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

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Advantages and disadvantages of Flibe \((2\text{LiF}+\text{BeF}_2)\) 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 \((456^\circ\text{C})\), 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 \( \text{LiF+n} \Rightarrow \text{TF+He} \)

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

Limitations of Flibe blanket system

- Transformation of TF to \( \text{T}_2 \)
- 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion power</td>
<td>1GWt</td>
</tr>
<tr>
<td>Tritium generation rate in Flibe blanket</td>
<td>190g/day (1.8MCi/day)</td>
</tr>
<tr>
<td>Target value of tritium leak to the environment</td>
<td>10Ci/day</td>
</tr>
<tr>
<td>Flibe flow rate</td>
<td>2.2m³/s</td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>500C</td>
</tr>
<tr>
<td>Outlet temperature</td>
<td>600C</td>
</tr>
<tr>
<td>Flibe velocity</td>
<td>5m/s</td>
</tr>
<tr>
<td>Tritium concentration in Flibe at outlet of blanket</td>
<td>5.2x10^-10 wfr (990Pa)</td>
</tr>
<tr>
<td>Duct diameter</td>
<td>0.74m</td>
</tr>
<tr>
<td>Duct area (blanket-(TR)-(HX)-pump-blanket)</td>
<td>40m²</td>
</tr>
<tr>
<td>Heat exchange area</td>
<td>700m²</td>
</tr>
<tr>
<td>Heat exchanger length</td>
<td>10m</td>
</tr>
<tr>
<td>Heat transfer coefficient</td>
<td>1x10^4 W/m²K</td>
</tr>
<tr>
<td>Duct thickness</td>
<td>5mm</td>
</tr>
<tr>
<td>Tritium diffusion coefficient in Flibe</td>
<td>5x10^-9 m²/s (estimated)</td>
</tr>
<tr>
<td>Tritium solubility in Flibe as T₂</td>
<td>5.3x10^-13 wfr.Pa</td>
</tr>
<tr>
<td>Tritium permeability through sus316</td>
<td>9.7x10^-11 g/msPa^0.5</td>
</tr>
</tbody>
</table>
Handling Flibe pot in glove box for investigating transformation of TF to T₂

Glove-box for tritium + Be handling (INL)

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

Purification:
BeO+HF=BeF₂+H₂O(removed)
Redox control:
Be+HF(TF)=BeF₂+H₂(T₂)
Redox control of tritium in self-cooled Flibe blanket

**Reduction-Oxidation condition**

\[
\text{LiF} + n \Rightarrow \text{TF} + \text{He} \quad \text{Be} + 2\text{TF} = \text{BeF}_2 + \text{T}_2
\]

- **TF (or HF) material balance**
  \[
  M_{\text{Flibe}} \frac{dx_{\text{TF}}}{dt} = Q_T - 2V_{\text{Flibe}} k_{\text{BeF}_2} \left( x_{\text{Be}} x_{\text{TF}} - \frac{x_{\text{BeF}_2} x_{\text{T}_2}}{K_{\text{BeF}_2}} \right) \\
  + W (x_{\text{TF,in}} - x_{\text{TF,out}}) - 2V_{\text{Flibe}} k_{\text{FeF}_2} \left( x_{\text{Fe}} x_{\text{TF}} - \frac{x_{\text{FeF}_2} x_{\text{T}_2}}{K_{\text{FeF}_2}} \right)
  \]

- **Material balance of Be dissolved**
  \[
  M_{\text{Flibe}} \frac{dx_{\text{Be}}}{dt} = r_{\text{Be}} - V_{\text{Flibe}} k_{\text{BeF}_2} \left( x_{\text{Be}} x_{\text{TF}} - \frac{x_{\text{BeF}_2} x_{\text{T}_2}}{K_{\text{BeF}_2}} \right)
  \]

- **Metallic impurity material balance**
  \[
  M_{\text{Flibe}} \frac{dx_{\text{Fe}}}{dt} = -V_{\text{Flibe}} k_{\text{FeF}_2} \left( x_{\text{Fe}} x_{\text{TF}} - \frac{x_{\text{FeF}_2} x_{\text{T}_2}}{K_{\text{FeF}_2}} \right)
  \]

\(k_{\text{BeF}_2}\) and \(r_{\text{Be}}\) 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 H₂ in Flibe

- Dissolution rate of Be in Flibe, \( m_{\text{Be}} = k_{\text{dis,Be}} A_{\text{Be}} t \)
- Dissolution rate of HF (TF) and H₂ (T₂) in Flibe, \( r_{\text{HF}} = k_{\text{HF}} (y_{\text{HF}} - y_{\text{HF,sat}}) A_{\text{Be}} \)

Experiment (marks) and numerical model (line) were consistent.
Transformation of HF(TF) to $T_2(H_2)$ by a Be rod inserted in Flibe

$$M_{\text{Flibe}} \frac{dx_{\text{TF}}}{dt} = Q_I - 2V_{\text{Flibe}}k_{\text{BeF}_2} \left( x_{\text{Be}}x_{\text{TF}} - \frac{x_{\text{BeF}_2}x_{T_2}}{K_{\text{BeF}_2}x_{\text{TF}}} \right) + W \left( x_{\text{TF,in}} - x_{\text{TF, out}} \right) - 2V_{\text{Flibe}}k_{\text{FeF}_2} \left( x_{\text{Fe}}x_{\text{TF}}^2 - \frac{x_{\text{FeF}_2}x_{T_2}}{K_{\text{FeF}_2}} \right)$$

HF supply condition

HF → $H_2$ conversion

Be + 2HF = BeF$_2$ + $H_2$

Fe + 2HF = FeF$_2$ + $H_2$
Concentration of Be and TF to attain steady-state transformation of TF to T$_2$ in FFHR-2 fusion reactor

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 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 H₂

Isotopic exchange enhances tritium desorption from Flibe

H₂ addition enhances T desorption from Flibe

Ar purge

Ar+H₂ purge

TF=80.2 kBq
HT=46.3 kBq

TF=19%
HT=81%

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Counter-current extraction tower for $T_2$ removal from Flibe

C. Counter-current gas-bubble column

- Material balance equation
  \[ L \frac{dy}{dx} = G \frac{dx}{y} \quad k_L \alpha_c \gamma (y - y_i) \, dz = k_G \alpha_c (x - x_i) \, dz \]
- Rate of gas-phase tritium transfer
  \[ H_G \left( \frac{G}{k_G \alpha_c} \right) = 3.07 \left( \frac{G}{\mu_L} \right)^{0.32} \left( \frac{\nu_L}{D_G} \right)^{2} \]
- Rate of Flibe-phase tritium transfer
  \[ H_L \left( \frac{L}{k_L \alpha_c} \right) = \frac{L}{430} \left( \frac{L}{\mu_L} \right)^{0.22} \left( \frac{\nu_L}{D_L} \right)^{0.5} \]
Calculation of $T_2$ extraction tower Flibe

Tritium concentration in extraction tower

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

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

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## Energy for Flibe-T disengage and recovery ratio

### Optimum condition

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

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)

- Estimated tritium permeation rate: $p_{T2} = 10^5 \text{Pa}$ ($x_{T2} = 1 \text{ppm}$), $600^\circ \text{C}$, $t = 1 \text{mm}$, $A = 1 \text{m}^2$
  \[ \dot{j}_{H2} \propto p_{H2,up} - p_{H2,down} \]
  \[ j_{H2} = D_{H2} K_{H2} (p_{H2,up} - p_{H2,down})/L \]

  $1 \times 10^4 \text{Ci/day}$
  (huge permeation rate)

- High tritium recovery system is demanded in FFHR-2

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 H₂ in Ar purge gas.
• Flibe-He counter-current extraction tower can recover T₂ 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.
- \( d_p = 0.5 \text{mm}, \quad h = 10 \text{m}, \quad \alpha = 1 \)
- Surface recombination resistance was ignored.
- Drop formation energy \( \sim 5.6 \text{kW} \)
- Pumping power for perforation \( \sim 1.6 \text{MW} \)

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

\[
t = \sqrt{\frac{2h}{g}}
\]

\[
Q_T = \alpha W_{\text{Flibe}} c_{\text{Flibe}} \left(x_{T,\text{in}} - x_{T,\text{out}}\right)
\]
Hydrogen permeability through metals

Material conditions

<table>
<thead>
<tr>
<th>Material</th>
<th>Li</th>
<th>Pb-17 Li</th>
<th>Sn-Li (Sn)</th>
<th>Plibe</th>
</tr>
</thead>
<tbody>
<tr>
<td>F/M steel</td>
<td>550°C–900°C</td>
<td>450°C</td>
<td>400°C–500°C</td>
<td>700°C (304/316 stainless steel)</td>
</tr>
<tr>
<td>V alloy</td>
<td>~700°C</td>
<td>~650°C</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Nb alloy</td>
<td>&gt;1300°C</td>
<td>&gt;600°C (&gt;1000°C in Pb)</td>
<td>600°C–800°C</td>
<td>&gt;800°C</td>
</tr>
<tr>
<td>Ta alloy</td>
<td>&gt;1370°C</td>
<td>&gt;600°C (&gt;1000°C in Pb)</td>
<td>600°C–800°C</td>
<td>?</td>
</tr>
<tr>
<td>Mo</td>
<td>&gt;1370°C</td>
<td>&gt;600°C</td>
<td>&lt;800°C?</td>
<td>&gt;1100°C?</td>
</tr>
<tr>
<td>W</td>
<td>&gt;1370°C</td>
<td>&gt;600°C</td>
<td>~800°C</td>
<td>&gt;900°C?</td>
</tr>
<tr>
<td>SiC</td>
<td>~550°C?</td>
<td>&gt;800°C?</td>
<td>&gt;760°C?</td>
<td>?</td>
</tr>
</tbody>
</table>
Fig. A.5 Tritium Diffusivities in Tritium Breeding Materials

Fig. A.6 Tritium Solubilities in Tritium Breeding Materials

*) left scale for LiO, Li(l), Pb-17Li(l) and SS 316L, right scale for Fibre and Finak
Variations of HF concentration in a small contact time

\[ r_{BeF_2} \propto \sqrt{D_{Be}t} \]

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