Pyrochemical methods for fuel salt reprocessing

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Separation techniques in pyrochemistry

- Electrolytic formation of the metallic element on solid or liquid cathode
- Selective oxide precipitation
- Volatilization using electrolysis by action of an oxidizing agent: F₂ or Cl₂
- Volatilization by action of an oxidizing agent: F₂ or Cl₂
- Liquid-liquid extraction (Molten salt-liquid metal)

LIQUID 1 OR SOLUTE

SOLID

LIQUID 2 OR SOLUTE

GAS
# Separation techniques in pyrochemistry

<table>
<thead>
<tr>
<th>REAGENT STATE</th>
<th>USED EFFECT</th>
<th>METHODS</th>
<th>PRODUCT STATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOLUTE (in fluoride or chloride media) (M&lt;sup&gt;n+&lt;/sup&gt;)</td>
<td>A- REDOX (oxidation state modification)</td>
<td>A1- Action of an oxidizing agent F&lt;sub&gt;2&lt;/sub&gt;, Cl&lt;sub&gt;2&lt;/sub&gt;</td>
<td>GAS (MF&lt;sub&gt;x&lt;/sub&gt;)</td>
</tr>
<tr>
<td></td>
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<td>A2- Action of an oxidizing electrical current</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>A3- Action of a reducing agent e.g. Li</td>
<td>METAL (M) SOLID</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A4- Action of a reducing electrical current</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B- ACIDO-BASICITY (oxide precipitation solubilization)</td>
<td>B1- Action of oxide ions donors (e.g. Li&lt;sub&gt;2&lt;/sub&gt;O)</td>
<td>SOLID (MO&lt;sub&gt;x&lt;/sub&gt;)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B2- Action of gaseous mixtures H&lt;sub&gt;2&lt;/sub&gt;O/HF/H&lt;sub&gt;2&lt;/sub&gt;</td>
<td></td>
</tr>
</tbody>
</table>
• Thermodynamic approach / experimental studies

  – Oxoacidity concept (Lux (1939) and Flood (1947)) in molten salts equivalent to acidity in aqueous solution

  – $O^{2-}$ : abundant ion, high stability with metallic cations, redox system $O_2/O^{2-}$

    • $H_2O + F^- (Cl^-) \rightarrow 2HF (HCl) + O^{2-}$

Oxobase/oxoacid systems:

  oxobase = o xoacid + $O^{2-}$

Oxoacidity : $pO^{2-} = -\log a(O^{2-})$
Chemistry in molten salts

- **Calculation of $E - pO^{2-}$ diagrams (similar to $E-pH$ diagrams)**
  - Example: Ni stability diagram in NaCl molten salt

\[
\frac{1}{2} O_2 (g) + 2Cl^- = \frac{1}{2} Cl_2 (g) + O^{2-}
\]

A gaseous mixture of Cl$_2$ and O$_2$ control potential and acidity of the molten salt
Chemistry in molten salts

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\]

A gaseous mixture of Cl\(_2\) and O\(_2\) control potential and acidity of the molten salt.
• **Calculation of \( E - pO^{2-} \) diagrams**

  – Influence of activity coefficients

    – \( a(M) = x(M) \times \gamma(M) \)

    – \( \gamma(M) \) represents the affinity of an element for the solvent
      \( \gamma(M) = 1 : \) no affinity
      Affinity increases = \( \gamma(M) \) decreases

    = Increase of the stability range of the element
• Dissociation of the salts:
  
  – \((\text{Li, Na, K})(\text{F, Cl}) \rightarrow (\text{Li, Na, K})^+ + (\text{F, Cl})^-\)
  
  • **MX is a basic salt**

  – \((\text{Be, Mg, Ca, Ba, Th})(\text{F, Cl})_2 + x(\text{F, Cl})^- \rightarrow (\text{Be, Mg, Ca, Ba, Th})(\text{F, Cl})_{x+2}^{-x}\)
  
  • **MX}_2 is an acidic salt**

• In a molten salt constituted of MX and MX}_2, the amount of free X\(^-\) depends on the ratio of MX over MX}_2.

• The activity of solutes introduced in the molten salt depends on the acidity (fluoro- or chloroacidity) of the salt.
Thermodynamic diagrams
Comparison Fe in aqueous solution and in LiCl-KCl (1)

Pourbaix Atlas, 1963

Fig. 4. — Diagramme d'équilibres tension-pH du système fer-eau, à 25°C
(en ne considérant comme corps solides que Fe, Fe_2O_3 et Fe_3O_4).
Thermodynamic diagrams
Comparison Fe in aqueous solution and in LiCl-KCl (2)

pa(Li₂O) = - \log a(Li₂O)

Li₂O represents the amount of oxide ions dissolved in the salt
Thermodynamic diagrams
Comparison Fe in aqueous solution and in LiCl-KCl (2)

\[ \text{pa}(\text{Li}_2\text{O}) = -\log a(\text{Li}_2\text{O}) \]

\( \text{Li}_2\text{O} \) represents the amount of oxide ions dissolved in the salt
LiF – ThF$_4$ 650°C
Thermodynamic diagrams

LiCl-KCl 500°C

E (V) / Cl₂

Nd₂O₃

NdOCl

NdCl₂

NdCl₃

Nd

LiCl/Li

pa (Li₂O)
Thermodynamic diagrams

LiF – ThF$_4$ 650°C
LiF – ThF$_4$ 650°C

Thermodynamic diagrams
LiF – ThF$_4$ 650°C
Thermodynamic diagrams

LiF – ThF$_4$ 650°C
Thermodynamic diagrams

LiF – ThF$_4$ 650°C

The diagram shows the phase behavior of LiF-ThF$_4$ at 650°C, with various compounds such as PuOF, PuF$_3$, PuF$_4$, PuO$_2$, Pu$_2$O$_3$, Pu, and the pressure-activity diagram for Li$_2$O and F$_2$. The diagram illustrates the stability regions of these compounds under the specified conditions.
Thermodynamic diagrams

LiF – ThF$_4$ 650°C
Reprocessing of MSFR fuel

- Coeur
  \[ E = E^\circ_{\text{UF}_4/\text{UF}_3} + \frac{2.3RT}{F} \log \frac{[\text{UF}_4]}{[\text{UF}_3]} \]

- Fluoration
  \[ E = E^\circ_{\text{F}_2/F} + \frac{2.3RT}{F} \log \frac{p(\text{F}_2)}{a(F^-)} \]

- Extraction réductrice
  \[ E = E^\circ_{\text{LiF}/\text{Li}} + \frac{2.3RT}{F} \log \frac{a(\text{LiF})}{a(\text{Li})_{\text{Bi}}} \]
Thermodynamic diagrams

LiCl-KCl 500°C

E (V) / Cl₂

Nd₂O₃
NdOCl
NdCl₂
NdCl₃
Nd

LiCl/Li

pa (Li₂O)

0 5 10 15 20
Reprocessing of MSFR fuel

1. Step 1
   - Fluorination
   - (Extraction U, Np I, Tc, Te, Nb, Mo, Se,...)

2. Step 2
   - Step 2.A
     - Reductive extraction An (Bi-Li₁)
   - Step 2.C
     - Back extraction An in LiF-ThF₄

3. Step 3
   - Back extraction Ln in LiCl-LiF and precipitation Ln₂O₃

4. Step 4
   - Recovery of salt and metallic phases

5. Step 5
   - Redox potential control and U amount

6. Helium bubbling
   - Xe, Kr (+ brothers)
   - Noble metals

Wastes flow through the process and are marked accordingly.
Reprocessing of MSFR fuel fluorination

\[ E = E_{\text{UF}_4/\text{UF}_3}^\circ + 2.3RT/F \log \frac{[\text{UF}_4]}{[\text{UF}_3]} \]

\[ E = E_{\text{F}_2/F}^\circ + 2.3RT/F \log p(\text{F}_2)/a(F^-) \]

\[ E = E_{\text{LiF/Li}}^\circ + 2.3RT/F \log a(\text{LiF})/a(\text{Li})_{\text{Bi}} \]
Fluorination device

Gas are separated on NaF traps at different temperatures:
- 400°C adsorption of FP
- 25°C adsorption of U and Np

$$\text{UF}_4 + \text{F}_2(g) \rightarrow \text{UF}_6(g)$$
Reprocessing of MSFR fuel fluorination

\[ E = E^\circ_{UF4/UF3} + 2.3RT/F \log [UF4]/[UF3] \]

\[ E = E^\circ_{F2/F} + 2.3RT/F \log p(F_2)/a(F^-) \]

\[ E = E^\circ_{LiF/Li} + 2.3RT/F \log a(LiF)/a(Li)_{Bi} \]
The use of a liquid solvent metal decreases the activity coefficient of the metallic element and increases its stability range.
LiF – ThF$_4$ 650°C
LiF – ThF$_4$ 650°C
Liquid metal selection

- Liquid-liquid extraction or reductive extraction. This process is a molten salt process. The metal has to be liquid in the working temperature range.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Ga</th>
<th>In</th>
<th>Sn</th>
<th>Bi</th>
<th>Tl</th>
<th>Cd</th>
<th>Pb</th>
<th>Zn</th>
<th>Sb</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>p.f./°C</td>
<td>30</td>
<td>157</td>
<td>232</td>
<td>271</td>
<td>304</td>
<td>321</td>
<td>327</td>
<td>420</td>
<td>631</td>
<td>660</td>
</tr>
<tr>
<td>p.é./°C</td>
<td>2204</td>
<td>2072</td>
<td>2602</td>
<td>1564</td>
<td>1473</td>
<td>765</td>
<td>1749</td>
<td>907</td>
<td>1587</td>
<td>2519</td>
</tr>
<tr>
<td>σ (barn)</td>
<td>2.9</td>
<td>193.5</td>
<td>0.63</td>
<td>0.033</td>
<td>3.4</td>
<td>2450</td>
<td>0.17</td>
<td>1.1</td>
<td>5.4</td>
<td>0.230</td>
</tr>
</tbody>
</table>
Reductive extraction or liquid-liquid extraction

**Definition and analytical relations (1)**

### Liquid(MS)/liquid(LM) extraction

- **Using a reducing agent**

  \[ MX_z(MS) + zLi(LM) \rightarrow M(LM) + zLiX(MS) \]

- **Using electrical current**

  \[ MX_z(MS) + ze^- \rightarrow M(LM) + zX^- \]

### Equilibrium constant \(K_M\)

\[
K_M = \frac{a(Li)^z_{MS} a(M)_{LM}}{a(Li)^z_{LM} a(MX_z)_{MS}}
\]

### Gibbs enthalpy of the reaction

\[
\Delta G^\circ_M = zG^\circ(LiX) + G^\circ(M) - zG^\circ(Li) - G^\circ(MX_z)
\]

\[
\Delta G^\circ_M = -2.3RT \log K_M
\]

\[
\Delta G^\circ_{MX_z/M} = G^\circ(M) + z/2G^\circ(X_2) - G^\circ(MX_z)
\]

\[
E^\circ_{MX_z/M} = \frac{-\Delta G^\circ_{MX_z/M}}{zF} \text{ (with ref : } X_2(g) / X^- \text{)}
\]
Reductive extraction or liquid-liquid extraction
Definition and analytical relations (2)

• Distribution coefficient $D_M$

\[
\log D_M = \log \frac{x(M),LM}{x(MX_z),MS}
\]

(Knowing that $a(i) = x(i) \times \gamma(i)$
$a(i) = \text{activity}, x(i) = \text{mole fraction}$
$\gamma(i)$ is activity coefficient)

Using a reducing agent

\[
\log D_M = \left\{ \frac{zF}{2.3RT} \left[ E^{\circ}_{MX_z/M} - E \right] + \log \frac{\gamma_M,LM}{\gamma_M,LM} \right. + 
\left. \log \frac{\gamma_{Li,LM}}{\gamma_{Li,LM}} + \log \frac{\gamma_{MX_z,MS}}{\gamma_{LiX,MS}} \right. \}
\]

Using electrical current

\[
E = E^{\circ}_{LiX/Li} - \frac{2.3RT}{F} \left[ \log D_Li + \log \gamma_{Li,LM} \right]
\]
Influence of activity coefficients on the extraction process

\[ \log D_M = \log K_M + z \log D_{Li} + \log \frac{\gamma_{Li,LM}}{\gamma_{M,LM}} + \log \frac{\gamma_{MX_z,MS}}{\gamma_{LiX,MS}} \]

Calculated values with \( \gamma (i) = 1 \)

Experimental results

- Calculated values using experimental determinations of \( \gamma \) in solvent metal

- A = B = 0

- B = 0
Influence of activity coefficients on the extraction process

The activity coefficients depend on the molten salt nature: in some cases, such as LiF-BeF$_2$, its value is close to 1 because BeF$_2$ is one of the most acidic salt: then, the solutes are less solvated by fluoride and their activity coefficient is close to 1.

\[
\log D_M = \log K_M + z \log D_{Li} + \log \frac{\gamma_{Li,LM}^z}{\gamma_{M,LM}} + \log \frac{\gamma_{MX_z,MS}^z}{\gamma_{LiX,MS}}
\]

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• Selectivity $S(M_1/M_2)$

$$S(M_1 / M_2) = \frac{x(M_1), LM}{x(M_2), LM} \frac{x(M_1X_z), MS}{x(M_2X_{z'}), MS} = \frac{D_{M_1}}{D_{M_2}}$$

$$\log S(M_1 / M_2) = \log D_{M_1} - \log D_{M_2}$$

• If $z = z'$ (identical oxidation states for $M_1$ and $M_2$), selectivity is no dependent on $E$ or $D_{Li}$, then:

$$\log S(M_1 / M_2) = \log \frac{K_{M_1}}{K_{M_2}} * \gamma_{M_2} \gamma_{M_1}$$
• Efficiency $\mu_E(M)$

$$\mu_E(M) = \frac{n(M), SM}{n(M)_i}$$

$$n(M)_i = n(M), MS + n(M), LM$$

$$\mu_E(M) = \frac{1}{1 + \left[ \frac{1}{D_M} \cdot \frac{n_{MS}}{n_{LM}} \right]}$$
Influence of parameters on extraction process

- Influence of $n_{MS}$ and $n_{LM}$

If $D_M = 1$ \((\log D_M = 0)\) \(\frac{x(M), LM}{x(MX_z), MS} = 1\)

\[\mu_E(M) = \frac{1}{1 + \left[ \frac{1}{D_M} \times \frac{n_{MS}}{n_{LM}} \right]}\]

<table>
<thead>
<tr>
<th>$n_{MS}/n_{LM}$</th>
<th>1/10</th>
<th>1</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_E(M)$ (%)</td>
<td>90.9</td>
<td>50</td>
<td>9</td>
</tr>
</tbody>
</table>
Influence of Li % in liquid metal on extraction efficiency

MS = LiF-ThF$_4$ (77.5-22.5 mol%)  
LM = Bi - Li  
T = 873 K  
n(MS)/n(LM) = 1  

La, Ce, Sm, Gd, Dy, Er, Pa, U, Pu, Am
Influence of stages on extraction efficiency (1)

Example

- Molten Salt = Chloride media
  LiCl-KCl at 450°C
- Liquid metal = Gallium
- \( n_{MS} = n_{LM} \)
- \( E = -2.45\) V

<table>
<thead>
<tr>
<th></th>
<th>( \log D_M )</th>
<th>( \mu_E )</th>
<th>( n(M)_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ce</td>
<td>0.99108</td>
<td>0.90738</td>
<td>0.140</td>
</tr>
<tr>
<td>Nd</td>
<td>1.8699</td>
<td>0.98669</td>
<td>0.150</td>
</tr>
<tr>
<td>Gd</td>
<td>2.8709</td>
<td>0.99866</td>
<td>0.0025</td>
</tr>
</tbody>
</table>
### Influence of stages on extraction efficiency (2)

<table>
<thead>
<tr>
<th></th>
<th>1st stage</th>
<th>2nd stage</th>
<th>3rd stage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n(LM)</td>
<td>n(MS)</td>
<td>$\mu_{E,t}$ (%)</td>
</tr>
<tr>
<td>Ce</td>
<td>0.127</td>
<td>0.0129</td>
<td>90.7</td>
</tr>
<tr>
<td>Nd</td>
<td>0.148</td>
<td>1.9965.10^{-3}</td>
<td>98.67</td>
</tr>
<tr>
<td>Gd</td>
<td>0.00249</td>
<td>3.35.10^{-6}</td>
<td>99.86</td>
</tr>
</tbody>
</table>

- Moles extracted as a function of the stages number (nbs)

\[ n_{\text{ext}} = n_{\text{init}} \times \left\{ 1 - \left[ 1 - \mu(M) \right]^{\text{nbs}} \right\} \]

- Moles not extracted as a function of the stages number (nbs)

\[ n_{\text{Next}} = n_{\text{init}} \times \left[ 1 - \mu(M) \right]^{\text{nbs}} \]
• Extraction processes can be studied using both thermodynamic data (redox potentials) and activity coefficients.

• The activity coefficient knowledge (in liquid metal and also in molten salt) is essential for this approach.

• Lack of data: Am, Cm, Zr, Te, Se, I...
Experimental determination of activity coefficients in liquid metals

- Principle of determination by potentiostatic method (in chloride or fluoride media)

\[
E_1 = E^\circ_{\text{M}^{n+}/\text{M}} + \frac{2.3RT}{nF} \log \frac{a(\text{MCl}_3)_{\text{salt}}}{a(\text{M})(\text{M})}
\]

\[
E_2 = E^\circ_{\text{M}^{n+}/\text{M}} + \frac{2.3RT}{nF} \log \frac{a(\text{MCl}_3)_{\text{salt}}}{a(\text{M})(\text{metal})}
\]

\[
\Delta E = E_1 - E_2 = \frac{2.3RT}{nF} \log \frac{a(\text{M})(\text{metal})}{a(\text{M})(\text{M})} = \frac{2.3RT}{nF} \log a(\text{M})(\text{metal})
\]

\[
\Delta E = \frac{2.3RT}{nF} \log x(\text{M})(\text{metal}) + \frac{2.3RT}{nF} \log \gamma(\text{M})(\text{metal})
\]

with \(a(\text{M}) = x(\text{M}) \times \gamma(\text{M})\) and \(a(\text{M})(\text{M}) = 1\).
**Principle of experimental determination of activity coefficient in liquid metal**

- Determination of potential of pure M
- Liquid metal potential measurement after introduction of various amounts of M in the liquid metal by coulometry at applied potential

\[
\begin{align*}
\Delta E_1 & \quad \Delta E_2 \\
\Delta E_3 & \\
\log X_{1M} & \\
\log X_{2M} & \\
\log X_{3M} & \\
\log \gamma & \\
\end{align*}
\]

\[
Q = znF \quad \log x_M
\]

\[
\text{slope} = \frac{-zF}{2.3RT}
\]
Voltammogram obtained at 100mV/s on a tungsten working electrode in a molten salt containing 2wt% of GdCl$_3$ in NaCl-CaCl$_2$ at 560°C
Experimental determination of activity coefficient: example Gd in Ga

- Cyclic voltammogram realized at 10mV/s on liquid gallium electrode (S = 1.3 cm²) in NaCl-CaCl₂ molten salt at 530 °C containing 2wt% of GdCl₃.
Experimental determination of activity coefficient: example Gd in Ga

- Open circuit potential measured as a function of time on a liquid gallium electrode after introducing of gadolinium by electrolysis at applied potential (E=-1.65V/Ref)
Variation of $\Delta E$ calculated as a function of the logarithm of the mole fraction of gadolinium contained in liquid gallium at 530°C

$$\log \gamma(\text{Gd/Ga}) = -10.17$$
Variation of \( \log \gamma(\text{Gd/Ga}) \) vs \( 1/T \) for various Gd mole fraction in liquid gallium

\[
\log \gamma(\text{Gd/Ga}) = 2.397 - \frac{10009}{T}
\]
Experimental determination of activity coefficients in molten salts

- Potential measurements of redox systems $\text{MCl}_x / \text{M}$

\[
E(\text{MCl}_n / \text{M}) = E^\circ(\text{MCl}_n / \text{M}) + \frac{2.3RT}{nF} \log a(\text{MCl}_n)
\]

\[
E(\text{MCl}_n / \text{M}) = E^\circ(\text{MCl}_n / \text{M}) + \frac{2.3RT}{nF} (\log x(\text{MCl}_n) + \log \gamma(\text{MCl}_n))
\]

- Experimental measurement
- Potential calculated from thermochemical data
- Experimental conditions
- Activity coefficient
- Function of $T$
- Function of electrolyte nature
Experimental determination of activity coefficients in molten salts

E_{\text{exp}}(\text{Th(IV)}/\text{Th}) = -2.92 \text{ V/Cl}_2 = -2.855 -0.065 \text{ (overpotential observed on W electrode)}

E^{\circ}_{\text{thermo}}(\text{Th(IV)}/\text{Th}) = -2.48 \text{ V/Cl}_2

\log \gamma(\text{Th(IV)}) = -7.35

\gamma_{++}^{\circ} = 0.0037

\Delta G^{\circ} = 957,226 \text{ J}

T = 500^\circ\text{C}
Measurement of oxide amount
yttria-stabilized zirconia membrane electrode (YSZME)

«Zirconia electrode»

tight seal
(CAF4)

Ag wire

ZrO₂-Y₂O₃

eutectic LiCl-KCl
+O²⁻→Ag⁺
Measurement of oxide amount

Calibration of «Zirconia electrode»

- $K = 10^{-10.33}$ in LiCl-KCl at 450°C
- gas composition
  - $p(\text{HCl}) = 1$ atm
  - $p(\text{H}_2\text{O}) = 10^{-2}$ atm
- during HCl bubbling:
  - $[O^2-] = 10^{-12.33}$ mol/kg

$$HCl(g) + O^2- \rightarrow H_2O(g) + 2Cl^-$$

$$LiCO_3 \rightarrow Li^+ + O^2- + CO_2(g)$$

$$K = \frac{a(O^2-)p(\text{HCl})^2}{p(\text{H}_2\text{O})}$$
Measurement of oxide amount
Calibration of «Zirconia electrode»

$E_{\text{zirconia}} = 0.038 + 0.071 \cdot pO^{2-}$
($R = 0.99918$)
(Theoretical slope = 0.07168)
Measurement of oxide amount
Titration – determination of solubility constant

\[ \text{Ce}^{3+} + \text{O}^{2-} + \text{Cl}^- \rightarrow \text{CeOCl} \]
\[ C_0 = [\text{Ce}^{3+}] + n(\text{CeOCl})/m \]
\[ \alpha C_0 = [\text{O}^{2-}] + n(\text{CeOCl})/m \]
\[ K_{s(\text{Ce})} = [\text{Ce}^{3+}][\text{O}^{2-}] \]

\[ \alpha = 1 + [\text{O}^{2-}]/C_0 - K_{s(\text{Ce})}/[\text{O}^{2-}]/C_0 \]
\[ pK_{s(\text{Ce})} = 8.7 \]

\[ 2\text{Y}^{3+} + 3\text{O}^{2-} \rightarrow \text{Y}_2\text{O}_3 \]
\[ C_0 = [\text{Y}^{3+}] + 2n(\text{Y}_2\text{O}_3)/m \]
\[ \alpha C_0 = [\text{O}^{2-}] + 3n(\text{Y}_2\text{O}_3)/m \]
\[ K_{s(\text{Y})} = [\text{Y}^{3+}]^2[\text{O}^{2-}]^3 \]

\[ \alpha = 3/2 + [\text{O}^{2-}]/C_0 - 3/2/C_0 (K_{s(\text{Y})}/[\text{O}^{2-}])^{1/2} \]
\[ pK_{s(\text{Y})} = 22.8 \]
1- Reduction on solid cathode:
92% d’U, 0.5% Pu and traces of FP

2- Reduction on liquid cathode:
50% U, 50% Pu, Am and traces of FP

Example: electrorefining of IFR
(Integrated Fast Reactor) fuel in USA (Argonne)
Conclusion

• Thermodynamic approach necessary to propose a reprocessing scheme

• This approach is used both in chloride and fluoride media

Experimental studies:

• Determination of parameters in given molten salts

• Experimental tests to estimate the extraction kinetic and validate the reprocessing
Experimental set-up
Experimental set-up
Experimental set-up

LiF-ThF₄-UF₄