Generation IV Fast Reactors

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The Generation IV international research programme on advanced reactors

The case for fast reactors

The technology:
- Sodium cooled (SFR)
- Lead cooled (LFR)
- Gas cooled (GFR)
- Molten Salt Fast Reactor (MSFR)

Conclusions
What is Generation IV

An international R&D programme to develop the most promising six systems for the next generation of nuclear power plants

- Generation I: Early Prototype Reactors
  - Shippingport
  - Dresden, Fermi I
  - Magnox

- Generation II: Commercial Power Reactors
  - LWR-PWR, BWR
  - CANDU
  - AGR

- Generation III: Advanced LWRs
  - ABWR
  - System 80+

- Generation III+ Evolutionary Designs Offering Improved Economics for Near-Term Deployment
  - Highly Economical
  - Enhanced Safety
  - Minimal Waste
  - Proliferation Resistant

- Generation IV
Generation IV – Proposed systems

3 Fast Reactors
- Sodium Cooled Fast Reactor (SFR)
- Lead Cooled Fast Reactor (LFR)
- Gas Cooled Fast Reactor (GFR)

3 other systems (thermal, epithermal)
- Molten Salt Reactor (MSR) (Epithermal)
- Supercritical Water Reactor (SCWR) (Thermal or possibly fast)
- Very High Temperature Reactor (VHTR) (Thermal)

Concepts for fast reactor versions of the MSR and SCWR now exist
The Case for Fast Reactors
What is a fast reactor?

A fast reactor makes use of fission induced by fast neutrons (E > 0.1MeV).

Characterised by having a compact core (no moderator) and a high power density (~400MW/m³ compared with ~5MW/m³ for thermal reactors).
Why build fast reactors?

Only 0.72% of natural uranium is fissile. For nuclear power to be sustainable it is essential we make better use of the natural resource.

- 0.72% uranium-235
- 0.0055% uranium-234
- 99.2745% uranium-238

Breeding of plutonium from uranium-238 in fast reactors allows considerably more of the natural uranium to be used.

Both breeding and the utilisation of plutonium are more efficient in fast fission systems.

Long lived minor actinides that occur in nuclear waste (americium, neptunium and curium) can be burned.

- Reduces radiotoxicity of wastes
- Significantly reduces waste storage times (to about 300 years instead of 300,000 years)
Plutonium Breeding Reaction

Starts with neutron capture in uranium-238

\[ ^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U \]

Uranium-239 has a half-life of 23 minutes and decays to neptunium-239 by beta decay

\[ ^{239}_{92}U \rightarrow ^{239}_{93}Np + \beta^- + \bar{\nu} \]

Neptunium-239 has a half life of 2.3 days and decays to plutonium 239 by a further beta decay

\[ ^{239}_{93}Np \rightarrow ^{239}_{94}Pu + \beta^- + \bar{\nu} \]
Forcast demand for natural uranium and reserves

Source:
A technology Roadmap for Generation IV Nuclear Energy Systems, USDOE, 2002
Plutonium breeding in thermal reactors

All reactors that contain uranium-238 will breed plutonium:

- Fast reactors are better at it than thermal reactors
- The measure of how good a reactor is at breeding is the “conversion ratio” (or exactly the same thing – the breeding ratio), $C$

$C = \text{number of fissile items created} / \text{number of fissile atoms consumed}$

For thermal reactors $C < 1$. For fast reactors $C \geq 1$ (but can be $< 1$ if we wish)

If we start with $N$ fissile atoms, after irradiation in a reactor core we end up with $C \cdot N$ fissile atoms. After many recycles we get the total number of fissile atoms available to be:

$N_T = N + CN + C^2N + C^3N + C^4N + \ldots$

For $C < 1$, $N_T = N / (1 - C)$, so for a LWR $C \sim 0.3 \rightarrow 0.5$, so $N_T = 1.4 \times N \rightarrow 2 \times N$

Conclusion – large-scale MOX recycle in LWRs allows nuclear fission power to be maintained for a short time after the exhaustion of natural uranium but precludes the future use of fast reactors
Plutonium breeding in fast reactors

Using fast reactors we increase the amount of fissile material available by a factor of 100 (not just by a factor of $1.4 \rightarrow 2$ if we only recycle Pu as MOX in LWRs)

Because:

$$N_T = N + CN + C^2N + C^3N + C^4N + \ldots \rightarrow \infty \text{ for } C \geq 1$$

In reality we are limited by the amount of uranium-238 that have …

But we still have enough fuel to last about 4000 years!
Global energy reserves – no fast reactors

FOSSILE FUELS POTENTIAL RESERVES

- **Uranium** 40 Gtoe
- **Gas** 150 Gtoe
- **Oil** 165 Gtoe
- **Coal** 400 Gtoe

Uranium use in thermal neutrons reactors

Identified conventionnal resources, Gtoe

(\textit{mémento sur l'énergie}, CEA, 2010)
(Pétrole 165 Gt, charbon 826 Gt, gaz 180 Tm$^3$, uranium 3,3 Mt)
Global energy reserves – no fast reactors

**FOSSILE FUELS POTENTIAL RESERVES**

- **Uranium use**
  - in thermal neutrons reactors
  - 40 Gtoe
  - GAS: 150 Gtoe
  - Coal: 400 Gtoe
  - Oil: 165 Gtoe

- **Uranium use**
  - in fast neutrons reactors
  - 4000 Gtoe

**Identified conventional resources, Gtoe**

(mémento sur l’énergie, CEA, 2010)
(Pétrole 165 Gt, charbon 826 Gt, gaz 180 Tm³, uranium 3.3 Mt)
The bonus – the ability to transmute: minor actinide burning to reduce the radiotoxicity of waste
A closed fuel cycle is a necessity for a fast reactor fleet.

Reprocessing and fuel re-fabrication facilities are central parts of a fast reactor-driven nuclear park.
The Technology
Sodium-cooled fast reactor (SFR)

<table>
<thead>
<tr>
<th>Reactor Parameters</th>
<th>Reference Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outlet Temperature</td>
<td>530-550 °C</td>
</tr>
<tr>
<td>Pressure</td>
<td>~1 Atmospheres</td>
</tr>
<tr>
<td>Rating</td>
<td>1000-5000 MWth</td>
</tr>
<tr>
<td>Fuel</td>
<td>Oxide or metal alloy</td>
</tr>
<tr>
<td>Cladding</td>
<td>Ferritic or ODS ferritic</td>
</tr>
<tr>
<td>Average Burnup</td>
<td>~150-200 GWD/MTHM</td>
</tr>
<tr>
<td>Conversion Ratio</td>
<td>0.5-1.30</td>
</tr>
<tr>
<td>Average Power Density</td>
<td>350 MWth/m³</td>
</tr>
</tbody>
</table>
UK fast reactors


Both now shut down and partially decommissioned.
French fast reactors

Rapsodie (at Cadarache) – Pu/U238 mixed oxide fuel, sodium-cooled, 24MWth (later 40MWth), (1966-1983)
Phenix (at Marcoule) – Pu/U238 mixed oxide fuel, sodium-cooled, 560MWth, (1973 - )


The need for a fast reactors to provide security of supply and management of plutonium and minor actinides is now enacted in French law.

• The ASTRID programme aims to deploy a Gen IV SFR demonstrator in the early 2020’s for commercialisation by 2040.
Sodium-Cooled Fast Reactors in other Countries

USA – EBR I, Enrico Fermi, EBR II, Clinch River, FFTF

Russian Federation – BR5, BOR 60, BN 350, BN600

Japan – Joyo, Monju

W. Germany – KNK II, SNR-300 (built but never operated)
Superphenix
Superphenix fuel element
Superphenix core
Problems with the liquid sodium coolant

Reactors violently with water, need the intermediate heat exchange loop to prevent reaction with primary coolant.

High void worth – leads to large reactivity insertion if gas or vapour bubbles form in the coolant, or if the coolant is lost.

It is not possible to operate at higher temperatures because of sodium boiling.
Fast reactors – the future beyond SFR

The Generation IV programme has identified 3 fast reactor systems for further development:

- SFR - Sodium-cooled fast reactor
- LFR - Lead-cooled fast reactor
- GFR - Gas-cooled fast reactor
- + the molten salt fast reactor (MSFR)

Minor actinide destruction and plutonium management – sustainability and proliferation benefits.
Lead-cooled fast reactor (LFR)
# Proposed LFR Operating Parameters

<table>
<thead>
<tr>
<th>Reactor Parameters</th>
<th>Reference Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pb-Bi Battery (nearer-term)</td>
</tr>
<tr>
<td>Coolant</td>
<td>Pb-Bi</td>
</tr>
<tr>
<td>Outlet Temperature (°C)</td>
<td>~550</td>
</tr>
<tr>
<td>Pressure (Atmospheres)</td>
<td>1</td>
</tr>
<tr>
<td>Rating (MWth)</td>
<td>125–400</td>
</tr>
<tr>
<td>Fuel</td>
<td>Metal Alloy or Nitride</td>
</tr>
<tr>
<td>Cladding</td>
<td>Ferritic</td>
</tr>
<tr>
<td>Average Burnup (GWD/MTHM)</td>
<td>~100</td>
</tr>
<tr>
<td>Conversion Ratio</td>
<td>1.0</td>
</tr>
<tr>
<td>Lattice</td>
<td>Open</td>
</tr>
<tr>
<td>Primary Flow</td>
<td>Natural</td>
</tr>
<tr>
<td>Pin Linear Heat Rate</td>
<td>Derated</td>
</tr>
</tbody>
</table>
Lead Cooled Fast Reactor Concepts

GIF LFR reference concepts

SSTAR  (10 - 100 MWe)
  Natural convection cooled

ELSY  (600 MWe)
  Forced convection cooled
Gas-cooled fast reactor (GFR)

<table>
<thead>
<tr>
<th>Reactor Parameters</th>
<th>Reference Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor power</td>
<td>600 MWth</td>
</tr>
<tr>
<td>Net plant efficiency</td>
<td>48%</td>
</tr>
<tr>
<td>(direct cycle helium)</td>
<td></td>
</tr>
<tr>
<td>Coolant inlet/outlet temperature and pressure</td>
<td>490°C/850°C at 90 bar</td>
</tr>
<tr>
<td>Average power density</td>
<td>100 MWth/m3</td>
</tr>
<tr>
<td>Reference fuel compound</td>
<td>UPuC/SiC (70/30%) with about 20% Pu content</td>
</tr>
<tr>
<td>Volume fraction, Fuel/Gas/SiC Conversion ratio</td>
<td>50/40/10%</td>
</tr>
<tr>
<td>Burnup, Damage</td>
<td>Self-sufficient; 5% FIMA; 60 dpa</td>
</tr>
</tbody>
</table>
Cut-away view of a proposed 2400 MWth indirect-cycle GFR

- main heat exchanger (indirect cycle)
- Decay heat removal heat exchanger
- core barrel
- steel reactor pressure vessel
- re-fuelling equipment
- core
- control and shutdown rod drives
Schematic diagram of the DHR system in natural convection mode

Exchanger #2

pool

Exchanger #1

dedicated DHR loops

guard containment

core
2400 MWth indirect-cycle GFR inside a spherical “guard vessel”
The indirect combined cycle is proposed for the ANTARES HTR and is the reference cycle for the GenIV GFR system.
Molten Salt Reactor (MSR)

- Works with an epithermal neutron spectrum.
- The fuel is a liquid and the fuel is also the primary coolant.

<table>
<thead>
<tr>
<th>Reactor Parameters</th>
<th>Reference Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net power</td>
<td>1000 MWe</td>
</tr>
<tr>
<td>Power density</td>
<td>22 MWth/m³</td>
</tr>
<tr>
<td>Net thermal efficiency</td>
<td>44 to 50%</td>
</tr>
<tr>
<td>Fuel-salt – inlet temperature</td>
<td>565°C</td>
</tr>
<tr>
<td>– outlet temperature</td>
<td>700°C (850°C for hydrogen production)</td>
</tr>
<tr>
<td>– vapor pressure</td>
<td>&lt;0.1 psi</td>
</tr>
<tr>
<td>Moderator</td>
<td>Graphite</td>
</tr>
<tr>
<td>Power Cycle</td>
<td>Multi-reheat recuperative helium</td>
</tr>
<tr>
<td></td>
<td>Brayton cycle</td>
</tr>
<tr>
<td>Neutron spectrum burner</td>
<td>Thermal–actinide</td>
</tr>
</tbody>
</table>
MSR – Closed On-Site Fuel Cycle (Equilibrium Conditions)

U238 or Th232 → Molten Salt Reactor → U + Pu + minor actinides → Fission products + U + Pu + minor actinides (Am, Np, Cm) → On-site reprocessing plant
Molten Salt Fast Reactor (MSFR)
The European Sustainable Nuclear Industry Initiative (ESNII)

Supporting infrastructures, research facilities - loops, testing and qualification benches, irradiation facilities incl. fast spectrum facility (Myrrha) and fuel manufacturing facilities
Conclusions

The case made for the development of Fast Reactors made in the 1940’s and 1950’s is still relevant today, even though:

- Expansion of the global reactor fleet has been slower than anticipated originally (after TMI-2 and Chernobyl) but has resumed.
- More uranium has been discovered, but uranium resource is still not large.

Without fast reactors, nuclear fission will simply be a interesting footnote in human history.

With fast reactors we can generate 4000 years of electricity (and other energy forms) using a small refinement of 1970’s technology.

- A large fraction of the fuel we require in the UK is already above ground
- Using fast reactors, the UK is self-sufficient in plutonium and uranium-238 for at least for a few centuries.
Conclusions (continued)

Sodium cooled fast reactor technology is suitable for reviving an industrial capability for their construction at home and internationally

- We have a legacy of SFR design and construction experience
- No large (high) pressure components are require (except for steam generator water/steam headers)

The EC is supporting the development of all three fast reactor technologies (SFR, LFR and GFR) and accelerator driven systems (ADS).

We have the opportunity to re-engage as partners with France in the development of ASTRID and the development of a subsequent commercial fleet

(Rolls-Royce and AMEC have both signed MoUs with CEA to collaborate on the development of ASTRID)