SNETP- ESNII
Generation IV reactors, related fuel cycle and disposal issues

M. Sepielli
SNETP Governing Board
IGDTP-SNETP IEG

Kalmar (Sweden), October 27-30, 2014
- Optimum use of natural resources
- Nuclear waste minimization
- Minimum impact on the environment
- Safety / Economics / Non proliferation
Gen IV System Concepts

GEN IV Reactor Concepts

<table>
<thead>
<tr>
<th>Reactor concept</th>
<th>GFR</th>
<th>LFR</th>
<th>MSR</th>
<th>SFR</th>
<th>SCWR</th>
<th>VHTR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co coolant</td>
<td>Helium</td>
<td>Pb or Pb-Bi</td>
<td>Molten salt</td>
<td>Sodium</td>
<td>Supercritical water</td>
<td>Helium</td>
</tr>
<tr>
<td>Spectrum (F/In, T-Thermal)</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>Thermal efficiency (%)</td>
<td>40</td>
<td>44-50</td>
<td>42</td>
<td>44</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Thermal power (MW)</td>
<td>~2400</td>
<td>125-3500</td>
<td>~2000</td>
<td>1500-4000</td>
<td>~3500</td>
<td>400-600</td>
</tr>
<tr>
<td>Power density (MW/m²)</td>
<td>30-100</td>
<td>10-150</td>
<td>22</td>
<td>150-300</td>
<td>100</td>
<td>5-10</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>70</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Temperature core inlet outlet (°C)</td>
<td>400/560</td>
<td>400/560</td>
<td>195/300</td>
<td>400/350</td>
<td>250/310</td>
<td>640/1000</td>
</tr>
<tr>
<td>Fuel</td>
<td>Carbide or nitride</td>
<td>Nitride, (metallic)</td>
<td>Molten salt (fluorides)</td>
<td>Oxide, carbide, (metallic)</td>
<td>Oxide (UO₂, MOX)</td>
<td>Oxide or oil-carbide</td>
</tr>
<tr>
<td>Fuel burnup (at%)</td>
<td>5-10</td>
<td>10-15</td>
<td>15-20</td>
<td>5</td>
<td>&gt; 10</td>
<td></td>
</tr>
<tr>
<td>Fuel cycle</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Open</td>
</tr>
</tbody>
</table>

GIF roadmap 2013

- VHTR
- SFR
- SCWR
- MSR
- LFR
- GFR

Viability □ Performance □ Demonstration
Fuel System Options in GEN IV Fast Reactors

| Table 1 Priority table. Items indicated in red are priority for the different fuel types. |
|---------------------------------|----------------------------------------|----------------------------------------|
| | UPuO\textsubscript{x} | UPuC | UPuN |
| **GFR** | | | |
| 100W/cm | Priority : 3 | Priority : 1 | Priority : 2 |
| Tclad 800°C | SiC+liner | SiC+liner | SiC+liner |
| Tfuel 1100°C | 0 - 2 - 5 % Am | 0 - 2 - 5 % Am | 0 - 2 - 5 % Am |
| Pu: 15-20% | >95%dth | >95%dth vs open/closed porosity | 80-85%dth |
| | | 5% < M2C3 < 15% | N/M: 1.0 and > 1.0 |
| **LFR** | | | |
| ~400W/cm | Priority : 1 | Priority : 2 | |
| Tclad ~500°C | 0 - 2 - 5 % Am | T91 316 Ti | |
| Tfuel °C | >95%dth | 0 - 2 - 5 % Am | 80-85%dth |
| T91 | O/M 1.96 – 1.98 – 2.00 | O/M 1.96 – 1.98 – 2.00 | |
| **SFR** | | | |
| 500W/cm | Priority : 1 | Priority : 2 | Priority : 3 |
| Tclad 620°C | ODS - 15/15 | ODS - 15/15 | |
| Tfuel 2400°C (O) and 1400°C (C) | 0 - 2 - 5 % Am | 0 - 2 - 5 % Am | 0 - 2 - 5 % Am |
| Pu: 15-20% | >95%dth | >95%dth | 80-85%dth |
| | O/M 1.90 – 1.95 – 1.98 | O/M 1.90 – 1.95 – 1.98 | O/M 1.90 – 1.95 – 1.98 |
## GEN IV Fuel Characteristics

<table>
<thead>
<tr>
<th>Reactor concept</th>
<th>GFR</th>
<th>SFR</th>
<th>LFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power density (MWth/m³ of fuel element)</td>
<td>200</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>Linear power (W/cm)</td>
<td>C/N : 100</td>
<td>O: 500</td>
<td>idem</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C : 500-800</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>M: 500</td>
<td></td>
</tr>
<tr>
<td>Burn up (at%) And dose</td>
<td>5-10</td>
<td>15-20</td>
<td>10-15</td>
</tr>
<tr>
<td></td>
<td>40-80 dpaSiC</td>
<td>200 dpa</td>
<td>175 dpa</td>
</tr>
<tr>
<td>Pin geometry:</td>
<td></td>
<td></td>
<td>idem</td>
</tr>
<tr>
<td>- Φ pellet</td>
<td>4.32</td>
<td>9.5 (2mm Φ hole)</td>
<td></td>
</tr>
<tr>
<td>- Φ int. clad</td>
<td>4.95</td>
<td>9.73</td>
<td></td>
</tr>
<tr>
<td>- Φ ext. clad</td>
<td>6.55</td>
<td>10.73</td>
<td></td>
</tr>
<tr>
<td>Temperature clad in/out at PPN (°C)</td>
<td>850/800</td>
<td>537/500</td>
<td></td>
</tr>
<tr>
<td>Max. temp.</td>
<td>1000</td>
<td>620</td>
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<tr>
<td>Fuel</td>
<td>Carbide or nitride</td>
<td>Oxide, carbide, or metallic</td>
<td>Nitride (or metallic)</td>
</tr>
<tr>
<td>Fuel temp (°C)</td>
<td>C/N: 1100</td>
<td>O: 2400</td>
<td>idem</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C: 1400</td>
<td></td>
</tr>
</tbody>
</table>

Melting temp. UPuO₂: 2740° C, UPuN : 2720° C (dissoc. ~1800° C), UPuC : 2325° C.
## GEN IV Reactor Concepts

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<td>Sodium</td>
<td>Supercritical water</td>
<td>Helium</td>
</tr>
<tr>
<td>Spectrum ((F_{fast}, T_{thermal}))</td>
<td>(F)</td>
<td>(F)</td>
<td>(T)</td>
<td>(F)</td>
<td>(T/F)</td>
<td>(T)</td>
</tr>
<tr>
<td>Thermal efficiency (%)</td>
<td>48</td>
<td>44-50</td>
<td>42</td>
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<td>1500-4000</td>
<td>~3800</td>
<td>400-600</td>
</tr>
<tr>
<td>Power density (MWth/m³)</td>
<td>50 - 100</td>
<td>10 - 150</td>
<td>22</td>
<td>200-300</td>
<td>100</td>
<td>6 - 10</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>70</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Temperature core inlet/outlet (°C)</td>
<td>490 / 850</td>
<td>400/ 550</td>
<td>565 / 700</td>
<td>400 / 550</td>
<td>280 / 510</td>
<td>640 / 1000</td>
</tr>
<tr>
<td>Fuel</td>
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</tr>
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<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Open</td>
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## GEN IV Fuel & Structural Materials

<table>
<thead>
<tr>
<th>System</th>
<th>Fuel Materials</th>
<th>Structural Materials</th>
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<tbody>
<tr>
<td></td>
<td>Oxide</td>
<td>Metal</td>
</tr>
<tr>
<td>GFR</td>
<td>S</td>
<td>P</td>
</tr>
<tr>
<td>MSR</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>SFR</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td>LFR</td>
<td>S</td>
<td>P</td>
</tr>
<tr>
<td>SCWR-Thermal</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>SCWR-Fast</td>
<td>P</td>
<td>S</td>
</tr>
<tr>
<td>VHTR</td>
<td>P</td>
<td></td>
</tr>
</tbody>
</table>

P: Primary Option
S: Secondary Option
## GEN IV Fuel & Structural Materials

<table>
<thead>
<tr>
<th>System</th>
<th>Spectrum, $T_{\text{outlet}}$</th>
<th>Fuel</th>
<th>Cladding</th>
<th>In-core</th>
<th>Out-of-core</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFR</td>
<td>Fast, 850°C</td>
<td>MC/SiC</td>
<td>Ceramic</td>
<td>Refractory metals and alloys, Ceramics, ODS Vessel: F-M</td>
<td>Primary Circuit: Ni-based superalloys 32Ni-25Cr-20 Fe-12.5W-0.05C Ni-23Cr-18W-0.2 CF-M w/ thermal barriers Turbine: Ni-based alloys or ODS</td>
</tr>
<tr>
<td>LFR</td>
<td>Fast, 550°C and 800°C</td>
<td>MN</td>
<td>High-Si Fe-M,</td>
<td>High-Si austenitics, ceramics, or refractory alloys</td>
<td></td>
</tr>
<tr>
<td>MSR</td>
<td>Thermal, 700–800°C</td>
<td>Salt</td>
<td>Not Applicable</td>
<td>Ceramics, refractory metals, High-Mo Ni-base alloys (e.g., INOR-8), Graphite, Hastelloy N</td>
<td>High-Mo Ni-base alloys (e.g., INOR-8)</td>
</tr>
<tr>
<td>SFR (MOX)</td>
<td>Fast, 550°C</td>
<td>MOX</td>
<td>ODS</td>
<td>F-M ducts 316SS grid plate</td>
<td>Ferritics, austenitics</td>
</tr>
<tr>
<td>SFR (MOX)</td>
<td>Fast, 550°C</td>
<td>MOX</td>
<td>ODS</td>
<td>F-M ducts 316SS grid plate</td>
<td>Ferritics, austenitics</td>
</tr>
<tr>
<td>SCWR</td>
<td>Thermal, 550°C</td>
<td>MOX</td>
<td>Dispersion</td>
<td>Same as cladding options</td>
<td>F-M</td>
</tr>
<tr>
<td>SCWR</td>
<td>Fast, 550°C</td>
<td>MOX</td>
<td>Dispersion</td>
<td>Same as cladding options</td>
<td>F-M</td>
</tr>
<tr>
<td>VHTR</td>
<td>Thermal, 1000°C</td>
<td>TRISO</td>
<td>ZrC coating and surrounding graphite</td>
<td>Graphites PyC, SiC, ZrC Vessel: F-M</td>
<td>Primary Circuit: Ni-based superalloys 32Ni-25Cr-20Fe-12.5 W-0.05CNi-23Cr-18 W-0.2CF-M w/ thermal barriers Turbine: Ni-based alloys or ODS</td>
</tr>
</tbody>
</table>

**Abbreviations:**
- F-M: Ferritic-martensitic stainless steels (typically 9 to 12 wt% Cr)
- ODS: Oxide dispersion-strengthened steels (typically ferritic-martensitic)
- MN: (U,Pu)
- NMC: (U,Pu)C
- MOX: rU PuOx
Fast reactors and closed loop fuel cycle

FROM SNE- TP

TO IGD-TP
Radiotoxicity drop with Gen IV

- **III gen reactor**
  - Exhaust fuel
  - Long lived waste
- **IV gen reactor**
  - Fission products
  - Short-lived radwaste
  - Natural uranium
  - Surface repository
  - Artificial barriers
- **U Pu AM**
- **Fast reactor**
- **Geological repository**
  - Long lived residuals
  - Natural barriers
- **Surface repository**
  - Artificial barriers
  - surface repository
- **U nat U depl**
- **U Pu AM**

**Key Points**:
- **Radiotoxicity drop with Gen IV**
- **Fast reactor**
  - IV gen
  - Short-lived radwaste
  - Long-lived residuals
- **Geological repository**
  - Long lived waste
  - Natural barriers
  - Or ADS?
- **Surface repository**
  - Artificial barriers
- **U Pu AM**

**Time Frames**:
- ~430 years
- ~340,000 years
Single component radiotoxicity decay
Reprocessing schemes and resulting waste

Scheme 3a
“TRU burning in FR”
Based on Integral Fast Reactor concept.
Avoids any separation of pure plutonium.

Scheme 3b
“Double strata fuel cycle”
Burns all plutonium in conventional LWRs and fast reactors.

Scheme 3bV (variant)
Circumvents the FR stage by transferring the plutonium from the PWR-MOX stage directly to the ADS fuel cycle.

Scheme 3cV1
“All-FR strategy”
Based on Gen-IV gas-cooled fast reactor.

Scheme 3cV2 (variant)
Based on EFR using MOX fuel reprocessed by UREX+. Uranium is not recycled.
The main reprocessing methods presently used:

• Co-extraction

• New extraction

• Uranium extraction (UREX)

• Electrochemical processing
Treatment of spent fuel

- **Spent Fuel**
  - **Hydro**
    - Fuel dissolution
    - PUREX
    - DIAMEX
    - SANEX
    - Innovative SANEX
    - 1 Cycle SANEX
  - Advanced Partitioning Strategies
  - Fuel Refabrication Studies
  - SNE-TP
  - Process Integration

- **Pyro**
  - Fuel dissolution
  - GANEX 1st Cycle
  - GANEX 2nd Cycle
  - ELECTRO REFINING
  - ALTERNATIVE ELECTROCHEMICAL PROCESSES
  - REDUCTIVE EXTRACTION
  - Waste Management
  - Other European Projects

Assessment of reprocessing flowsheets for different fuel cycle scenarios with a view to their future demonstration at the pilot level.
Block diagram of the pyrochemical process for metal fuel

1. Spent Fuel
   - Disassembly and Chopping
     - Duct
     - Clad, NM
2. Electrorefining
   - Gas waste, (T, Xe, Kr)
   - Spent Salt
   - TRU
   - Salt, Cd
3. Cathode Processing
   - U - salt
   - U - TRU - Cd - salt
4. Pin Casting
   - Zr
5. New Fuel
6. Melting
7. TRU Extraction
8. Crucible
9. Consolidation
10. Immobilization
11. Metal Waste
12. Salt Waste (Cs, Sr, RE)

TRU: Pu, Np, Am, Cm
RE: Rare Earth
NM: Noble Metal
Schematic illustration of the pyrochemical process for oxide fuel
Electrorefining of metal fuel

MA: Minor Actinides
AM: Alkaline Metals

RE: Rare Earths
AEM: Alkaline Earth Metals

NM: Noble Metals
Electrorefining of nitride fuel
Electroreduction of oxide fuel (USA, Japan, Korea) (anode made of platinum wire (left) or graphite (right))
<table>
<thead>
<tr>
<th>Properties</th>
<th>UPO₂</th>
<th>UPC</th>
<th>UPN</th>
</tr>
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<tbody>
<tr>
<td>Density, g/cm³</td>
<td>11.0</td>
<td>13.6</td>
<td>14.3</td>
</tr>
<tr>
<td>HM Density, g/cm³</td>
<td>9.7</td>
<td>12.9</td>
<td>13.5</td>
</tr>
<tr>
<td>( T_{\text{melt}} ) °C</td>
<td>2775</td>
<td>2480</td>
<td>2780</td>
</tr>
<tr>
<td>Thermal conductivity, W/mK</td>
<td>2.9</td>
<td>19.6</td>
<td>19.8</td>
</tr>
<tr>
<td>PUREX compatible</td>
<td>Yes</td>
<td>No</td>
<td>yes</td>
</tr>
</tbody>
</table>
Electroreduction of oxide fuel
(Russian method)
Conditioning of chloride salt wastes from pyroprocesses with different matrices

- SODALITE
- SAP
- MURATAITE-PYROCHLORE
Outline of sodalite synthesis from kaolinite through nepheline
SODALITE matrix

Kaolinite + NaOH

Synthesis of nepheline

Nepheline

700°C

700°C
SODALITE matrix

Mixing and grinding of nepheline with LiCl-KCl
SODALITE matrix

Components used for labo. scale Pressureless Consolidation experiments

![Components](image)

- **Alumina crucible**
- **Internal vessel**
- **Steel rod, ab. 280 g**

*Mix of nepheline, salt waste and glass frit between alumina crucible and internal vessel*
SAP matrix

Transparent hydrogels

Products obtained after each of the three main steps for preparation of SAP matrix
SODALITE matrix

Assembly of the components

Final consolidation product

Φ 32.9 mm

Assembly of the components for thermal treatment at 925°C for 7 hours
SAP matrix

Sources of Si – Al – P

TEOS, Tetraethyl orthosilicate or tetraethoxysilane, Si(OC\(_2\)H\(_5\))\(_4\)

Aluminum (III) chloride, AlCl\(_3\)

Phosphoric Acid, H\(_3\)PO\(_4\)
Outline of SAP synthesis by a conventional sol-gel process
Octahedral framework in the structure of Mu-5: arrangement of pyrochlore clusters formed by corner sharing of TiO6 and Ti4O6 octahedra (a); linkage of pyrochlore clusters by Ti3O6 octahedra (b); whole framework as combination of linked pyrochlore clusters and murataite-like framework formed by Ti2O6 and Ti5O6 octahedra ©; murataite-like framework (d)
Evaluation of long-term behaviour of conditioned salt wastes

- Static leaching tests up to 150 days

- Assessment of the main parameters which influence fission products release (pH, temperature, contact time)

- Determination of the interactions between host matrix and individual fission elements
Issues from SNETP - SRIA in fuel reprocessing

- Advanced reprocessing for MA separation, using hydro and pyro-metallurgical processes (UE Projects ACSEPT -> SACSESS)
- Conversion process from separation to re-fabrication
- Synthesys of new fuel and performance assessment in reprocessing
- Irradiation behaviour of MA-bearing MOX and carbide fuels, dedicated PIE programmes
- Industrial implementation of P&T&RF laboratories
General SRIA issues from new waste to geological disposal

- Increasing fuel burn-up, most of TRU / MA
- Reducing FP as much as possible
- Reducing of Pu towards non proliferation
- Improve stability of chemical and physical form
- GD with more relaxed requirements in terms of volumes and masses, easy conditioning and storage, safety and economics
- Locating in depth