Advanced Nuclear Fuel Development and Management in UK
U.S. Nuclear Waste Technical Review Board
Spring Board Meeting, May 12-13 2021
Overview

UK Nuclear Policy
Spent Fuel Storage and Disposal Policy Implementation
Implementation of Changes to Fuel
Current Work on New fuels
UK government white paper, 14 December 2020. Supportive of all forms of new nuclear energy

**Large Nuclear**

We will aim to being at least one large-scale nuclear project to the point of Final Investment Decision (FID) by the end of the parliament, subject to clear value for money and all relevant approvals.

Government “will examine the potential role of government finance during construction”

**Fusion**

We aim to build a commercially viable fusion power plant by 2040.

“The government has already committed over £400 million towards new UK fusion programmes”

**Hydrogen**

We will publish a dedicated Hydrogen Strategy in early 2021 which positions the UK as a world leader in the production and use of clean hydrogen.

“A variety of production technologies will be required to satisfy the level of anticipated demand for clean hydrogen in 2050. This is likely to include methane reformation with CCUS, biomass gasification with CCUS and electrolytic hydrogen using renewable of nuclear generated electricity.”

**Net Zero Innovation Programme (NZIP)**

£100 billion
Geological disposal of higher activity radioactive waste is UK Government policy.

- High and Intermediate level waste
- Fuel declared as waste

Radioactive Waste Management Ltd will be the developer of the disposal facility.

Approach for GDF site selection based on voluntarism and partnership - starting with local communities expressing an interest, with no commitment.

- Expressions of interest period started December 2018.
- Earliest spent fuel disposal expected ~2075

Spent Fuel Management Policy

Spent fuel management is a matter for the commercial judgement of its owners, subject to meeting the necessary regulatory requirements.

The UK is transitioning to an Open Fuel Cycle
The option for a future transition to a Closed Fuel Cycle remains open.

The UK Geological Disposal Facility is intended to be capable of receiving all the spent fuel and vitrified waste from UK research and test reactors, closed Magnox reactors, current power reactors and 16 GWe of new power reactors.
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Legal Framework

Advanced Nuclear Fuel Development and Management in UK

New Build justified with open fuel cycle

Justification

Legislation

Regulation

Health and safety

Environmental

Transport

Security

Licenses
Permits
Modifications

7
Disposability assessment process provides:

- Stakeholder confidence that materials can be packaged in a manner that is compliant with GDF design assumptions.
- A route to adapt GDF concept/design if required.

New Reactor Systems

UK Generic Design Assessment Process

• Generic design approval prior to site specific-licensing

• SNF management strategy
  • on-site storage
  • transport infrastructure
  • disposition

• Design and operational safety cases

• Integrated waste strategy

• Submissions required at all stages of GDA process, with commensurate levels of detail
Novel Reactor Systems

UK Government AMR Feasibility and Development Programme requirements

From initial phase of government funding, tenderers are required to address:

• SNF management strategy
• SNF disposition option
• Demonstrate understanding of challenges for back-end management strategy, including
  • Storage (short and long term, whether on or off site)
  • Transport
  • Recycle (if appropriate)
  • Packaging
  • Disposability

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Phase 1
• Advanced Reactor Concepts LLC
• DBD Limited
• Blykalla Reaktorer Stockholm AB (LeadCold)
• Moltex Energy Limited
• Tokamak Energy Ltd
• U-Battery Developments Ltd
• Ultra Safe Nuclear Corporation
• Westinghouse Electric Company UK

Phase 2
• Tokamak Energy Ltd (fusion)
• U-Battery Developments Ltd (HTGR)
• Westinghouse Electric Company UK (LCFR)

> Generic Design Assessment to follow
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SNF Ownership & Liabilities

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Regulator

Utility

Fuel Management Entity

Disposal Facility Entity

Vendor

Government

Public / Society
Magnox and AGR reactors were developed and deployed by government organisations. SNF liabilities derived from historical context.

**Responsibility**

- **Utility**
  - Generate SNF
  - Short term storage
  - Transport to centralised storage

- **NDA**
  - Interim storage
  - Package and transport to GDF

- **RWM**
  - Approval of disposal plans
  - GDF development
  - GDF operation
  - SNF emplacement

**Changes**

- **Utility**
  - Request / approve

- **NDA**
  - Agree changes prior to loading

- **RWM**
  - Agree changes to disposal plans on request
New Build Fuel

New reactors and SZB developed and deployed by commercial organisations. SNF liabilities derived from entirely commercial context.

Responsibility

- **Utility**: Generate SNF, Short term storage, Transport to centralised storage
- **Utility**: Interim storage Package and transport to GDF
- **RWM**: Approval of disposal plans, GDF development, GDF operation, SNF emplacement

Changes

- **Utility**: Request / approve
- **RWM**: Agree changes to disposal plans on request
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Nuclear Innovation Programme

Part of a £505m Energy Innovation Programme from the Department of Business, Energy and Industrial Strategy (BEIS)

"the first significant public investment in future civil nuclear fission (energy generation) research and innovation for a generation"

NIRAB 2019
AFCP Overview

Advanced Nuclear Fuel Development and Management in UK

Schematic modified from map in US 2016 Quadrennial Technology Review 2016

Delivered by over 90 UK organisations
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Strategic Outcomes

IDEAS

INFRASTRUCTURE

INDUSTRY ALIGNMENT

NET ZERO FUTURES ROADMAP

PEOPLE

SUPPLY CHAIN

STAKEHOLDER ENGAGEMENT

INTERNATIONAL INFLUENCE
Accident Tolerant Fuels

- Following the Fukushima-Daiichi accident in 2011 international efforts have focused on improvements to the safety of LWR fuels
- Gradual shift in focus towards cost reduction through:
  - Improved fuel reliability (reduced outages)
  - Improved fuel performance (higher burn-up, longer cycle lengths)
  - Higher density fuel materials (reduced volumes or enrichment costs)
- Storage and disposal of ATF needs to be considered as part of the full lifecycle cost analysis
Cost Reduction Drivers


For nuclear an increase in the capacity factor of ~2% can improve the LCOE by ~5%


Fuel failures leading to unplanned outages are reducing but ATF could provide further reductions
Coated Zr Cladding

- Focus on Cr based coatings.
- Reaction with steam forms a protective Cr$_2$O$_3$ surface layer.
- Limited by Cr-Zr eutectic formation between 1300-1400°C.
**International Collaboration**

**MIT Reactor capsule irradiation**
- 50-54 days irradiation at full power ~0.4 dpa
- PWR water chemistry (1400ppm B, 4.6ppm Li 50cc/kg dissolved H₂) at 300°C, 10.3MPa.
- Post-test examinations to include visual examination and weight gain

**INCA Irradiation Test in LVR-15**
- Part of the NEA FIDES international fuel and materials testing programme
- Dry test to measure creep behaviour of Cr coated cladding
- Samples to be provided for test beginning in mid-2021

**QUENCH-ATF bundle tests**
- €1.6m NEA joint programme involving 8 countries using the KIT facility
- Bundle of 24 tubes, 2.5m in length are to be tested under LOCA or severe accident conditions
- UK coated tubes to be provided for testing in 2022

**Burst tests at ORNL**
- Simulated LOCA testing of pressurised tubes
- Initial testing completed
Coating Performance

- Significantly reduced weight gain (>90%) in accelerated 400°C steam and standard PWR autoclave testing.
- Reduced H₂ generation with potential to reduce hydride formation in cladding and delayed hydride cracking.
- Dissolution of Cr is expected to be low, but could form CrO₄²⁻ altering water chemistry.

Hydrogen content is proportional to weight gain
SiC Composites

- SiC composites are attractive due to their high temperature oxidation resistance and lower neutron absorption than Zr alloys.
- Key challenges are: cost of manufacture (especially high purity fibres), joining technologies for end plugs, hydrothermal corrosion during normal operation and the licensing of a material with very different mechanical properties to current metallic cladding.
- Lack of data on long term storage behaviour of SiC composites although not expected to be a cause for concern.

New fibre winding capability (University of Birmingham)

Laser brazed joint (University of Manchester)
Doped UO$_2$ Fuels

UK has 3 participants in EU Horizon 2020 project DISCO which is looking at effects of dopants on fuel behaviour in repository. Final outputs due end of 2021.

Experimental work includes 23 leach tests:
- Bicarbonate water, Young cement water and Synthetic COx water
- Oxic, anoxic, reducing (H$_2$); without and with Fe (corrosion products)
- Wide range of materials:
  - MOX, doped UO$_2$ (Cr, Al, Gd), Th/UO$_2$;
  - unirradiated, alpha-doped and irradiated fuels
- Initial indications are that
  - Dopants do not increase dissolution rates
  - Fe decreases radionuclide releases
High Density Fuels

Higher density = economic benefit

Higher thermal conductivity = safety benefit
# High Density Fuel Comparison

<table>
<thead>
<tr>
<th>Material</th>
<th>U density increase (%)</th>
<th>Irradiation Performance</th>
<th>Water Tolerance</th>
<th>Ease of Manufacture</th>
<th>Isotopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>UO₂</td>
<td>-</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Very good</td>
<td>No issues</td>
</tr>
<tr>
<td>U₃Si₂</td>
<td>17</td>
<td>Poor</td>
<td>Difficult</td>
<td></td>
<td>No issues</td>
</tr>
<tr>
<td>UN</td>
<td>40</td>
<td>Uncertain. Lack of data in relevant LWR conditions. Swelling expected to be higher.</td>
<td>Poor</td>
<td>Fair but would benefit from more direct routes</td>
<td>^15N enrichment required to avoid ^14C</td>
</tr>
<tr>
<td>UC</td>
<td>34</td>
<td>Very poor</td>
<td>Fair</td>
<td></td>
<td>No issues</td>
</tr>
<tr>
<td>UB₂</td>
<td>21</td>
<td>Good</td>
<td>Difficult but potential for alternate routes</td>
<td>Depletion in ^10B required (unless used as a burnable absorber)</td>
<td></td>
</tr>
</tbody>
</table>
Water Reactivity

48hrs at 300°C, 100bar.
Potential strategies to improve water tolerance

Dopants
Microencapsulation

Composites
Coatings

UO₂
U₃Si₂
UN
UB₂
Spent Fuel Inventories

- Spent fuel inventories for high density fuel concepts can be calculated
- Fission product speciation can be assessed using SIMfuels (simulated irradiated fuels)
- Testing of irradiated fuels in storage and disposal conditions will be necessary

Electronegativity vs \( M^{3+} \) ion radius

Predicted inventory of UN spent fuel (60MWd/kg, 1yr cooling)

Predicted speciation in UN spent fuel
Summary

• UK regulatory process requires demonstration of fuel lifecycle management prior to reactor construction and fuel design changes, including 3rd party approvals where necessary.

• UK is ramping up research into new fuels with engagement of fuel vendors and international partners.

• Near term ATF concepts (such as coated cladding) show promise. Deployment is not expected to be limited by back-end considerations.

• Longer term use of advanced cladding or high-density fuels will require substantially more research and development, including in the area of spent fuel storage and disposal.
Acknowledgement

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