Advanced Nuclear Fuel Development and Management in UK

U.S. Nuclear Waste Technical Review Board
Spring Board Meeting, May 12-13 2021

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Overview

UK Nuclear Policy

Spent Fuel Storage and Disposal Policy Implementation

Implementation of Changes to Fuel

Current Work on New fuels

National Strategy (1)

UK government white paper, 14 December 2020. Supportive of all forms of new nuclear energy

https://www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future

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"

"As the first major commitment of the programme, in 2021 we will open the **Generic Design Assessment** to SMR technologies"

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

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National Strategy (2)

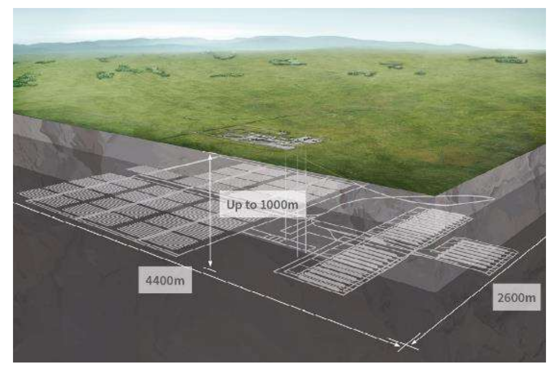
Geological disposal of higher activity radioactive waste is UK Government policy.

- 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



(Ref: Nuclear Decommissioning Authority. Geological Disposal - Steps towards implementation, Executive Summary March 2010, ISBN 978 1 84029 402 6)

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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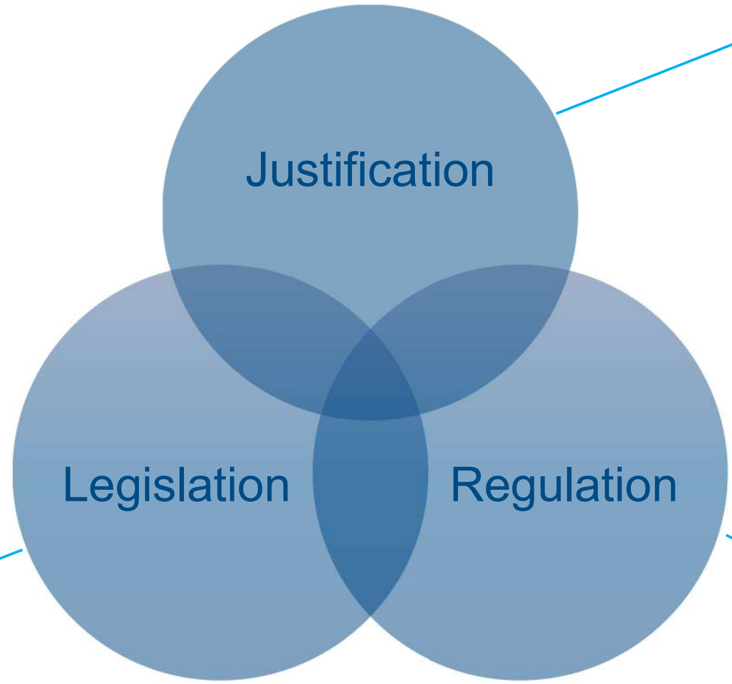
Legal Framework



New Build justified with open fuel cycle

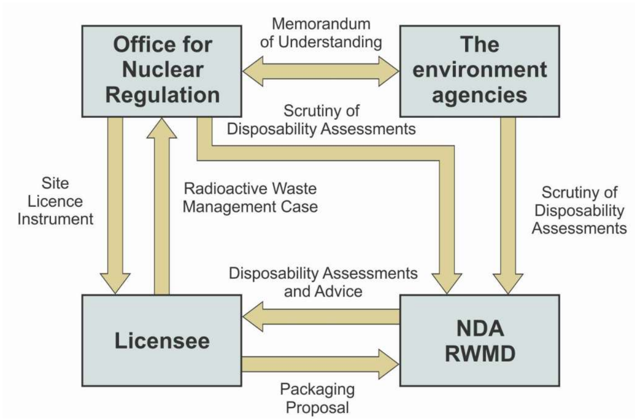
Health and safety
Environmental
Transport
Security

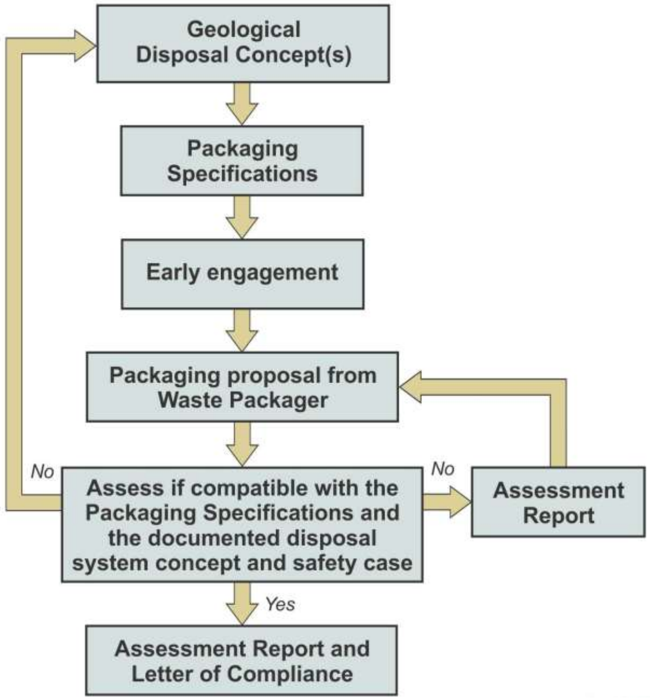
Licenses
Permits
Modifications

Disposability

Disposability assessment process provides

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



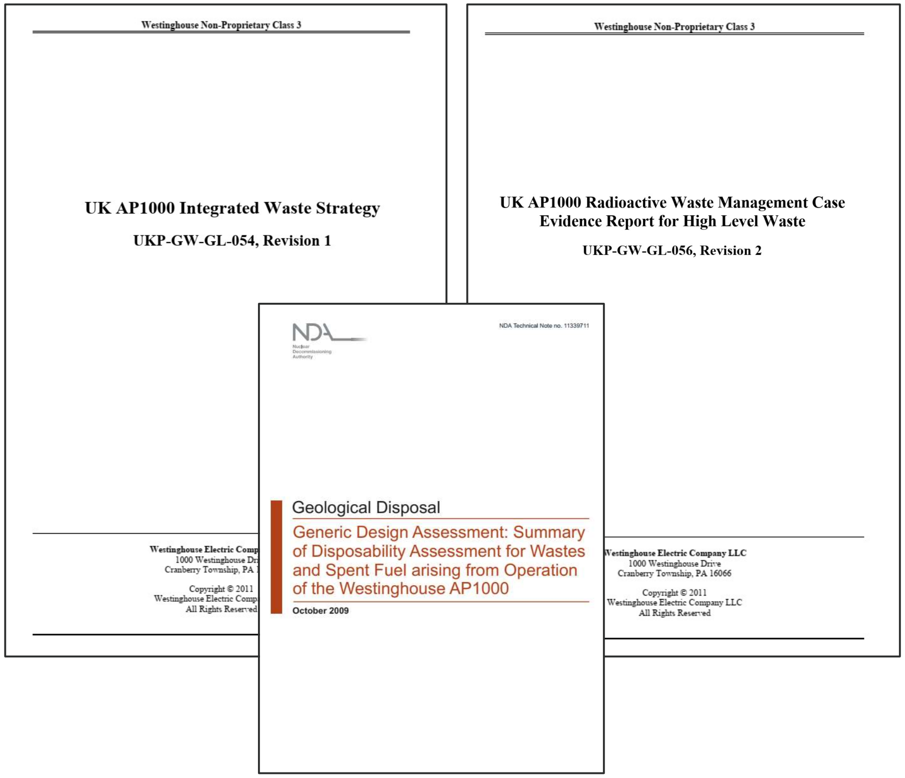


NDA. An Overview of the RWM Disposability Assessment Process. WPS/650/03, 2014.

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



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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**

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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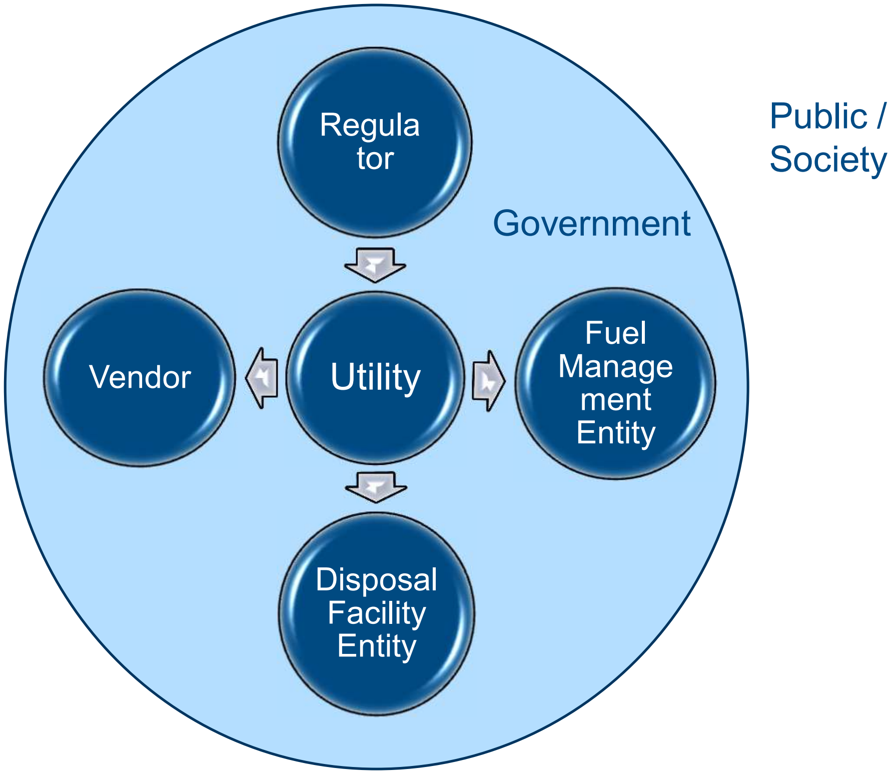
SNF Ownership & Liabilities



AGR Fuel

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

Responsibility

Utility → NDA → RWM

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

Excluding regulatory approvals

Utility → NDA → RWM

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

Excluding regulatory approvals

- Utility: Request / approve
- RWM: Agree changes to disposal plans on request

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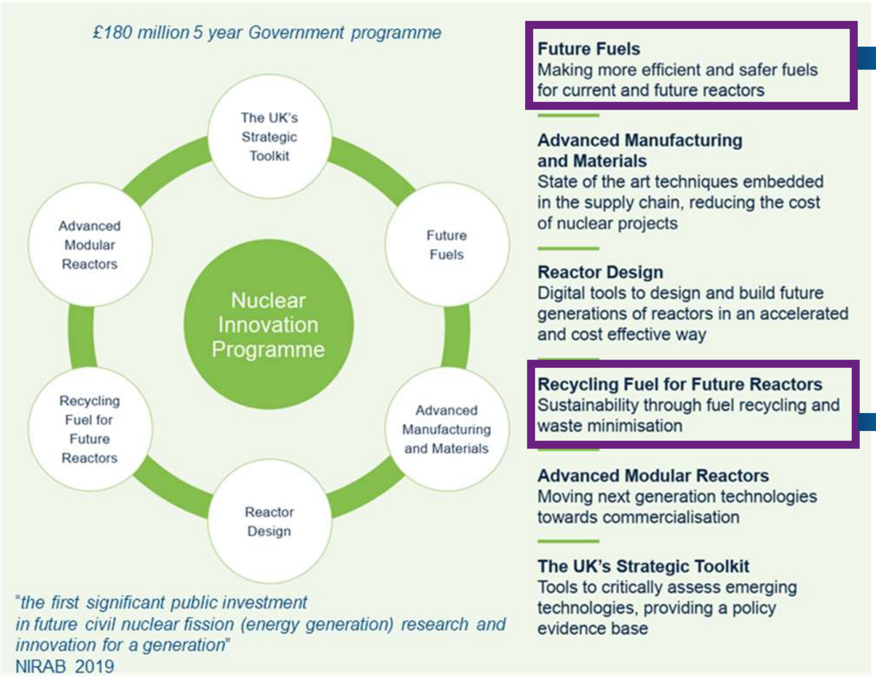
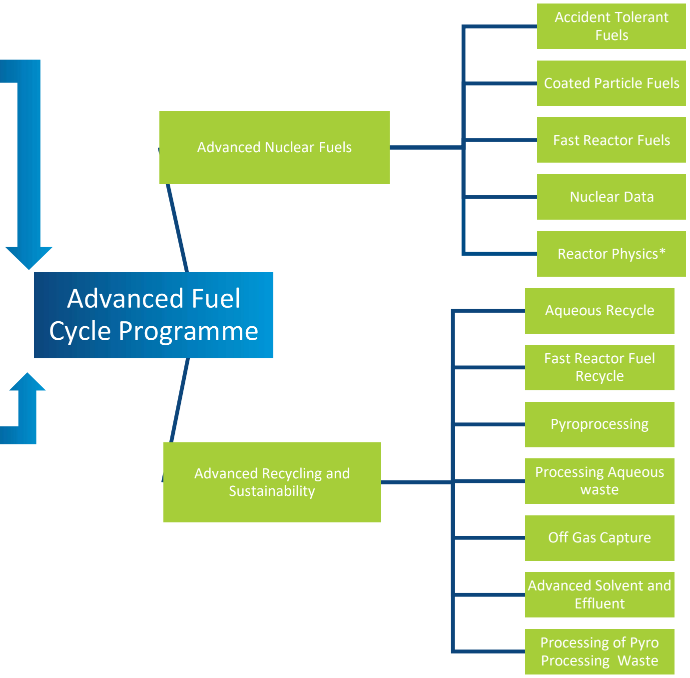
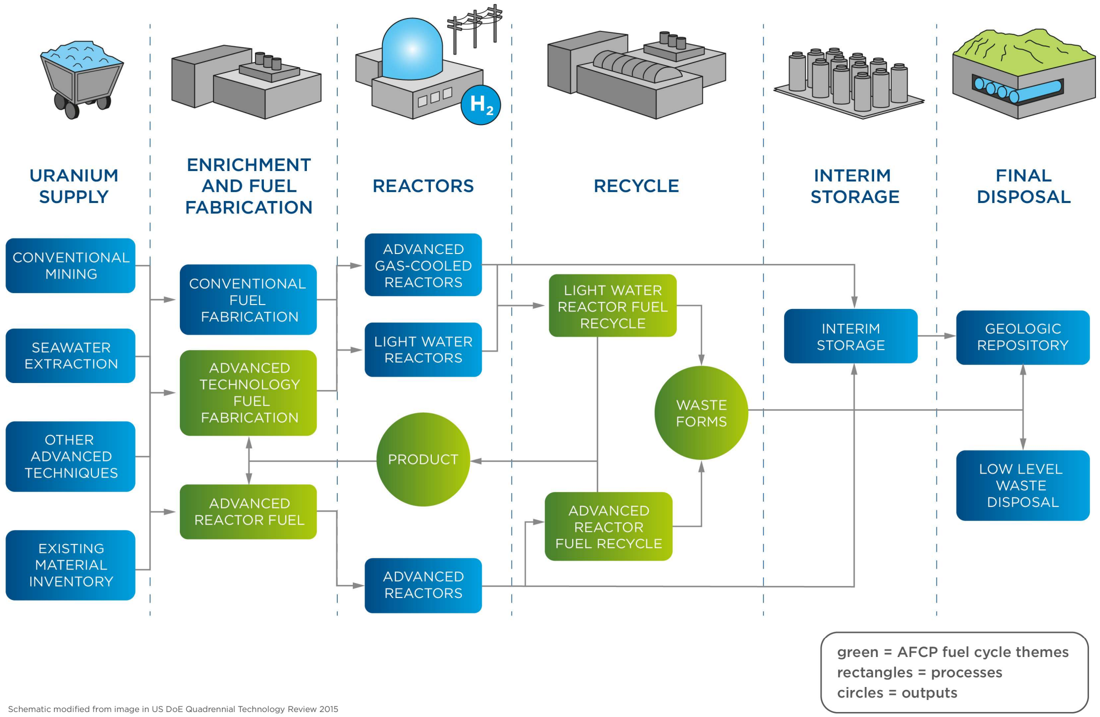
Nuclear Innovation Programme

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



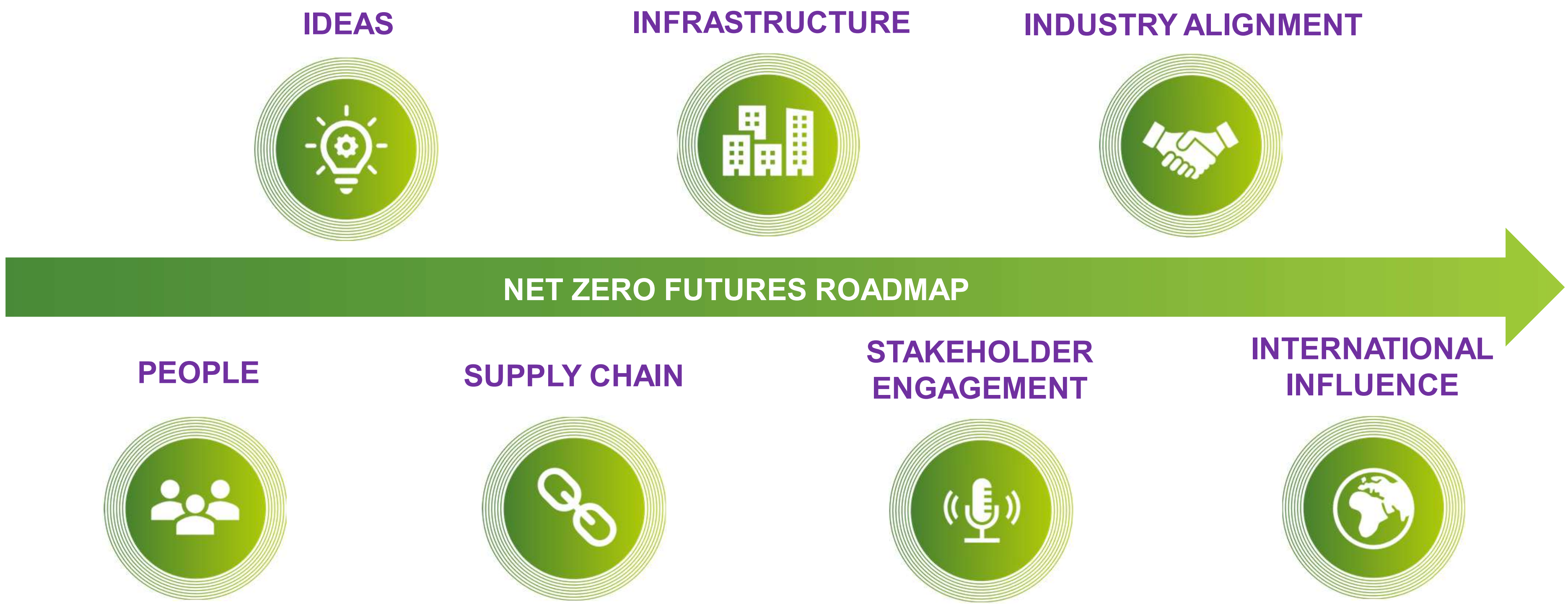


AFCP Overview



Schematic modified from image in US DoE Quadrennial Technology Review 2015

Strategic Outcomes



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

COVER STORY | FUEL & FUEL CYCLE

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Enhancing economics with ATF

Adoption of advanced technology fuels (ATF) is on the rise, but their economic impact is poorly understood. The UK's Advanced Fuel Cycle Programme is shifting understanding. By **Simon Middleburgh, Mustafa Bolukbasi** and **Dave Goddard**

AFCP
Advanced Fuel Cycle Programme

The Advanced Fuel Cycle Programme

The Advanced Fuel Cycle Programme (AFCP) is driving innovation to underpin a clean energy future in the United Kingdom. Part of the £180m Nuclear Innovation Programme – the biggest public investment in nuclear fission research in a generation – AFCP aims to understand the role of nuclear fuels and advanced fuel cycle in a Net Zero world.

Led in partnership by the UK National Nuclear Laboratory (NNL), AFCP pioneers a collaborative approach to innovation. The programme unites over 100 organisations across the globe, engaging with partners in over 10 countries. Domestically, AFCP is partnering with over 60 UK organisations spanning industry, national laboratories, government and universities – including Bangor University, where this novel economical assessment work is centred – to maximise the UK's rich capability, infrastructure and multigenerational energy innovators.

Working together, AFCP's research network covers the fuel cycle and considerations of spent fuel implications for ATF decisions. Under its four major focus areas – capability, capacity, cost reduction and collaboration – the programme is constructing the foundation for which tangible, future-focused advanced fuels and recycling concepts can fully evolve. ■

OVER RECENT YEARS, THERE HAS been a continuing desire across the nuclear power sector to improve the safety and operational performance of light water reactor (LWR) fuels. This has driven the development of 'accident tolerant fuels' – also referred to as advanced technology fuels (ATFs). Now ATFs are undergoing rapid innovation to harness their full potential within the Net Zero puzzle.

Safe, clean fuels must also be cost efficient. The UK's Advanced Fuel Cycle Programme (AFCP), see box, is leading the transition of novel ATFs from being purely safety-driven to economic. Led by the UK National Nuclear Laboratory (NNL), AFCP is funded by the Department for Business, Energy and Industrial Strategy (BEIS). Leveraging partnerships across the nuclear sector, AFCP is investigating how novel ATFs would lower the overall cost of nuclear power. This timely study aims to assess feasibility of near-term ATF adoption by the global nuclear power industry.

Comparing costs

The overall cost of nuclear power is similar to that of other energy options. But when broken down its costs are structured differently from other baseload electricity-generating technologies, such as coal and gas. Its cost more closely resembles that of renewable technologies, such as wind and geothermal (*Figure 1*). Like renewables, the dominant cost for nuclear power is construction.

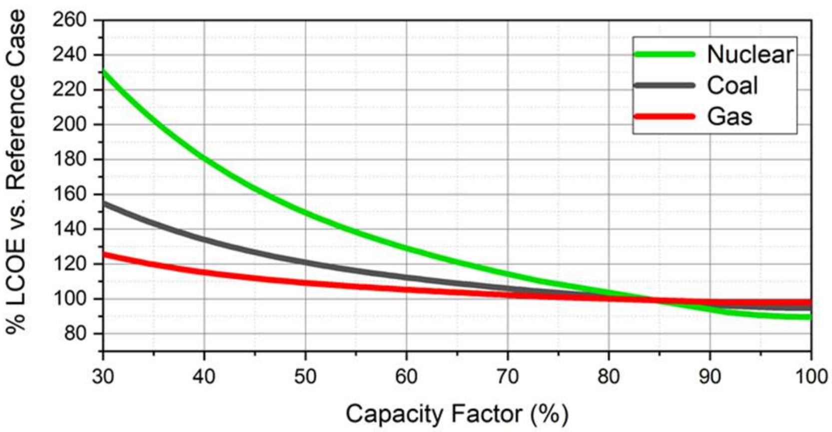
The cost of fuel for nuclear power is a small proportion (10-15%) of the overall levelised cost of electricity (LCOE).

24 | September 2020 | www.neimagazine.com

NEI Magazine, September 2020

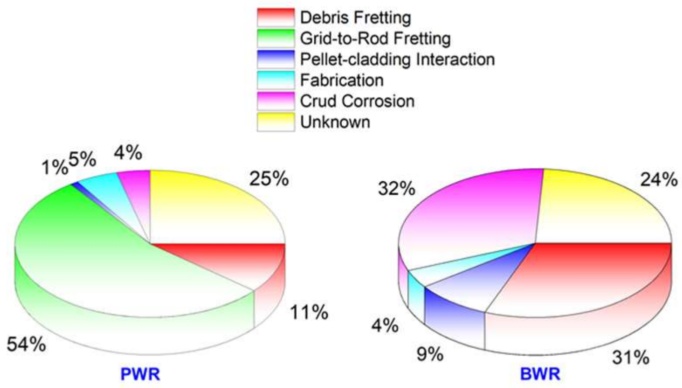
Cost Reduction Drivers

Energy Technologies Institute, "The ETI Nuclear Cost Drivers Project: Summary Report" 2018.



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

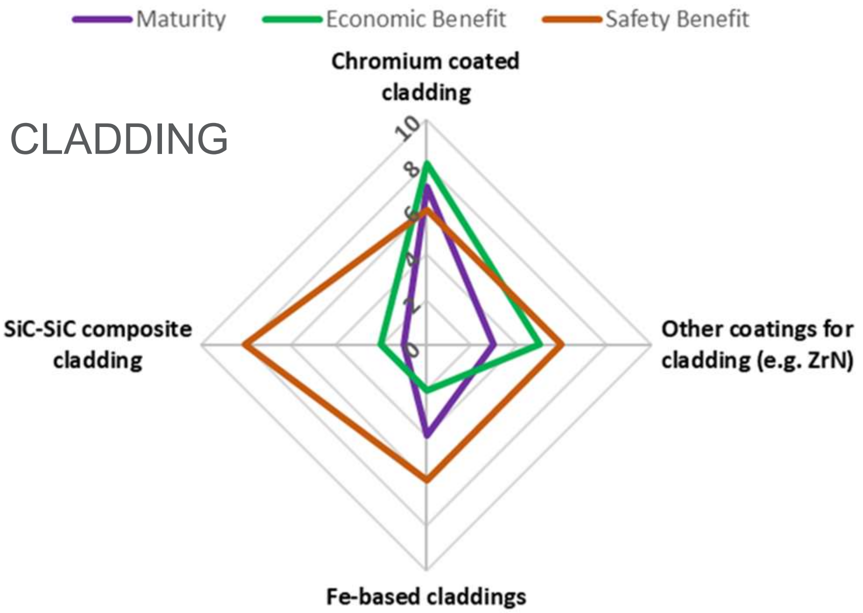
IAEA Nuclear Energy Series NF-T-2.1 "Review of Fuel Failures in Water Cooled Reactors" Chapter 3, (2010).



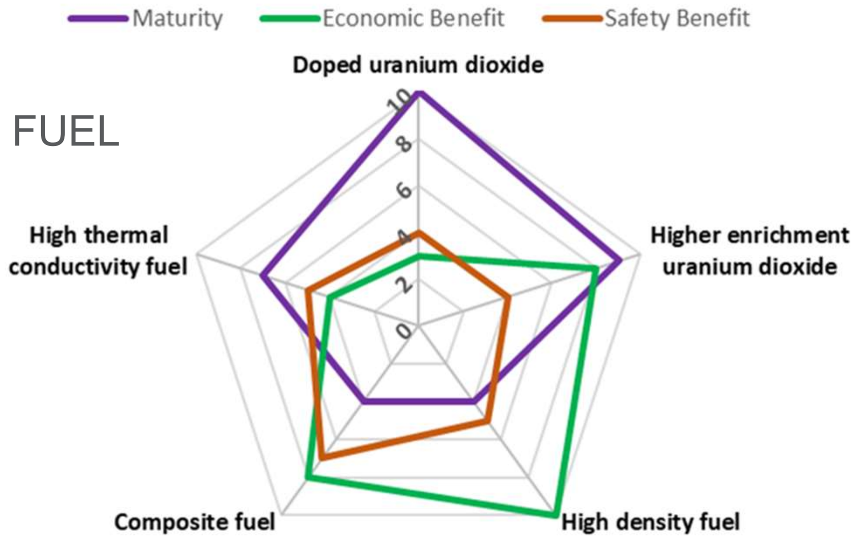
Fuel failures leading to unplanned outages are reducing but ATF could provide further reductions

ATF Technologies

CLADDING



FUEL

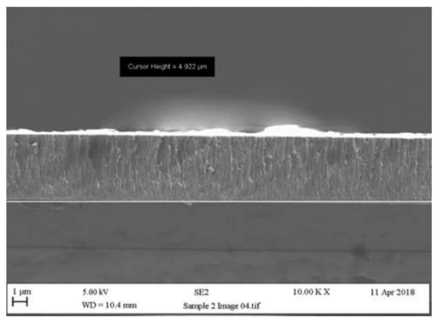


Coated Zr Cladding

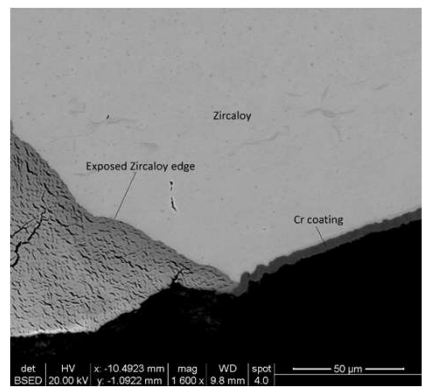
- Focus on Cr based coatings.
- Reaction with steam forms a protective Cr_2O_3 surface layer.
- Limited by Cr-Zr eutectic formation between 1300-1400°C.

New full length coating technology developed and awaiting installation

Cr coated ZIRLO cladding tubes



Cross-section through Cr coating



700°C oxidation test for 72 hours shows protective ability of Cr coating

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 H_2) 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

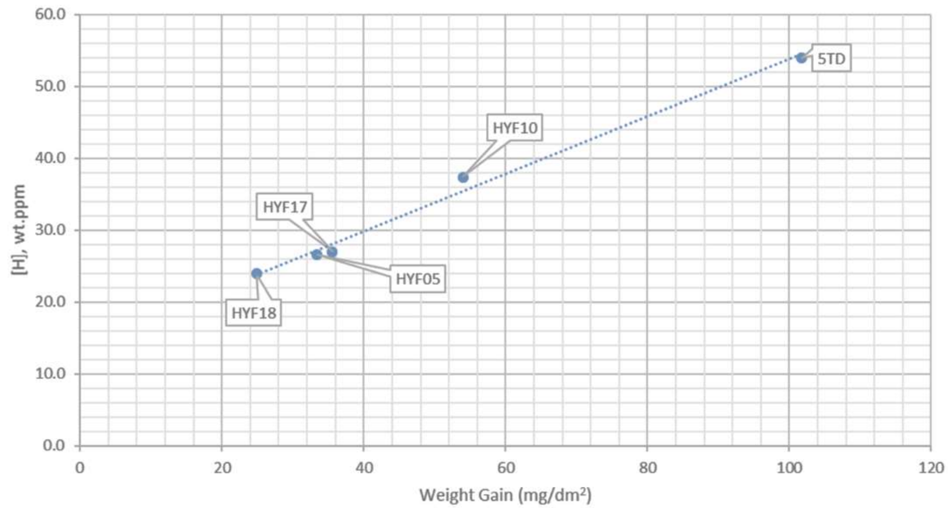
- €1.6m NEA joint programme involving 8 countries using the KIT facility
- Bundle of 24 tubes, 2.5m in length are to be tested under LOCA or severe accident conditions
- UK coated tubes to be provided for testing in 2022

Burst tests at ORNL

- Simulated LOCA testing of pressurised tubes
- Initial testing completed

Coating Performance

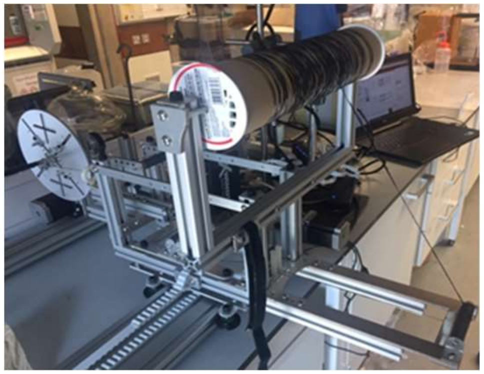
- Significantly reduced weight gain (>90%) in accelerated 400°C steam and standard PWR autoclave testing
- Reduced H_2 generation with potential to reduce hydride formation in cladding and delayed hydride cracking.
- Dissolution of Cr is expected to be low, but could form CrO_4^{2-} altering water chemistry.



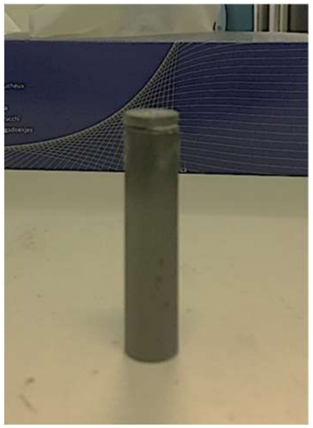
Hydrogen content is proportional to weight gain

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

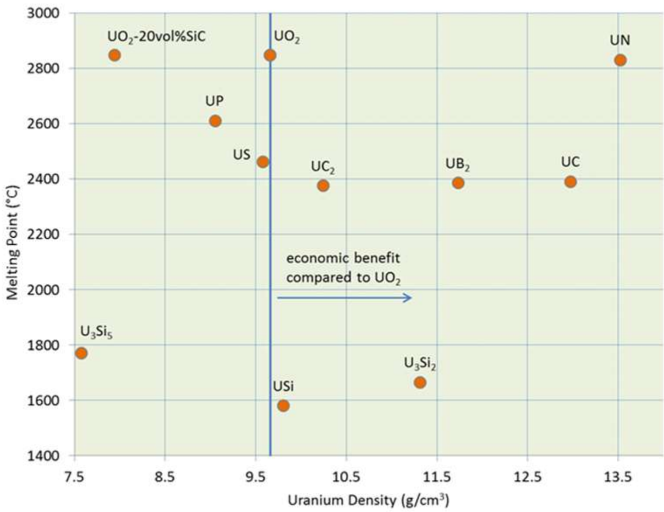
UK has 3 participants in EU Horizon 2020 project DISCO which is looking at effects of dopants on fuel behaviour in repository. Final outputs due end of 2021.

DisCo
Modern Spent Fuel Dissolution and Chemistry in Failed Container Conditions

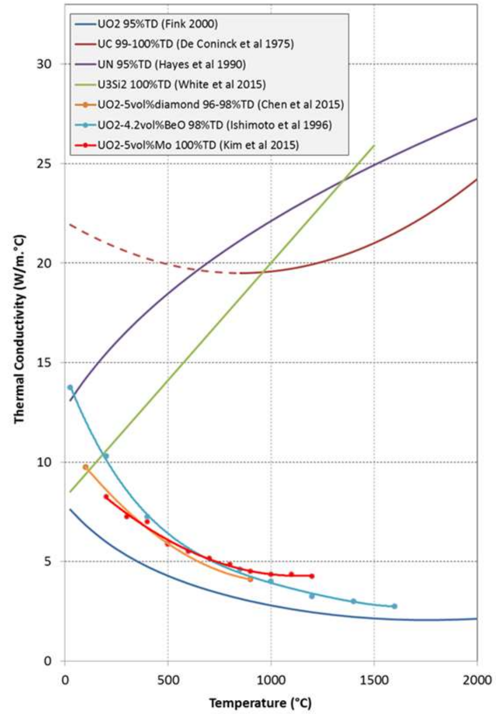
Experimental work includes 23 leach tests:

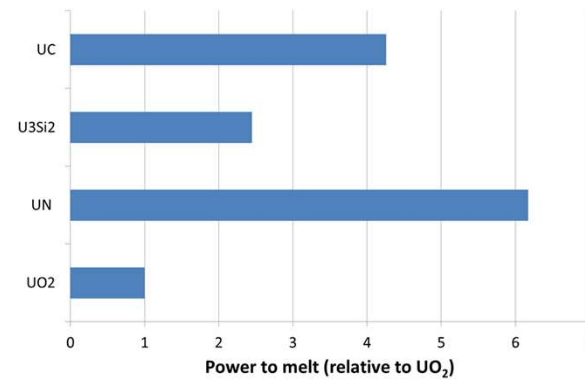
- Bicarbonate water, Young cement water and Synthetic COx water
- Oxic, anoxic, reducing (H_2); without and with Fe (corrosion products)
- Wide range of materials:
  - MOX, doped UO_2 (Cr, Al, Gd), Th/UO_2;
  - unirradiated, alpha-doped and irradiated fuels
- Initial indications are that
  - Dopants do not increase dissolution rates
  - Fe decreases radionuclide releases

High Density Fuels



Higher density = economic benefit



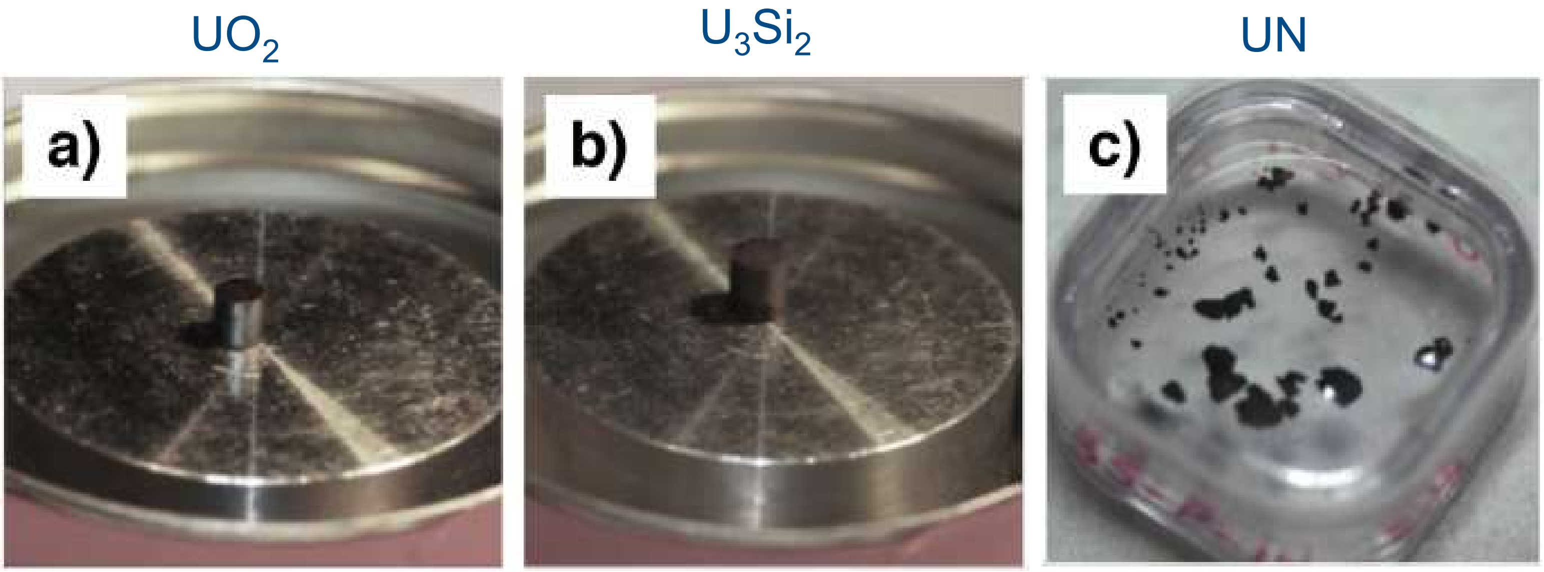


Higher thermal conductivity
= safety benefit

High Density Fuel Comparison

Material	U density increase (%)	Irradiation Performance	Water Tolerance	Ease of Manufacture	Isotopics
UO_2	-	Excellent	Excellent	Very good	No issues
U_3Si_2	17	Uncertain. Lack of data in relevant LWR conditions. Swelling expected to be higher.	Poor	Difficult	No issues
UN	40		Poor	Fair but would benefit from more direct routes	^{15}N enrichment required to avoid ^{14}C
UC	34		Very poor	Fair	No issues
UB_2	21		Good	Difficult but potential for alternate routes	Depletion in ^{10}B required (unless used as a burnable absorber)

Water Reactivity



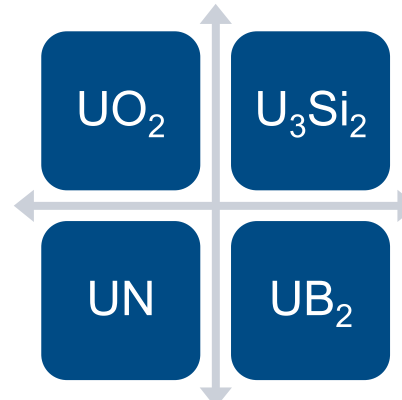
48hrs at 300°C, 100bar.

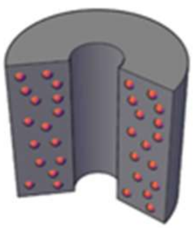
Images from Nelson et al , J. Nucl. Mater, **500,** (2018), 81-91

Potential strategies to improve water tolerance

Dopants

Composites



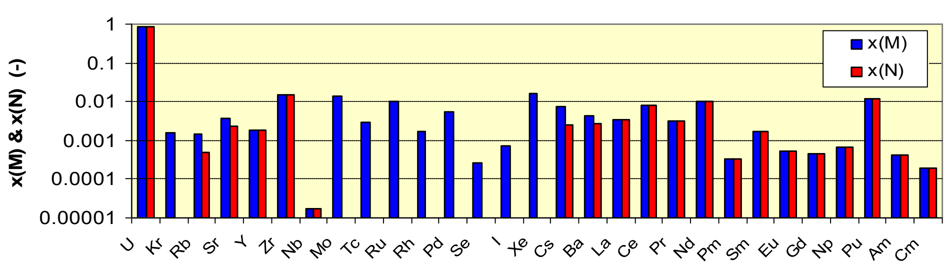


Microencapsulation

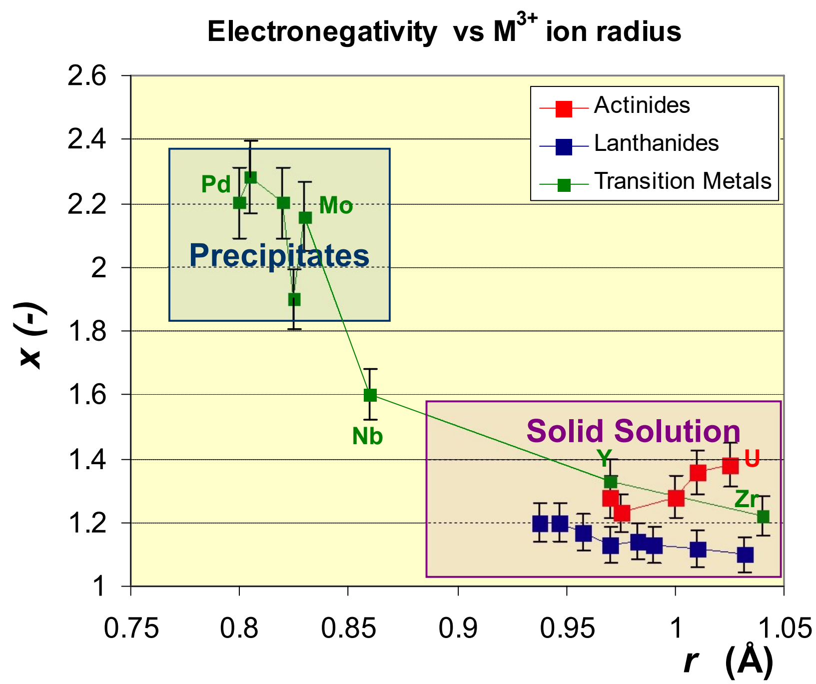
Coatings

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



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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