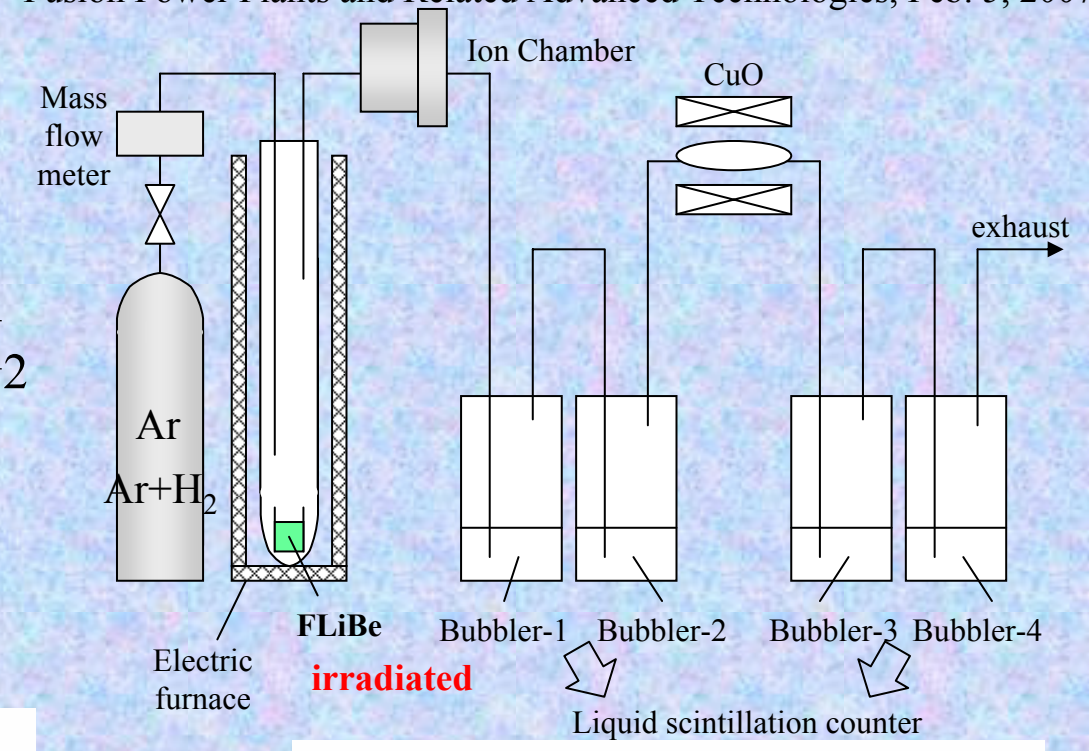
Tritium generation rate of 1.6MCi/day should be maintained for 1GW fusion power.

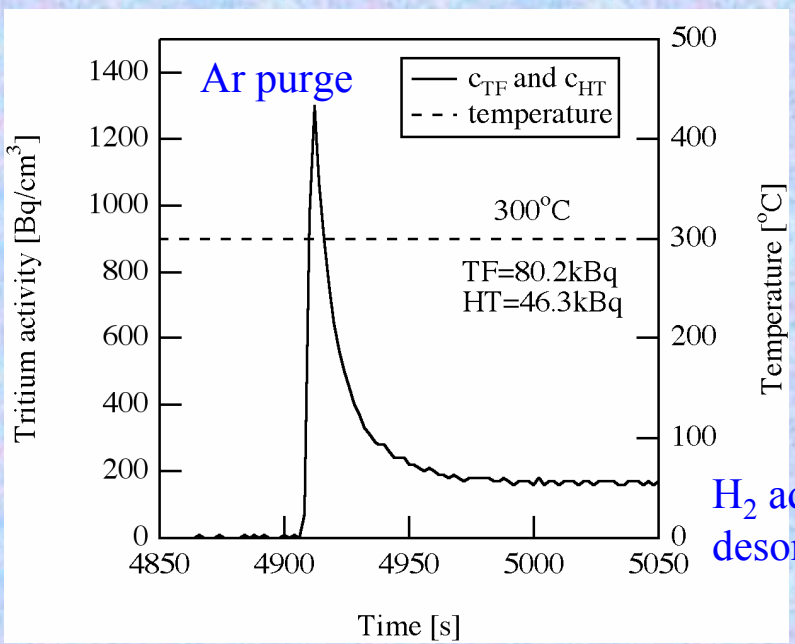
When Flibe saturated with Be, the TF concentration is maintained 10^{-2} ppm (1Pa).

The TF concentration is durable for FFHR-2 operation condition.

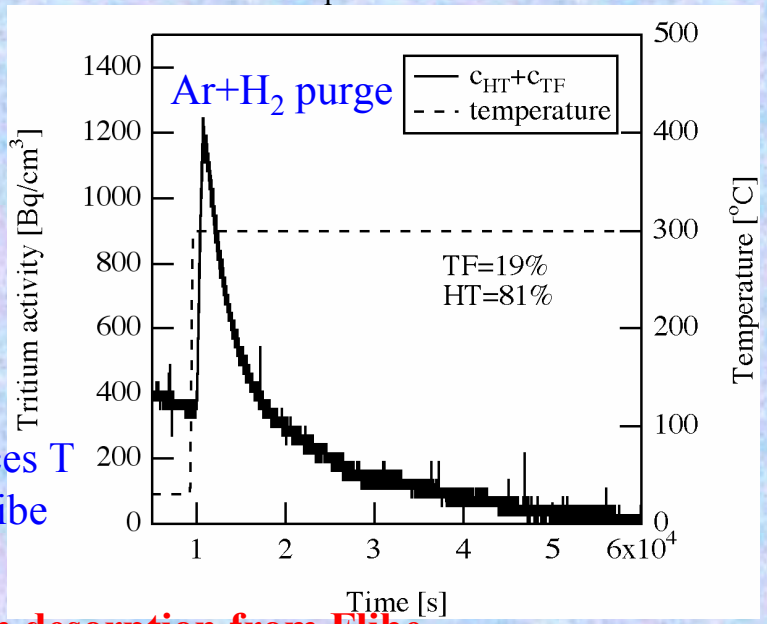


Tritium generation in n-irradiated Flibe and isotopic exchange with H_2





H_2 addition enhances T desorption from Flibe



Isotopic exchange enhances tritium desorption from Flibe

Counter-current extraction tower for T_2 removal from Flibe

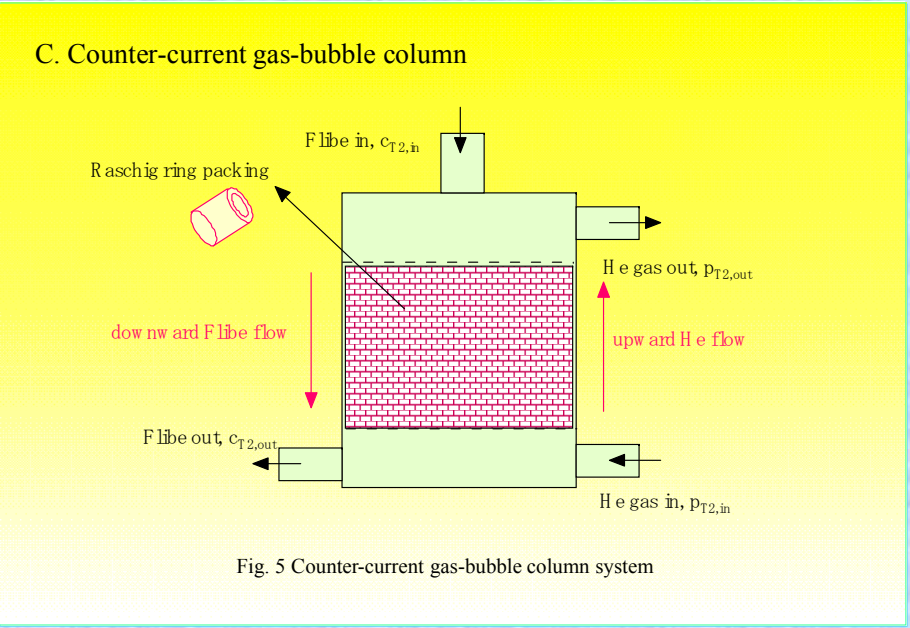
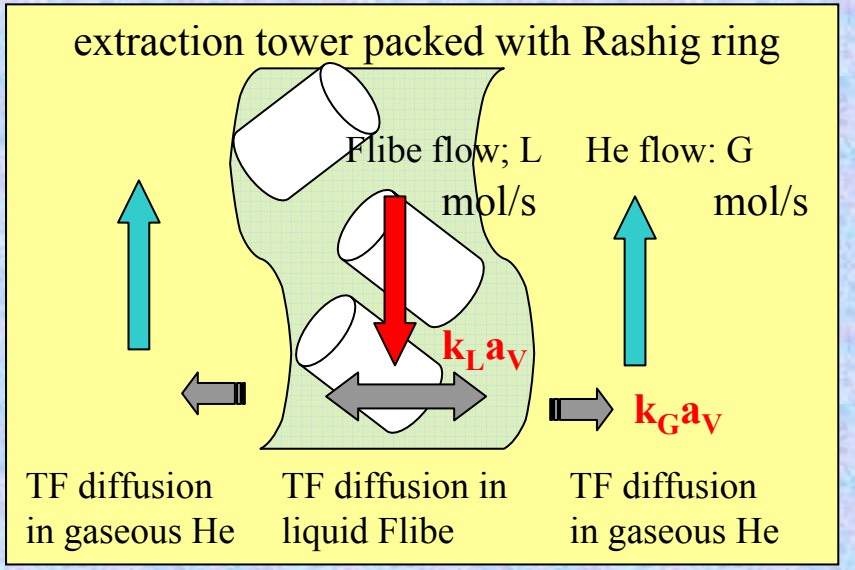


Fig. 5 Counter-current gas-bubble column system



- Material balance equation

$$Ldy = Gdx \qquad k_L a_v \gamma_s (y - y_i) dz = k_G a_V c_t (x - x_i) dz$$

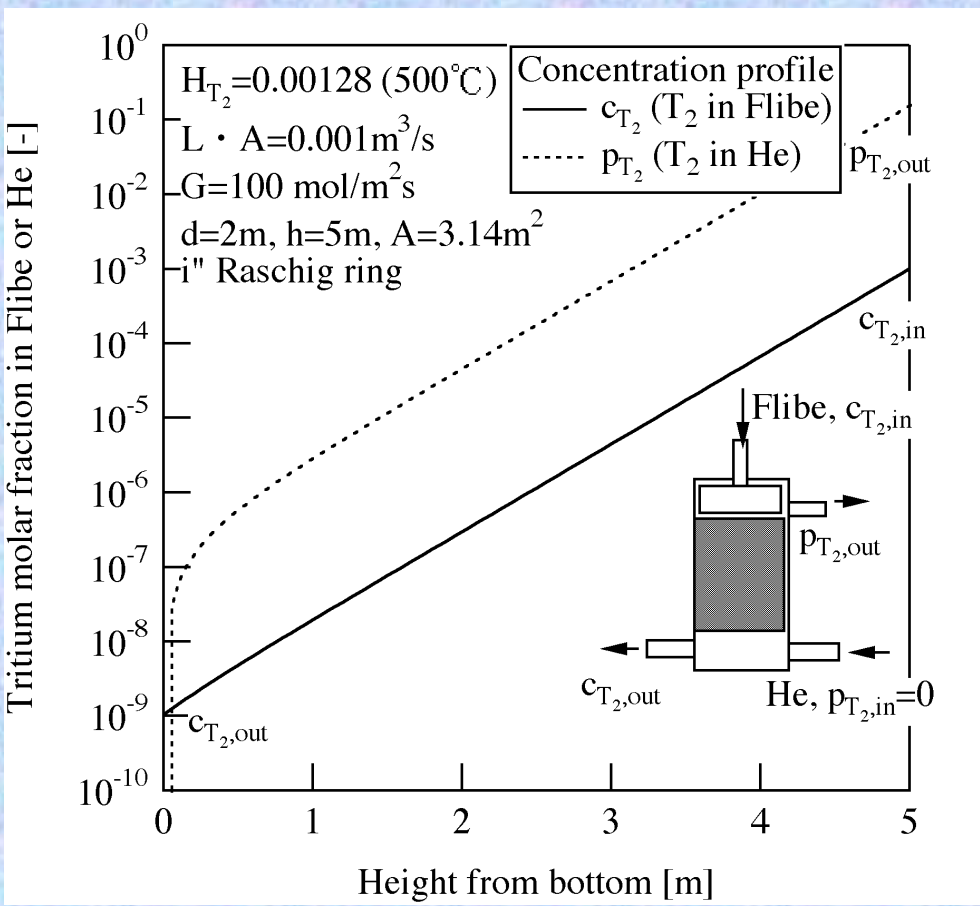
- Rate of gas-phase tritium transfer

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

Rate of Flibe-phase tritium transfer

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

Calculation of T_2 extraction tower Flibe



Tritium concentration in extraction tower

raschig ring

Packing materials ensure Flibe to keep good contact with He:

Numerical concentration profile through extraction tower

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

Energy for Flibe-T disengage and recovery ratio

Optimum condition

Diameter of dispersed Flibe drop	100 μm	200 μm	300μm	1000 μm
Energy of Flibe passing through percolator	140 W	8.7 W	1.7 W	14 mW
Pressure difference through percolator	700 atm	44 atm	8.6 atm	0.07 atm
Surface tension energy of dispersed Flibe drops	11 kW	5.6 kW	3.7 kW	1.1 kW
Tritium recovery ratio by 10 m spray tower	100 %	100 %	98 %	21 %

Energy of Flibe passing through the column $$W = \frac{\pi}{4} d^2 u N \Delta p$$

Pressure drop $$\Delta p = \frac{32 \eta \ell u}{d^2}$$

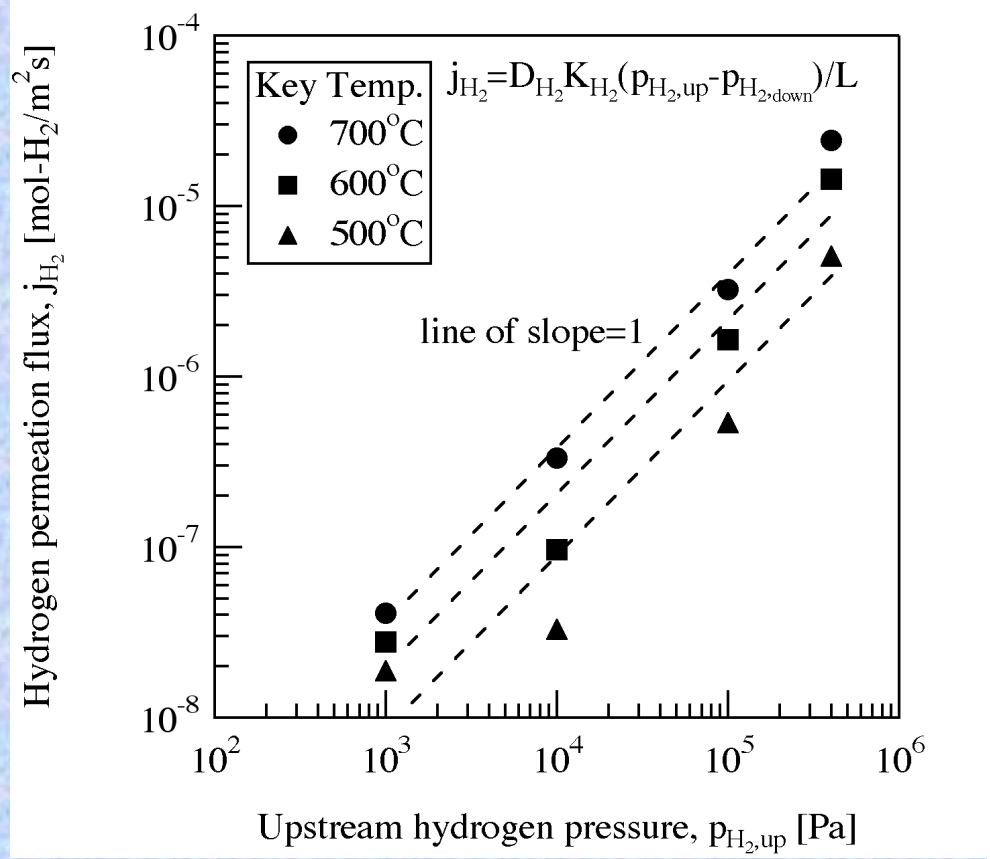
Hydrogen permeation through Flinak (Flibe simulant)

$j_{H2} \propto p_{H2,up} - p_{H2,down}$

- Estimated tritium permeation rate: $p_{T2}=10^5$Pa (x_{T2}=1ppm), 600°C, t=1mm, A=1m^2

  ⇨ 1x10^{4}Ci/day (huge permeation rate)

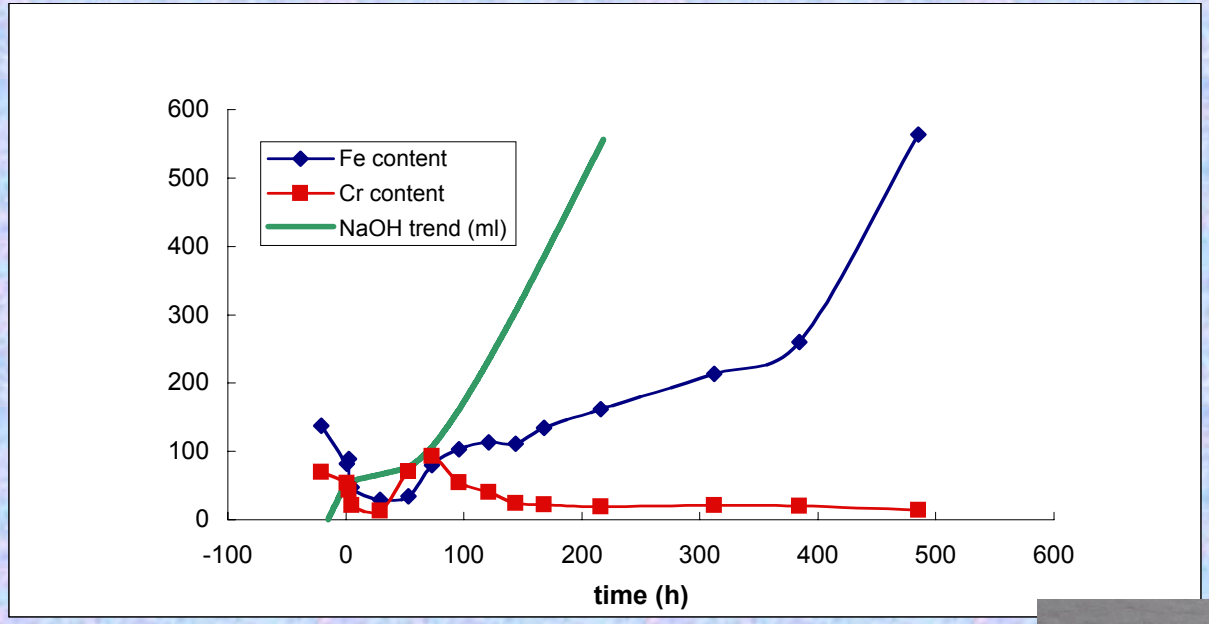
- High tritium recovery system is demanded in FFHR-2



Hydrogen permeation rate through molten salt

Ceramic coating to decrease hydrogen permeation is necessary.

Corrosion test of JLF-1 in Redox controlled or non-redox controlled Flibe



Dissolution rate of Fe, Cr into Flibe is affected by reduction-oxidation condition

JLF-1 before or after Flibe immersion

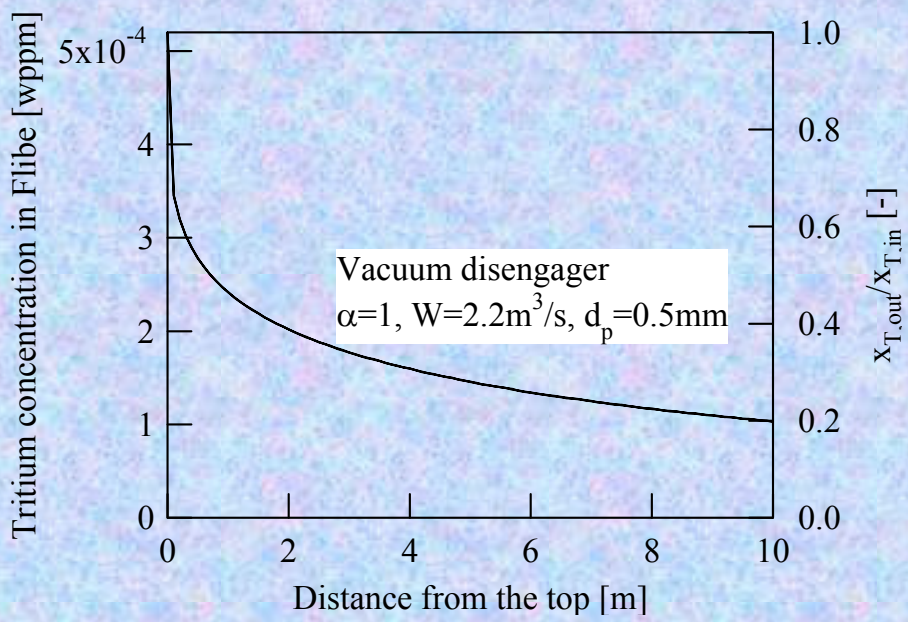
Conclusions

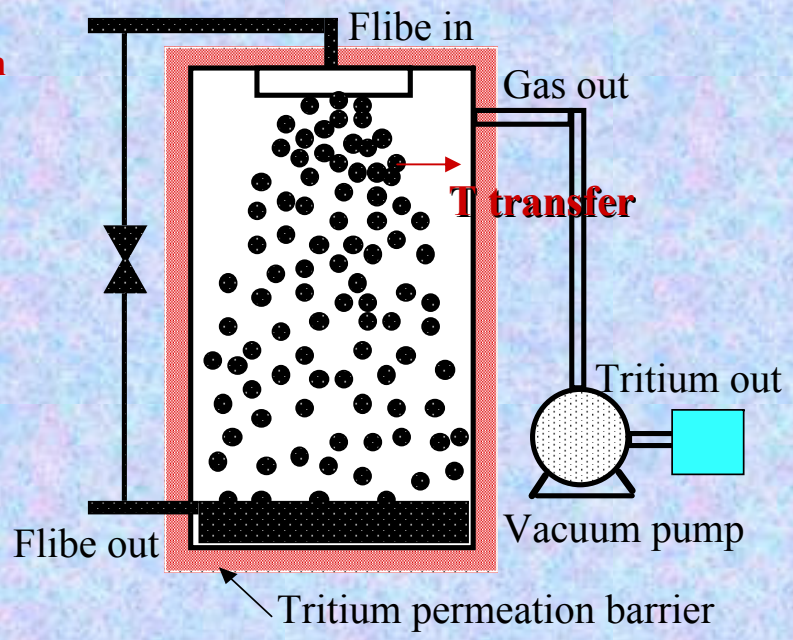
- The reaction of Be-HF for Redox control is sufficiently fast compared to the Flibe residence time in FFHR-2.
- Mass-transfer parameters for Redox control by Be are determined.
- The TF concentration after Redox control is predicted 0.02 ppm in Flibe under FFHR-2 condition.
- Tritium chemical form released from Flibe is changed from TF to HT by the addition of H_2 in Ar purge gas.
- Flibe-He counter-current extraction tower can recover T_2 from redox-controlled Flibe flow efficiently.
- The extraction tower needs less energy and less pressure drop when it is designed properly.
- Tritium leak rate will be high unless we take measures to decrease tritium permeating through tubes

Analysis of vacuum disengager

Assumptions

- Flibe drops free fall from the top and **dissolved tritium is desorbed by a vacuum pump**.
- d_p=0.5mm, h=10m, α=1
- Surface recombination resistance was ignored.
- Drop formation energy ∽5.6kW
- Pumping power for perforation ∽ 1.6MW

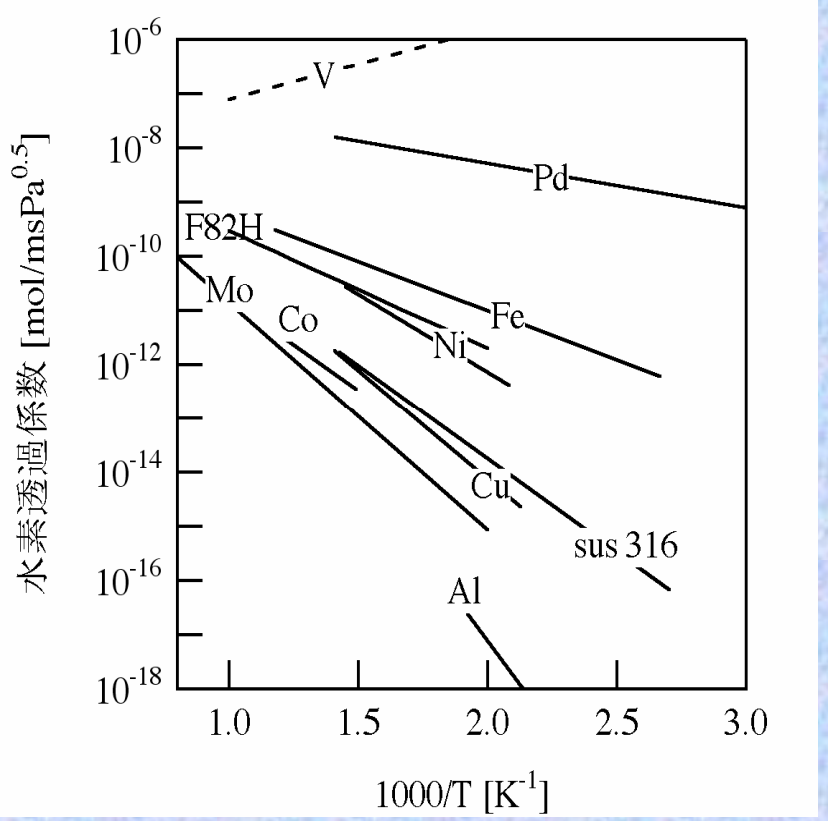




$$\frac{x_{T,out}}{x_{T,in}} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{4Dn^2\pi^2 t}{d^2}\right)$$

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

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



Hydrogen permeability through metals

By APEX

Material conditions

Table 15
Maximum allowable temperatures of structural alloys (bare walls) in contact with high-purity liquid coolants, based on a 5 μm/yr corrosion limit (Sn–Li corrosion limits are based on experimental studies conducted with liquid Sn)

	Li	Pb–17 Li	Sn–Li (Sn)	Flibe
F/M steel	550–600°C	450°C	400–500°C	700°C (304/316 stainless steel)
V alloy	~700°C	~650°C	?	?
Nb alloy	>1 300°C	>600°C(>1 000°C in Pb)	600–800°C	>800°C
Ta alloy	>1 370°C	>600°C(>1 000°C in Pb)	600–800°C?	?
Mo	>1 370°C	>600°C	<800°C?	>1 100°C?
W	>1 370°C	>600°C	~800°C	>900°C?
SiC	~550°C?	>800°C?	>760°C?	?

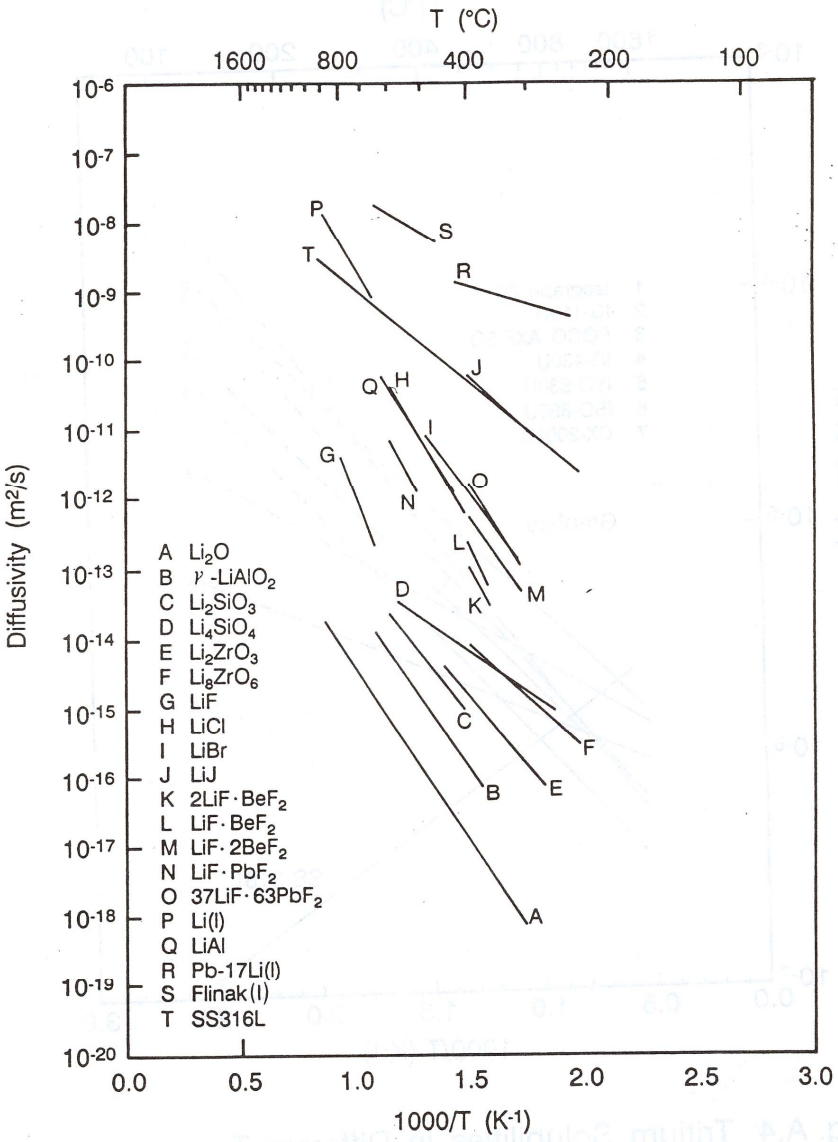


Fig. A.5 Tritium Diffusivities in Tritium Breeding Materials

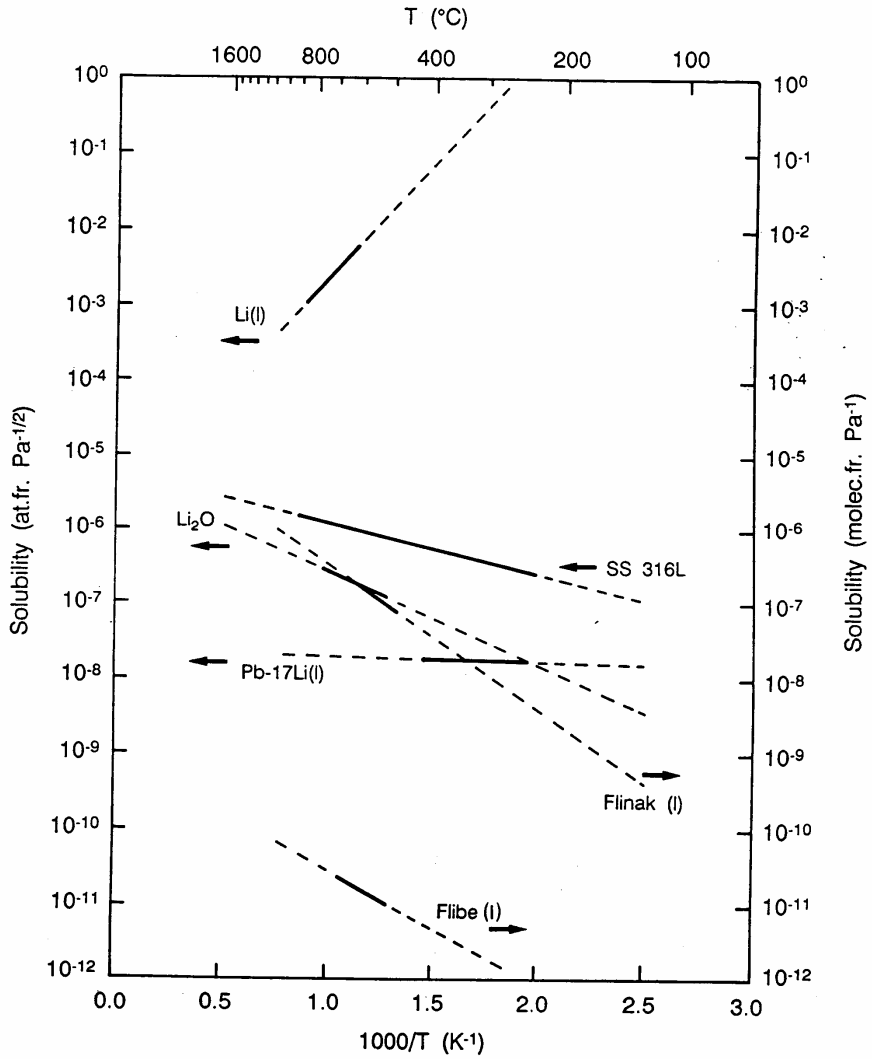


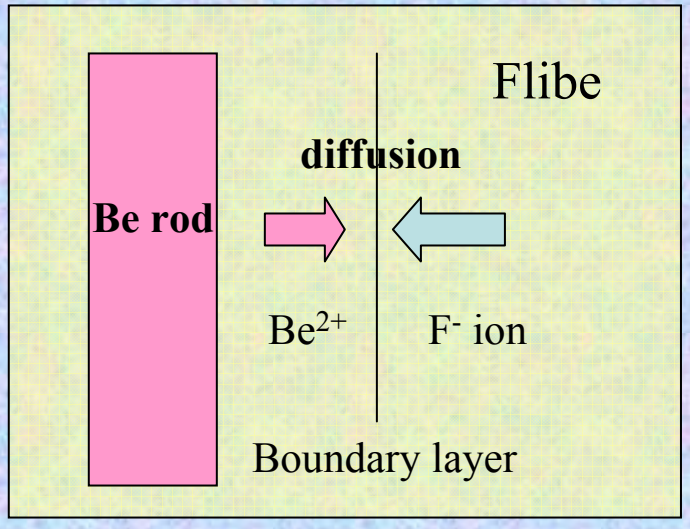
Fig. A.6 Tritium Solubilities in Tritium Breeding Materials

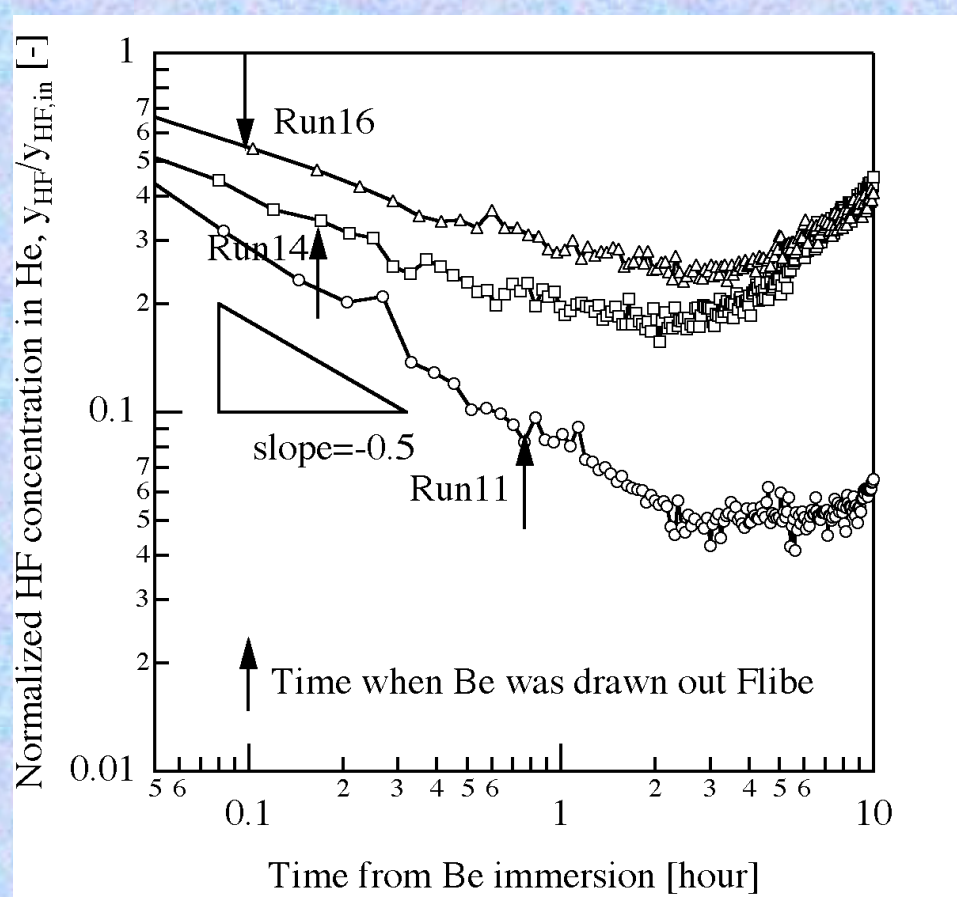
*) left scale for Li_2O, Li(l), Pb-17Li(l) and SS 316L, right scale for Flibe and Flinak)

Variations of HF concentration in a small contact time

$$r_{BeF2} \propto \sqrt{D_{Be} t}$$

Initial reaction rate is limited by Be and F^- ion diffusion in Flibe





Initial redox reaction process is limited by Be diffusion through boundary layer formed on Be rod