Topic 1: Fuel Fabrication

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CEIDEN – NNL meeting, Sellapark, 1st February 2016

UK Fuel Ambition: Development of Fuels with Enhanced Safety, Economic & sustainability Benefits using Indigenous UK R&D Skill & Facility Base

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Enhanced Economics

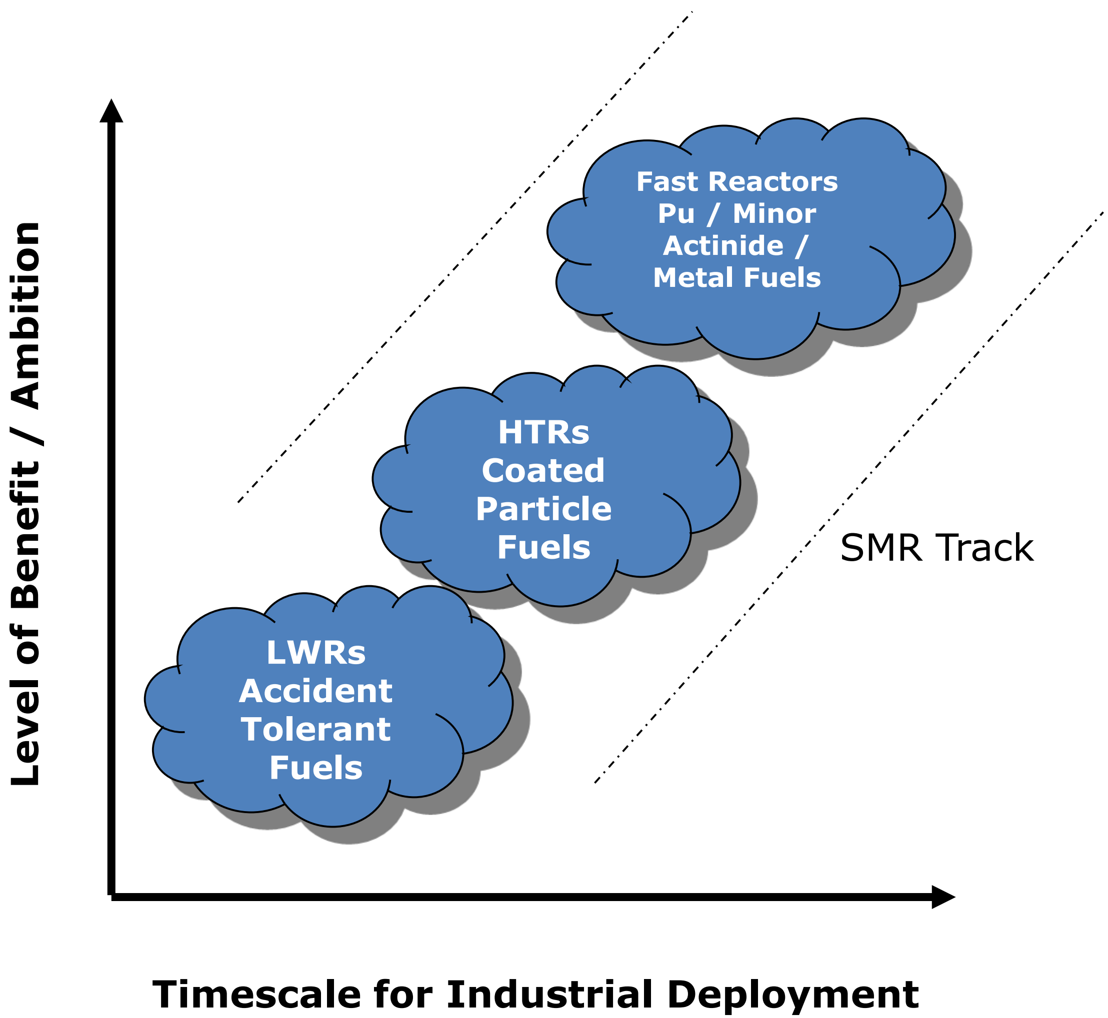
- Better Burn Ups
- Better Operational Flexibility
- Better Manufacturability

Enhanced Safety during Accident Conditions

- Enhanced Coolant Containment
- Enhanced Fuel Retention within Cladding

Enhanced Sustainability

- replace Unat with Urep
- reduce repository burden



Challenges for fuel development

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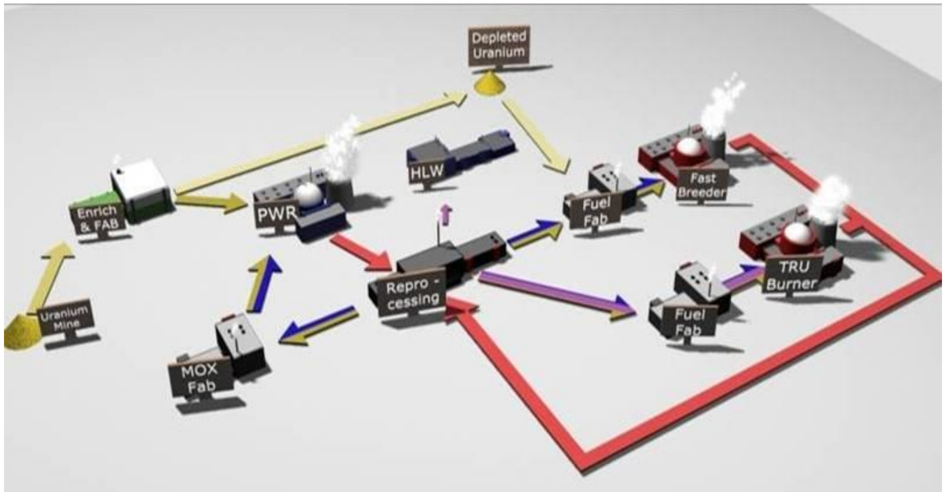
Advanced fuel and cladding ‘material and chemical’ properties not fully understood

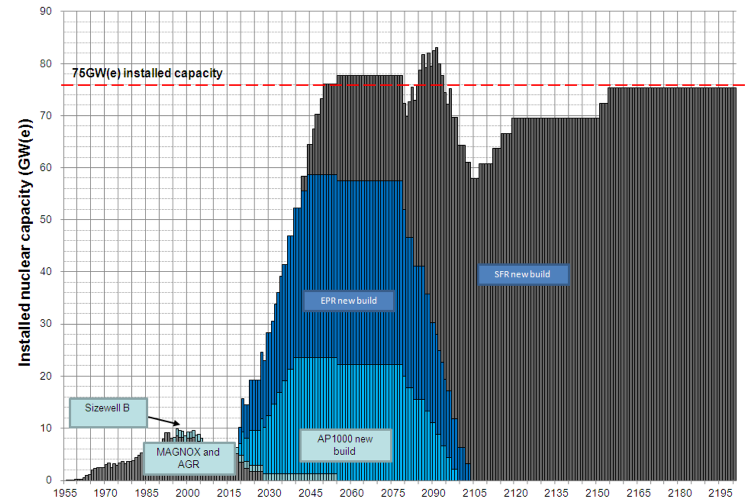
R&D required to understand effect of these on neutron economy, production of activation products and how properties alter under irradiation / high temperature conditions

Steps needed:

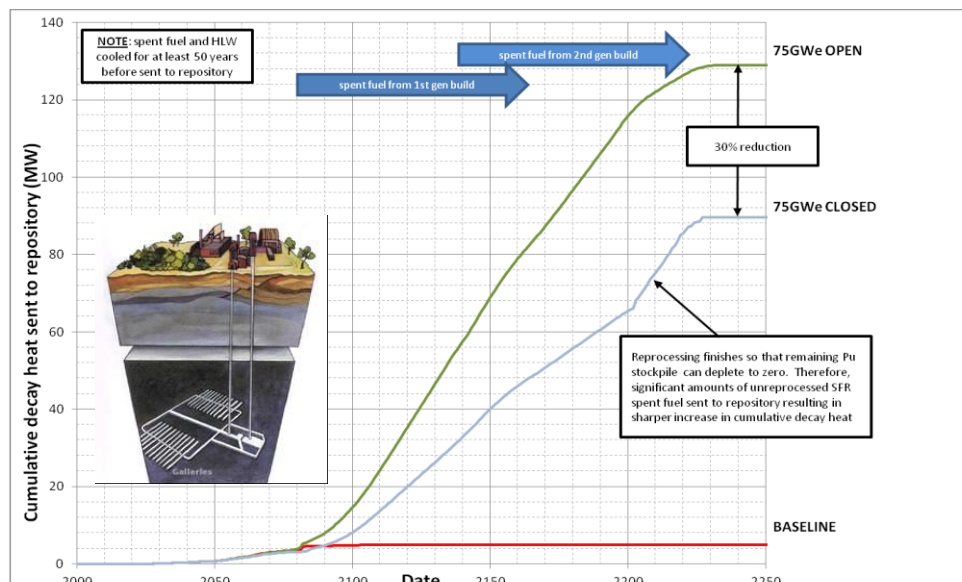
- Further investigation and development of new materials
- Industrial prototypes through existing/new fabrication technology
- New data measurements and evaluations through irradiation tests and modelling - *especially for industrial prototypical fuels*

Fuel Cycle and technology assessment





- Track material such as fuel throughout fuel cycle
- ~2000 radionuclides
- Compares metrics for competing reactor technology
- Analyse complex systems
- Benchmarked on historical fuel cycle operational data



Evaluation, assessment, optimisation

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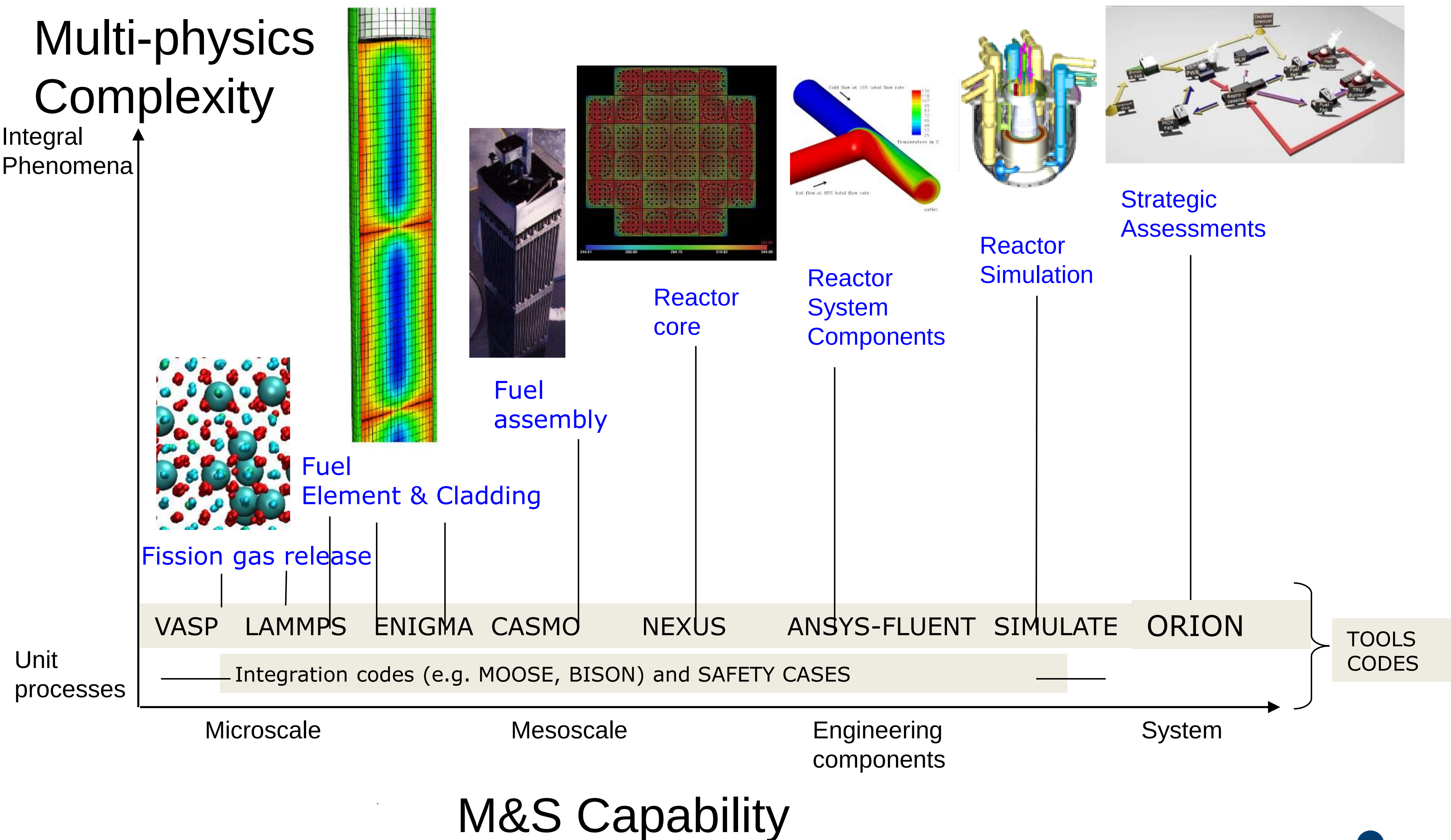

Evaluating the performance of novel fuels-clad systems

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To quantify the potential benefits of ATF’s and to explore the design optimisation issues associated with a higher density, higher thermal conductivity fuel such as U_3Si_2 fuel, an in-reactor modelling capability will be required.

ENIGMA is the UK's primary tool for thermal reactor fuel performance modelling under steady state and off-normal conditions.

Its capabilities currently include the modelling of various fuel pellet types (including UO_2 and MOX) in various claddings (including zirconium-based alloys and steels). Work has now begun to extend ENIGMA's capabilities to include other fuel types such as U_3Si_2.

Fuel performance code development - ENIGMA

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Project to develop ENIGMA's capabilities to include advanced fuel types based on U_3Si_2.

Objectives

- to adapt and extend the fuel property models to include the best-available correlations for U_3Si_2, derived from measurements carried out in support of the use of U_3Si_2 dispersion fuels in research and test reactors
- to test the adaptations in the revised version of the code

"For some of the changes, property measurements or post-irradiation examination (PIE) data were found in the literature on which the new models could be based, <u>but for others the absence of appropriate information meant that highly simplistic, or null, assumptions need to be made".</u>

Fuel performance code development -ENIGMA

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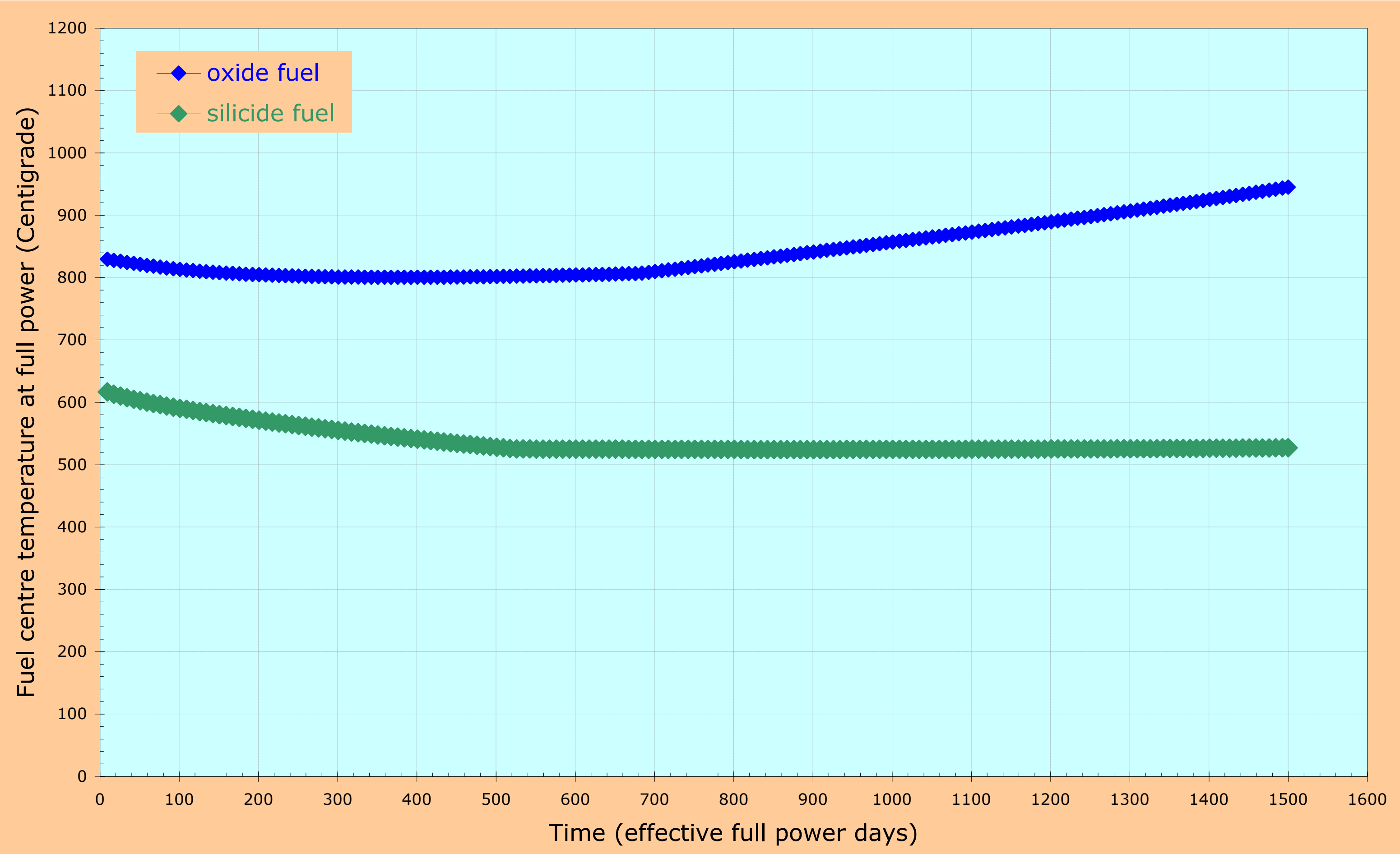
USi fuel

- Fuel performance modelling is at an early stage with little data to underpin the following parameters:
  - Thermal conductivity - Effects of porosity, irradiation and stoichiometry are currently unknown
  - Thermal expansion – measurements scarce and dependant on fabrication route
  - Elasticity – values independent of temperature and porosity currently assumed
  - Creep – no published data
  - Density and heat capacity - linear correlation of specific heat capacity and temperature assumed but the heat capacity of U_3Si_2 is thought to be lower than that of UO_2 at low temperature, but similar at high temperature
  - Densification and swelling – measurements used at higher burnups for metal plate fuel compared to typical LWR fuel
- Enrichment, Densities, Heavy metal content are yet to be determined through neutronic modelling

Fuel performance



The consequences of each change were examined in turn by running an idealised LWR fuel analysis through to high burnup and generating a set of standard plots of the key code predictions of interest (temperature, stress, strain, fission gas release etc). This allowed the relative importance of the different changes to be quantified

Core neutronic modelling results

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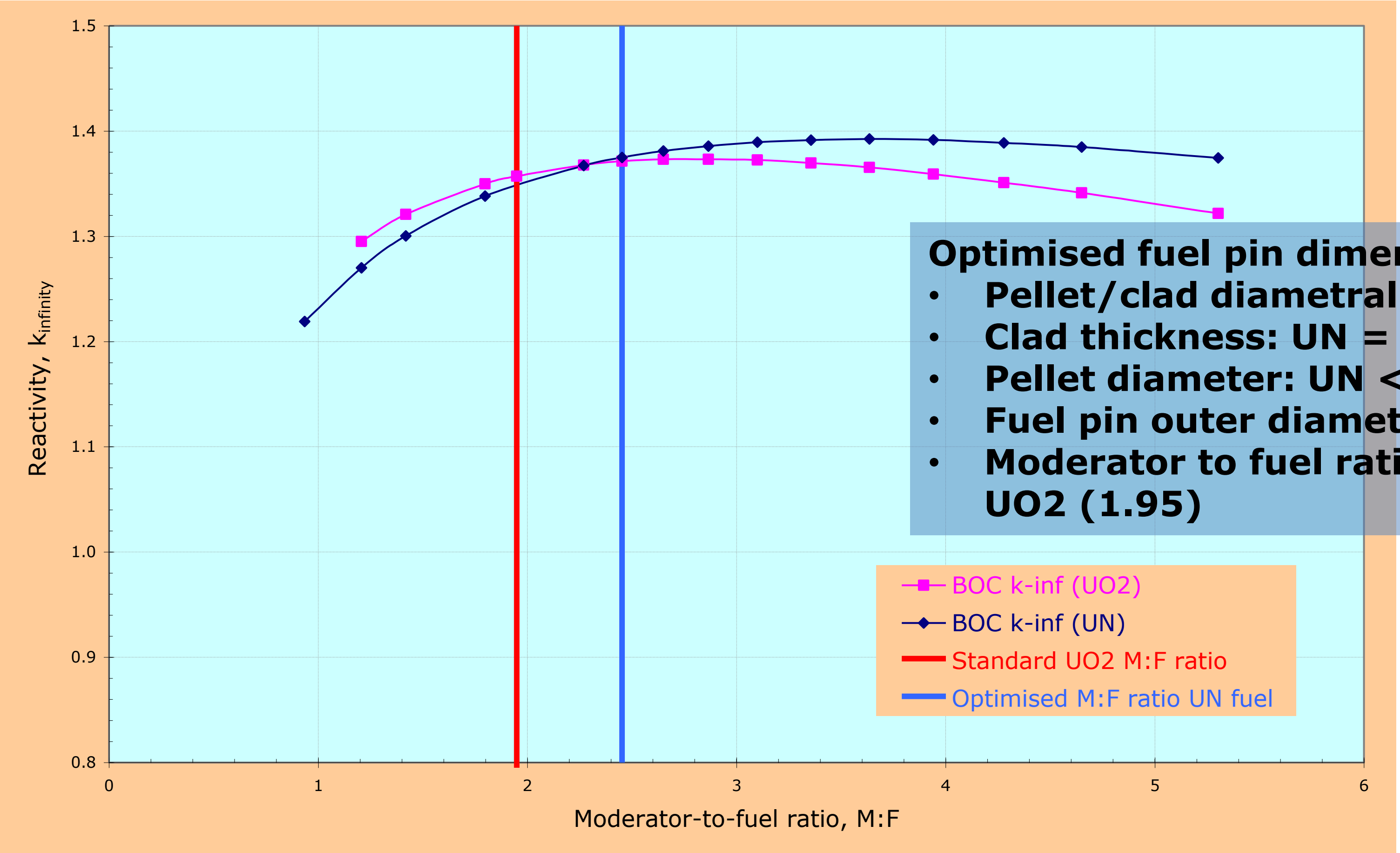


Optimised fuel pin dimensions

- **Pellet/clad diametral gap: UN = UO2**
- **Clad thickness: UN = UO2**
- **Pellet diameter: UN < UO2**
- **Fuel pin outer diameter: UN < UO2**
- **Moderator to fuel ratio: UN (2.5), UO2 (1.95)**

For UO2 the standard M:F ratio is set to a lower value than that which gives the maximum reactivity. This is done in order to ensure that if a decrease in M:F were to occur – for example if the coolant temperature were to increase – the reactivity decreases. In this way, a negative moderator temperature coefficient (MTC) is maintained.

Economic evaluations

UN fuel

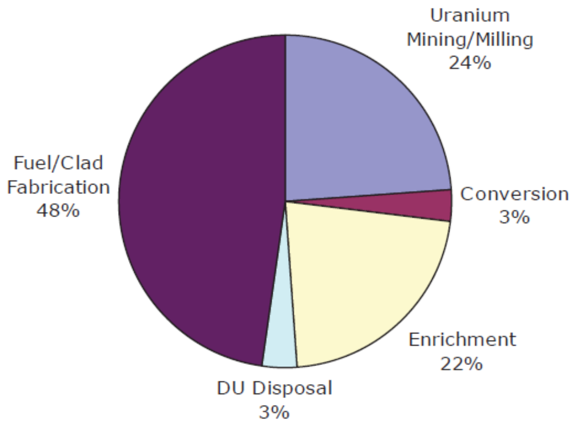
- Modelling results in a smaller diameter, lower enriched fuel
- Trade-off between higher density (compared to UO2) and criticality controls for a given enrichment
- Savings on fabrication extrapolated up to $4,032M for lifetime of a 16GWe LWR fleet

SiC cladding

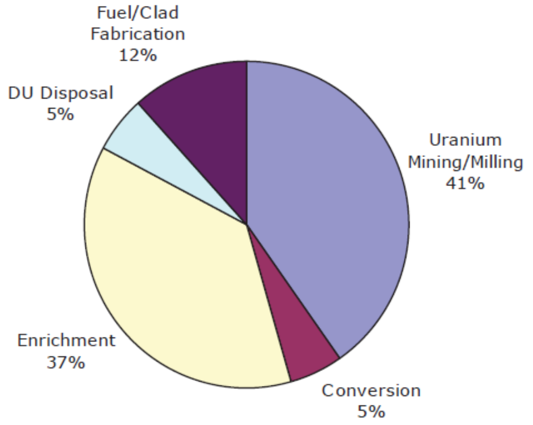
- Increased melting point and reduced neutron absorption leads to increased power output

- Benefits taken through:
  - core uprating or
  - decreased fuel loading frequency (or fewer assemblies per cycle)

- But thicker clad likely required for strength – suits smaller diameter UN fuels
- SiC clad fuel approximately 1.5x the cost of standard zirconium alloy clad fuel – will innovation/ mass production bring this down?



SiC clad assembly costs



Zirconium alloy clad assembly costs

Modelling provides fuel specifications

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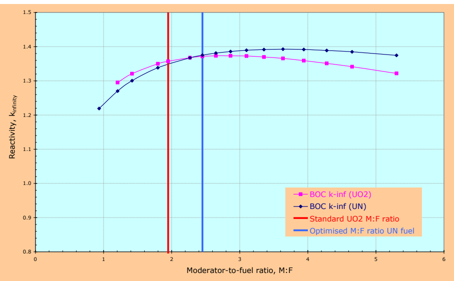

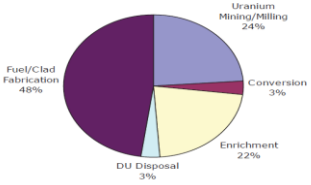

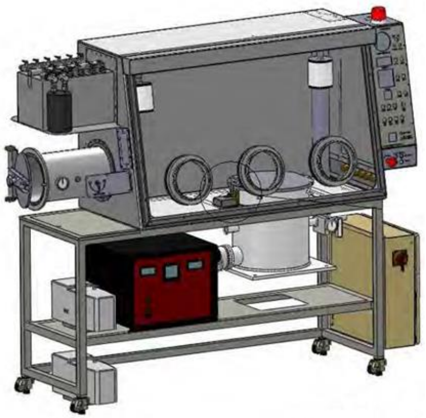

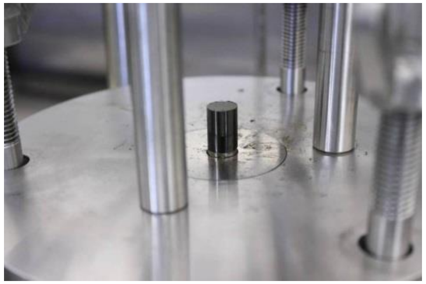

Fuel design specification → Equipment design → Equipment development & testing → Product Research & Development

Nuclear Fuel Centre of Excellence

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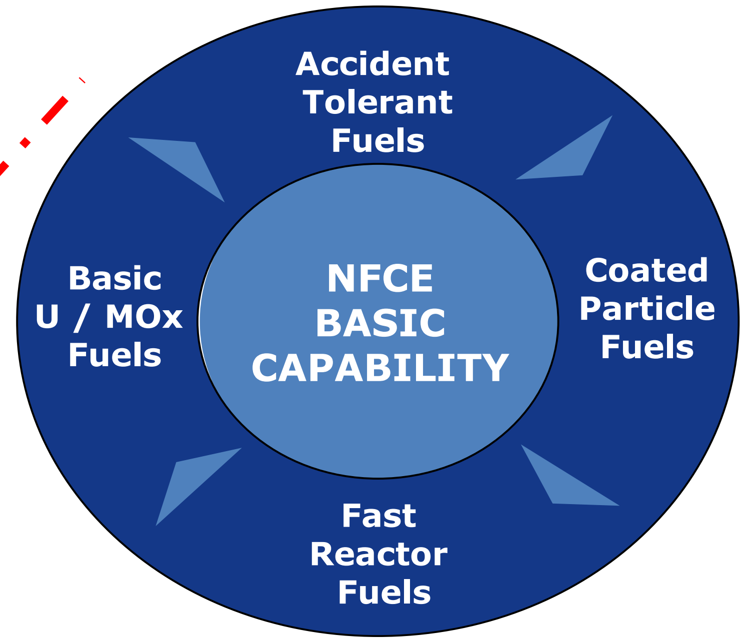

The ATF Challenge

Fukushima revealed vulnerabilities of the established UO_2/Zr alloy fuels to a LOCA (loss of coolant accident).

The challenge facing the international nuclear fuels community is to develop improved fuel/cladding materials that are more resilient and could be used in existing or new build reactors.

Economics of ATF

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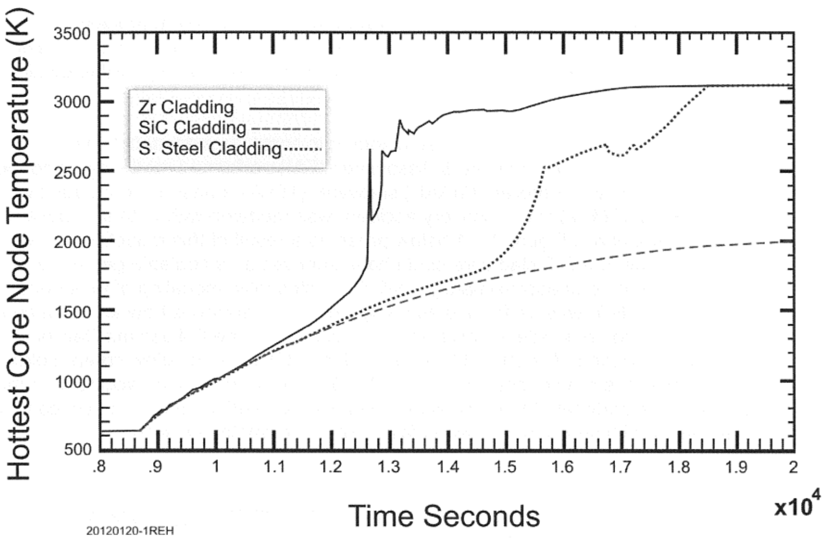
Nuclear Plant Accident Scenario	Estimated cost
Fission products contained and plant potentially reclaimed	$2Bn
Fission products escape to containment and plant cannot be reclaimed but cooling restored after short time	$10.6Bn
Cooling not restored for long time and fission products escape containment	$34Bn

Data from Lahoda et al, "What should be the objective of accident tolerant fuel" RT-TR-14-6, [2014]

Comparison of potential ATF claddings during cooling loss scenario



Key ATF attributes

- Tolerate higher temperatures (up to 1700°C)
- Reduce hydrogen generation
- Increase "grace period" from minutes → hours → days.

Overview of different ATF options

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(1) Apply a coating to the Zr alloy cladding material to improve oxidation resistance

- Smallest change to existing manufacturing processes.
- Candidates include Cr, MAX phases, SiC

(2) Replace the cladding with a better high temperature material

- SiC composites - for GenIV high temperature gas cooled reactors.
- Advanced steels (e.g. FeCrAl)

(3) Replace both fuel and cladding

- Doping UO_2 could improve thermal conductivity.
- Higher density fuel compounds (e.g. nitride or silicide) could improve thermal conductivity but water reactivity is a concern.

- Ceramic cladding such as SiC has much greater resistance to oxidation in water and steam, even at high temperatures
- Good radiation stability
- Low neutron capture cross-section
- Greater mechanical strength at high temperatures.

Why change the fuel material?

- UO_2 has poor thermal conductivity
- UN and U_3Si_2 have higher thermal conductivity

- Higher density fuels have same power output for a lower enrichment

- These economic benefits can offset the development costs of the new claddings and fuels.

High Density Fuel Options

Material	Theoretical density (TD) /g.cm^{-3}	Difference in heavy metal TD compared to UO_2	Thermal conductivity at 1100°C /Wm^{-1}K^{-1}	Melting Point /°C	Thermal expansion coefficient /x10^{-6}K^{-1}
UO_2	10.96	-	2.8	2840	10
UN	14.3	+40%	22.8	2762	8
U_3Si_2	12.2	+17%	17.3	1665	15

However….

- UN would need to be enriched in ^{15}N to avoid ^{14}C production in reactor and subsequent issue for storage/re-cycle/disposal.
- Both UN and U_3Si_2 are reactive to some extent with water. Need to understand water reaction under PWR conditions and potential consequences of a burst pin.
- Irradiation induced swelling is slightly worse than UO_2, however more testing is required under PWR operating and transient conditions.

USDoE ATF programme

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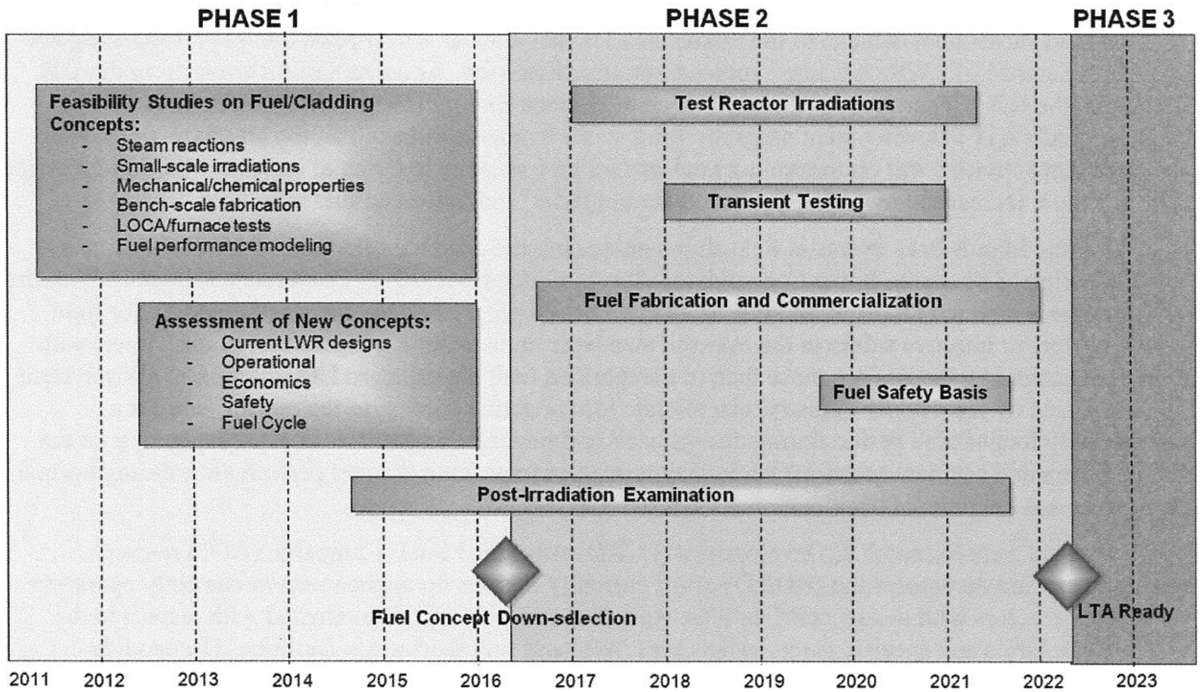
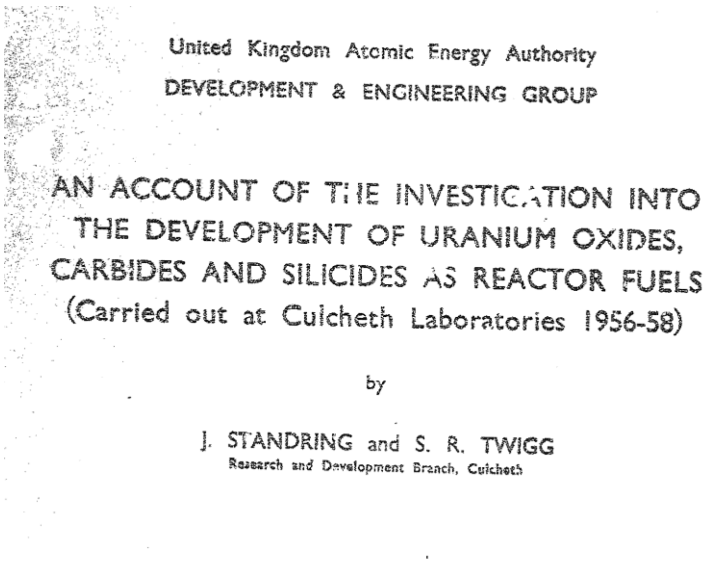
- USDoE have set out a timetable to have Lead Test Assemblies (LTAs) ready by 2022.
- NNL are supporting a Westinghouse led consortium to develop a new manufacturing route for U_3Si_2 fuel and deliver fuel for test irradiations in 2017.



From "LWR Accident Tolerant Fuel Performance Metrics", INL/EXT-13-29957 [2014]

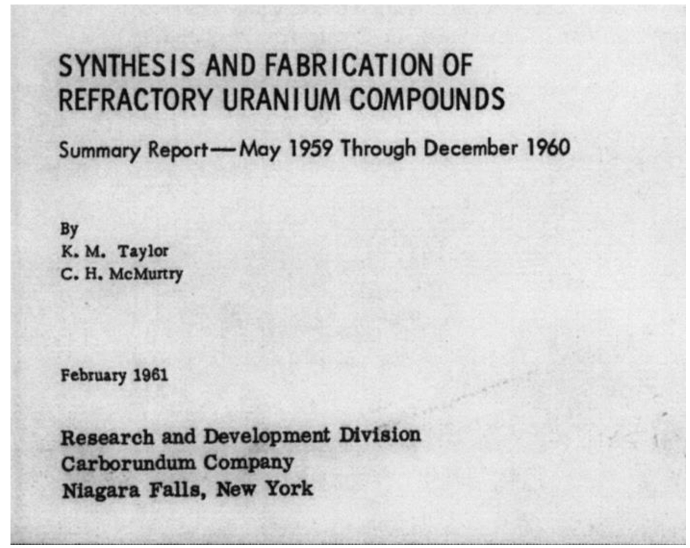
Manufacture of high density fuels


United Kingdom Atomic Energy Authority
DEVELOPMENT & ENGINEERING GROUP

AN ACCOUNT OF THE INVESTIGATION INTO THE DEVELOPMENT OF URANIUM OXIDES, CARBIDES AND SILICIDES AS REACTOR FUELS
(Carried out at Culcheth Laboratories 1956-58)

by

J. STANDRING and S. R. TWIGG
Research and Development Branch, Culcheth


SYNTHESIS AND FABRICATION OF REFRACTORY URANIUM COMPOUNDS

Summary Report—May 1959 Through December 1960

By
K. M. Taylor
C. H. McMurtry

February 1961

Research and Development Division
Carborundum Company
Niagara Falls, New York

- High density fuels were considered in the early days of the industry.
- U_3Si_2-Al dispersion fuels are also commonly used as research and test reactor fuels.
- Manufacturing routes have been developed to fabricate U_3Si_2 powder but not for large scale production.
- All current and historical routes combine U (metal) with Si.

Options for U_3Si_2 fuel manufacture

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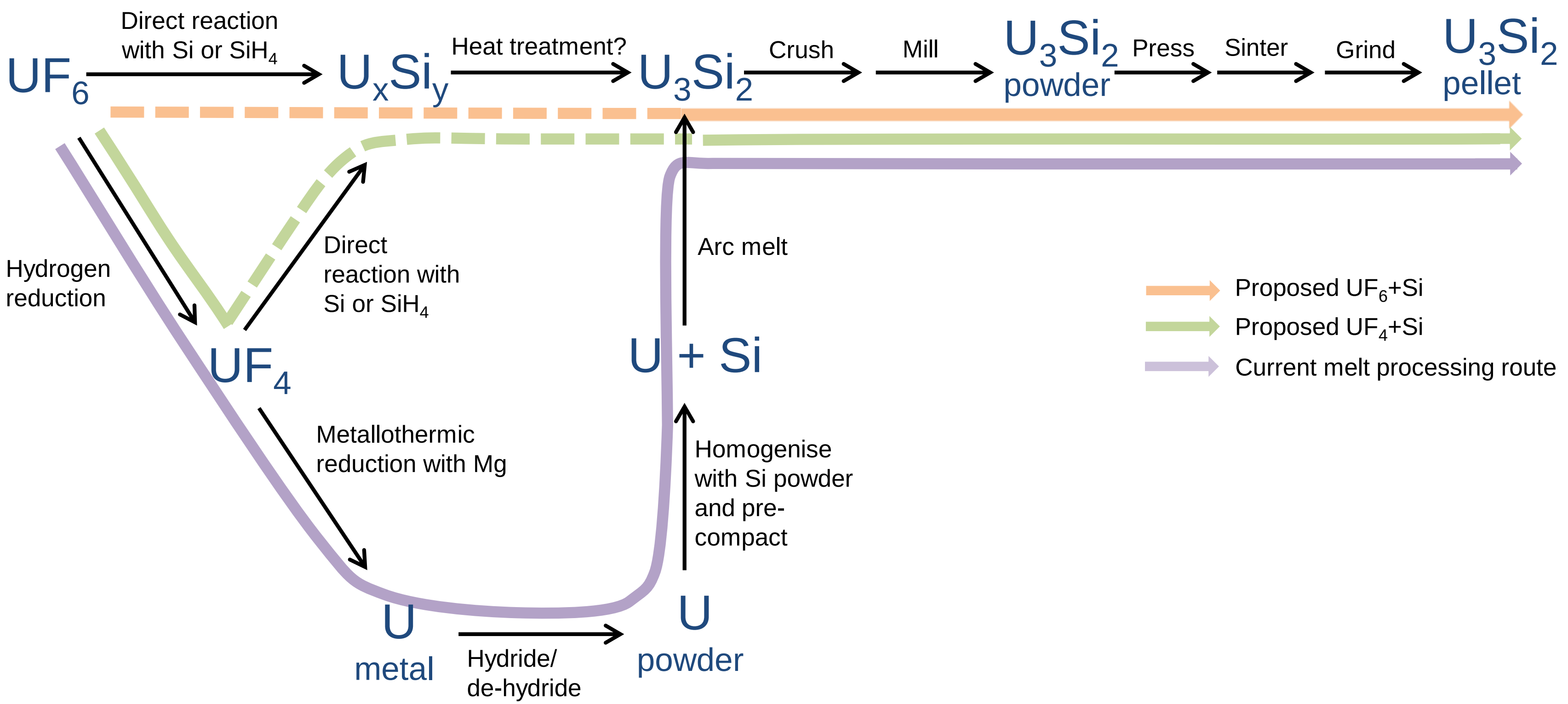

Previous work:
UF_6 + SiH_4 + Li reaction at 1000°C (Robinson et al, US Patent 3331666, 1967)
UF_6 + Si at 1450-1750°C (Lessing and Kong, US Patent 6120706, 2000)
No reports of UF_4 + Si or SiH_4 reactions

Thermodynamic assessment of UF_6 + Si

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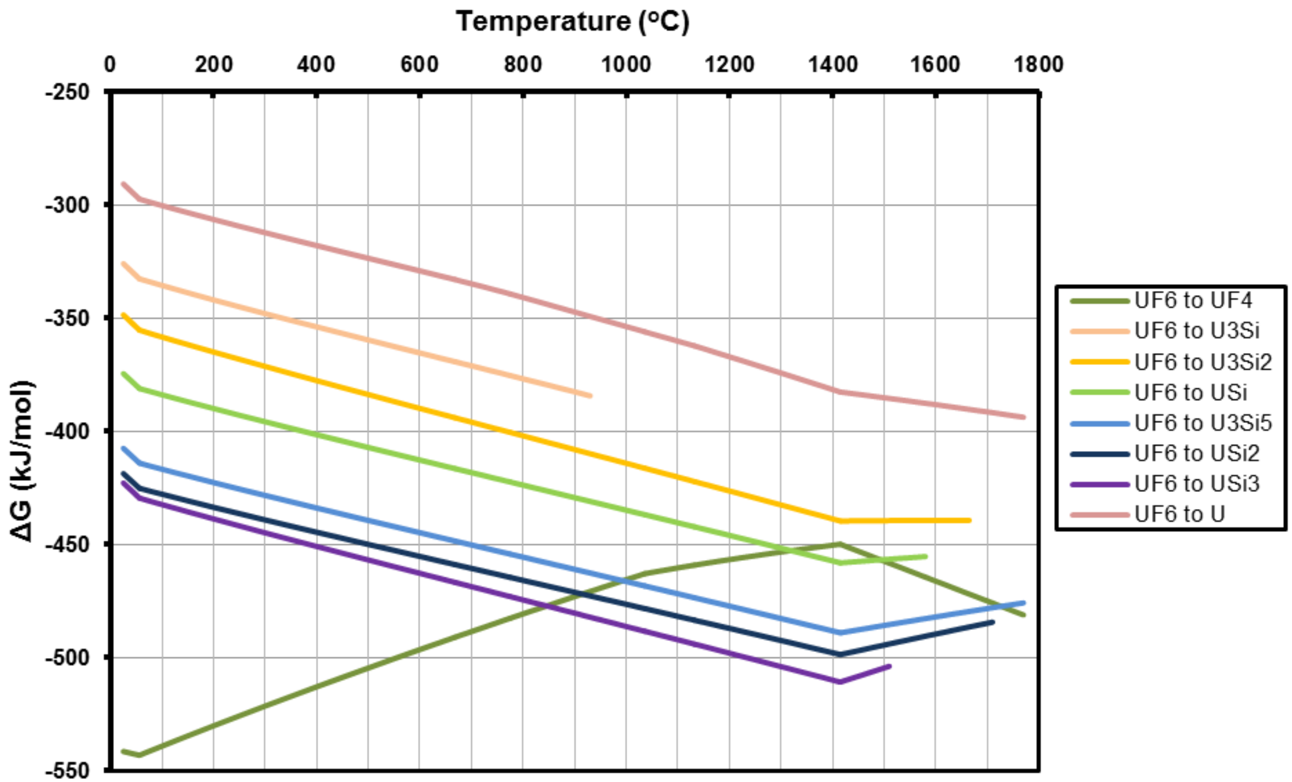
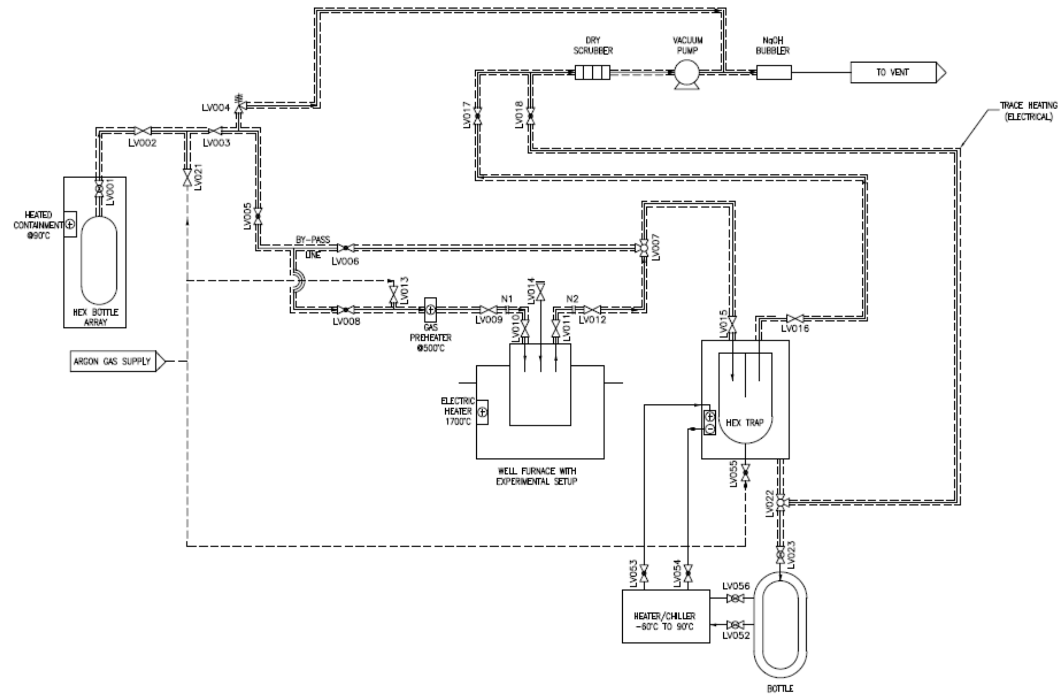


- Many possible reactions (ΔG is negative), but we don't know the kinetics.
- Undesirable competing reaction forming UF_4.
- Higher Si containing USi_x phases have a more negative ΔG.

Experimental plans

- Small scale tests of the UF_4+Si reaction using a TGA.
- UF_6 + Si + H_2 reaction rig to investigate kinetics of reactions.
- Nuclear Fuels Centre of Excellence (NFCE) equipment being installed to support this work.
- Arc-melter to develop conventional melt processing route.
- Inert glovebox line to develop pelleting process.
- Scale–up considerations, e.g. off gas (SiF_4) treatment or re-use and recycle routes.



UF_6 + Si (+ H_2) reaction rig design

R&D on GenIII & GenIV fuel

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Manufacture and performance assessment of many diverse fuel types;

Experience of manufacture and performance assessment of many diverse fuel types;

- metallic uranium fuel
- UO_2 fuel (PWR, AGR)
- $(U,Pu)O_2$ MOX fuel
- coated particle fuel for Dragon HTR
- carbide and nitride MOX fuel for experimental reactors

Active Participants in OECD

MAGNOX AGR BWR SGHWR PWR VVER HTR SFR GFR SMR’s

Pu & MA fuels

Plutonium capability at Central Laboratory

- Pu disposition work related to MOX fuel
- R&D on Fast Reactor fuel fabrication
- Recycle capability enables tailored fuel composition
- Waste separation & treatment
- Post Irradiation Examination of spent fuel
- Significant UK expertise & know-how at industrial scale (SMP, THORP)

Selected NFCE capabilities

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Material analysis

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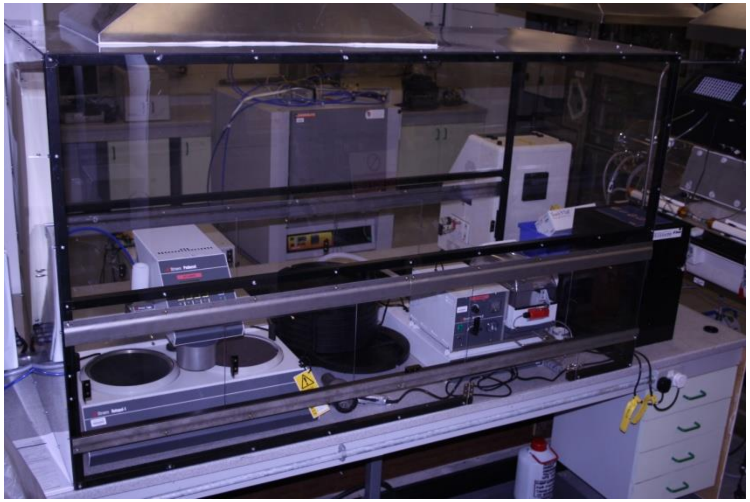
Pellet Dimensions and Density

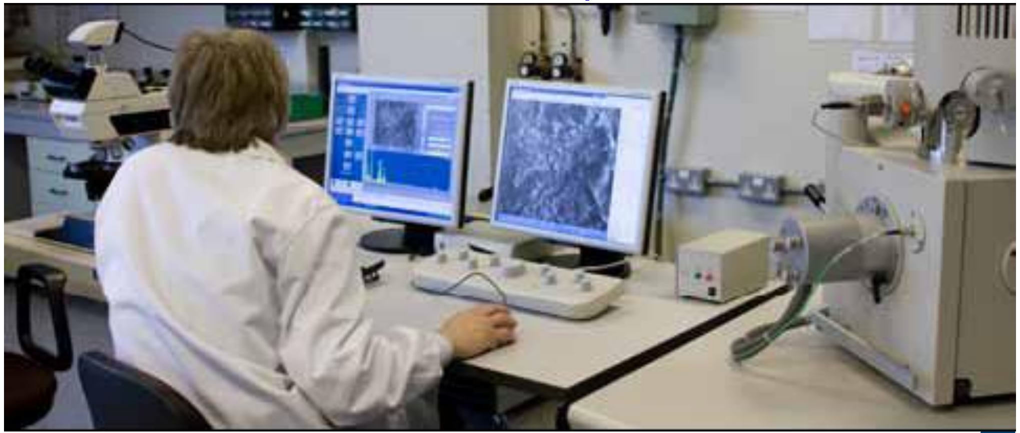
Powder Testing

Mechanical Properties

Microscopy cross section preparation facility



Micro Analysis



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