The Gas Fast Reactor System

Presented by:

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European Commission, Joint Research Centre

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Content

- The GFR concept within GIF
- Status of the GFR System and Project Arrangements
- Main technical challenges
- The ALLEGRO consortium and future prospects
Contributions to the GIF

Japanese Chairmanship since end of 2009 (3 year term):
Mr Yutaka Sagayama, from JAEA

- GFR – Gas-Cooled Fast Reactor (System Arrangement)
- LFR – Lead-Cooled Fast Reactor (MOU)
- MSR – Molten Salt Reactor (MOU)
- SFR – Sodium-Cooled Fast Reactor (SA)
- SCWR – Supercritical Water-Cooled Reactor (SA)
- VHTR – Very-High-Temperature Reactor (SA)

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<th>Canada</th>
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<th>Japan</th>
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Motivation for Gas Cooled Fast Reactors

• Fast reactors are important for the sustainability of nuclear power:
  – More efficient use of fuel
  – Reduced volumes and radio-toxicity of high level waste

• Sodium cooled fast reactors are the shortest route to FR deployment, but:
  – The sodium coolant has some undesirable features:
    » Chemical compatibility, void coefficient of reactivity, restricted core outlet temperature to avoid sodium boiling.

• Gas cooled fast reactors do not suffer from any of the above:
  – Chemically inert, void coefficient is small (but still positive), single phase coolant eliminates boiling.
  – Allows high temperature operation without the corrosion and coolant radio-toxicity problems associated with heavy liquid metal reactors (Pb-Bi and pure Pb).

• But …
  – Gaseous coolants have little thermal inertia – rapid heat-up of the core following loss of forced cooling;
  – High density fuels and claddings sustaining extreme temperatures and burnups need to be designed
Generation IV GFR

- Helium coolant
- Fast neutron spectrum
- High outlet temperature
- Back-up for SFR

+ Transparent coolant
+ High temperature/efficiency
+ Strong Doppler effect
+ Weak void effect

- Decay heat removal (LOCA)
  - High power density
  - Low thermal inertia

- Thermal power: 2400 MWth
- Coolant in/out: 400°C/850°C
- System pressure: 7 Mpa
Status of GFR System Cooperation

• GFR System Arrangement signed by Euratom, France, Switzerland and Japan

• Project Arrangement on “Conceptual Design & Safety” signed by Euratom, France and Switzerland

• Project on “Fuel & Core Materials” in preparation
Specific GFR Challenge 1: Fuel

- The greatest challenge facing the GFR is the development of robust high temperature refractory fuels and core structural materials,
  - Must be capable of withstanding the in-core thermal, mechanical and radiation environment.
  - High fissile material volume fraction of the fuel.
- Candidate compositions for the fissile compound include carbides, nitrides, as well as oxides.
- Favoured cladding material is SiCf/SiC in a pin formats
- Practical issues:
  - How to encapsulate the fuel in pin – sealing of end plugs
  - How to do we combine metallic and ceramic components into a workable fuel sub-assembly?
Fissile phase composition: comparison

<table>
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<tr>
<th></th>
<th>Carbide(U,Pu)C</th>
<th>Nitride(U,Pu)N</th>
<th>Oxide(U,Pu)O₂</th>
<th>Metallic fuel(U,Pu,Zr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical density (g/cm³)</td>
<td>13.58</td>
<td>14.32</td>
<td>11.5</td>
<td>14</td>
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<tr>
<td>Melting point (°C)</td>
<td>2420</td>
<td>2780</td>
<td>2750</td>
<td>1080</td>
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<tr>
<td>Thermal conductivity (W/m/K)</td>
<td>16.5</td>
<td>14.3</td>
<td>2.9</td>
<td>14</td>
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<tr>
<td>Swelling</td>
<td>1.6% to 2%/at%</td>
<td>0.8%/at%</td>
<td></td>
<td></td>
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<tr>
<td>Thermal stability</td>
<td>Stable</td>
<td>Stable until 1600-1800°C</td>
<td>Very stable</td>
<td></td>
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</tbody>
</table>

- Carbide preferred to nitride for its neutronic properties (N15 enrichment needed)
- Both have relatively high volatility
- Oxide back-up but with lower core performance
- Metallic fuel discarded due to low melting point
**NIMPHEHE Irradiation (CEA – EURATOM)**

- **Objective:** Behavior of UPuN and UPuC irradiated in Phénix (but SFR conditions, steel cladding)
- **PIE made at CEA and JRC/ITU**

**Nimphe 2: Nitride**
- Important fuel de-densification in pellet centre, restructuring.
- **Central hole**
- UPuN dissociation, **Pu metal phase on clad**

**Nimphe 2: Carbide**
- Gas bubbles at pellet center, **without central hole**

![Image of Nimphe 2: Nitride](image)

![Image of Nimphe 2: Carbide](image)
GFR Ceramic pin : a new design

Fuel pellet : UPuC (high density & conductivity)

Clad : SiC\textsubscript{f}/SiC (refractory & resistant)

SiC\textsubscript{f}/SiC leak-tightness loss beyond elastic limit

⇒ Sandwich → SiC\textsubscript{f}/SiC / metal / SiC\textsubscript{f}/SiC

Pellet-Clad interaction:

⇒ Improved by buffer (C and/or SiC)

C. Sauder & C. Lorrette (CEA/DMN)

Leak-tight domain with present-day CMC

Failure limit \((\sigma_e \sim 300\text{MPa} - \varepsilon_e \sim 0,9\%))

Elastic limit \((\sigma_e \sim 80\text{MPa} - \varepsilon_e \sim 0,04\%)\) Beginning of microcracking
The GFR fuel design: material interactions
Fuel/buffer/liner/cladding interactions

$\text{UC}_{1.04} / \text{C} / \text{SiC} / \text{Ta} / \text{SiC}_f-\text{SiC}$

2000°C
15 min

Moderate material interaction
Fuel mostly preserved (buffer effect)
C layer dissolved in fuel
SiC layer mostly preserved
Ta liner mostly preserved (no buffer effect)
Cladding mostly preserved

Courtesy of C. Guéneau (CEA)
Perspectives for GFR fuel

- **Fissile materials:**
  - Fabrication experience
  - Stability of irradiated UPuC at high temp. (1600-2000°C)
  - Introduction and effect of minor actinides on UPuC properties

- **Cladding + diffusion barrier or liner**
  - Determination of composite behaviour under irradiation
  - High temp. (1600-2000°C) effects
  - Liner: tightness efficiency, fabrication, effect of damage and stresses
  - Thermo-chemical compatibility

- **Fuel element development**
  - Pin optimisation under nominal and accidental conditions
  - Fabrication: prototype pin
  - Irradiation programmes
Specific GFR challenge 2: Decay Heat Removal (DHR)

- HTR “conduction cool-down” will not work in a GFR
  - High power density, low thermal inertia, poor conduction path and small surface area of the core conspire to prevent conduction cooling.
- A convective flow is required through the core at all times;
  - A natural convection flow is preferred following shutdown
    » This is possible when the circuit is pressurised
  - A forced flow is required immediately after shutdown when depressurised:
    » Gas density is too low to achieve enough natural convection
      - Heavy gas injection helps
    » Power requirements for the blowers are very large at low pressure
- The primary circuit must be reconfigured to allow DHR
  - Main loop(s) must be isolated
  - DHR loop(s) must be connected across the core
Decay heat removal (DHR): original strategy

- Redundant DHR loops
- Dedicated blowers on helium side
- Secondary water loop at 10 bar
- Water loop working in natural convection
- Final heat sink: water pools
- Two barriers
  - Primary loop
  - Dedicated guard containment
Cut-away view of the 2400 MWth indirect-cycle GFR

- main heat exchanger (indirect cycle)
- Decay heat removal heat exchanger
- re-fuelling equipment
- core
- steel reactor pressure vessel
- core barrel
- control and shutdown rod drives
**Improvements to DHR strategy:**

Remove the requirement for an external power source for DHR in GFR

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**System pressure**

- Nominal
- Back-up

**Containment**

- Natural convection
- Forced convection: Blowers "X" - battery powered
- Natural convection: After 24h
- Severe Accident
- Heavy gas injection
- Forced convection: Self-sustainable Brayton cycle

Guard vessel failure: Loss of back-up pressure
The ALLEGRO consortium

- Joint preparatory work started in 2010 with support of CEA
- Signature of a MoU by AEKI Budapest (HU), UJV Rez (CZ), and VUJE Trnava (SK) in May 2010.
- NCBJ (Poland) joined the consortium in June 2012.
- Roadmap of construction has been prepared, with the main chapters General design, Safety principles, Licensing, R&D, Governance and IPR issues.

Note: AEKI is the “MTA Centre for Energy Research” (MTA-EK) since January 2012.
ALLEGRO: GFR demonstration & experimental facility

<table>
<thead>
<tr>
<th>75 MW Core</th>
<th>Fast neutron Φ</th>
<th>Dose</th>
<th>In core vol.</th>
<th>Loading</th>
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</thead>
<tbody>
<tr>
<td>25% Pu</td>
<td>$9 \times 10^{14}$ n/cm$^2$/s</td>
<td>13 dpa/year</td>
<td>6 x 5 litres</td>
<td>8 days</td>
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</tbody>
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Experimental S/A

Fuel
Control (CSD)
Shutdown (DSD)
Reflector
Shield

Diagrid

3 DHR Loops
One IHX He-H$_2$O

GIF Symposium 2012
Status of ALLEGRO Project

➢ The design has been reviewed to take into account new safety criteria.
➢ A preliminary Conceptual Safety Features Review File (CSFRF) will be elaborated by 2012; an operational version is planned for end of 2013.
➢ Discussions with the Safety Authorities are underway.
➢ Several potential sites exist; site selection is planned for mid 2013
➢ Governance structure and financing issues are under discussion.
➢ The preparatory phase can be concluded by the end of 2013.
➢ The licensing & construction phase may start in 2014 if the design qualification and safety analysis have reached a sufficient level (agreement of the Safety Authority of the country of the site).
➢ Start of operation: 2023 - 2025
Conclusion

- There has been extensive progress made within the GIF GFR « Conceptual Design and Safety » Project, with a focus on safety aspects.

- GFR fuel development is critical for this reactor system; results of R&D have been exchanged on a voluntary basis, since there is no Fuel Project signed yet.

- Although quite substantial, R&D efforts in Europe have been slowed down, priority being given to SFR.

- In parallel to the R&D shared in GIF, a new initiative (ALLEGRO demonstrator) has been launched recently.
Representatives in the GFR Steering Committee

**EURATOM**: Richard Stainsby (AMEC), Joseph Somers (JRC)

**France**: J.-C. Garnier, P. Guédeney (CEA)

**Japan**: T. Mizuno, N. Uto (JAEA)

**Switzerland**: W. Hoffelner, K. Mikityuk (PSI)

**OECD/NEA**: H. Paillère (Secretary)

Thank you for your contribution to the progress of the GFR R&D