Accident Tolerant Fuel: A UK Perspective

Position Paper




Executive Summary

- Accident Tolerant Fuel (ATF) represents a significant opportunity for the UK to utilise expertise in nuclear fuel manufacturing to develop and commercialise ATF products, securing manufacturing jobs in the UK and developing export opportunities.
- The UK could benefit from future deployment of ATF in a new generation of Light Water Reactors (LWRs) including certain designs of Small Modular Reactors (SMRs).
- The UK should be an active participant in international collaborations on ATF, evaluating concepts and developing them through to commercial products.
- ATF research should target improvements in both cladding and fuel materials to ensure that new products demonstrate greater resilience in accident scenarios, and are also affordable.
- ATF needs to demonstrate performance which is at least as good as current UO_2/Zr alloy fuels in normal operation and design basis accidents as well as the more severe accident scenarios they are designed to protect against.
- This position paper has compared leading ATF cladding and fuel materials; research should prioritise the areas which are currently identified as being barriers to adopting the fuel/cladding materials.
- Opportunities for technology transfer between ATF and non-nuclear, fusion and Gen IV reactor systems should be explored.
- Spent fuel management of ATF needs careful consideration, but has received little attention to date. There is potential for UK expertise to have an impact in this area.

1. Introduction

Ceramic uranium dioxide (UO_2) pellets contained within a zirconium (Zr) alloy cladding has been the fuel of choice for light water reactors (LWRs) for over 40 years. While the behaviour of this fuel is well understood, the events at the Fukushima-Daiichi plant in Japan in 2011 revealed its inherent vulnerability to a prolonged station blackout. Although this type of event is extremely rare, the consequences are significant: the current estimate for the removal of fuel debris, clean-up of contaminated land and compensation payments resulting from Fukushima are estimated to be $191Bn (1). This has led researchers to focus their efforts on what can be done to improve the resilience of fuels in severe accident scenarios. Any improvements however must be economically viable to ensure that nuclear continues to be a competitive source of clean energy.

2. Defining Accident Tolerance

A modern LWR contains approximately 100 tonnes of fuel and 20 tonnes of cladding which together retain a significant amount of stored energy, which is released, together with heat from the decay of short-lived radionuclides, when a reactor is shutdown. In an accident situation where cooling of the fuel is interrupted the temperature of the fuel will increase. At around 800°C the Zr alloy cladding will balloon and burst releasing fission products into the primary coolant circuit. At around 1200°C the rate of the exothermic reaction between Zr and steam increases markedly releasing significant quantities of combustible hydrogen gas. This was the cause of the explosions that damaged the reactor buildings at the Fukushima-Daiichi plant and contributed to the release of radionuclides to the environment.

Put simply, during a prolonged station blackout, the accident tolerance of a fuel is directly related to the ability of the fuel to withstand increasingly high temperatures. This can also be thought of in terms of a "coping time", a measure of the time that operators have to re-instate cooling of the reactor to prevent major consequences. If the coping time could be extended from minutes to hours to days (or even indefinitely), it could significantly reduce the consequences of possible future severe accidents.

3. Economic and Performance Requirements

Reactor operators are showing interest in adopting new advanced fuels, so-called Accident Tolerant Fuel (ATF), which perform better in accident scenarios, provided there is no economic detriment in doing so. These fuels will also need to undergo stringent testing to ensure that their operating performance under normal operation and design basis accident conditions is at least as good as that of existing UO_2/Zr alloy fuels.

The introduction of a new fuel type requires extensive testing and evaluation as shown in Figure 1. Typically this entire process can take between 10-15 years, from concept to a fully commercial product. For ATF to play a role in providing added protection to existing LWR fleets acceleration of this fuel qualification process is desirable. This is because of the age of existing reactor fleets. In 10 years, when ATF might be available, 85% of the US LWR fleet and 73% of European LWRs will have been operating for more than 40 years (1). The urgency to proceed quickly is reflected in the US Department of Energy ambition to have ATF deployed in commercial reactors in the form of lead test rods or assemblies as early as 2022 (2). Although the window of opportunity for ATF deployment in existing reactor fleets will gradually close, countries with younger reactor fleets, such as China, could see enhanced benefits of ATF, as well as countries embarking on new build programmes, including the UK.

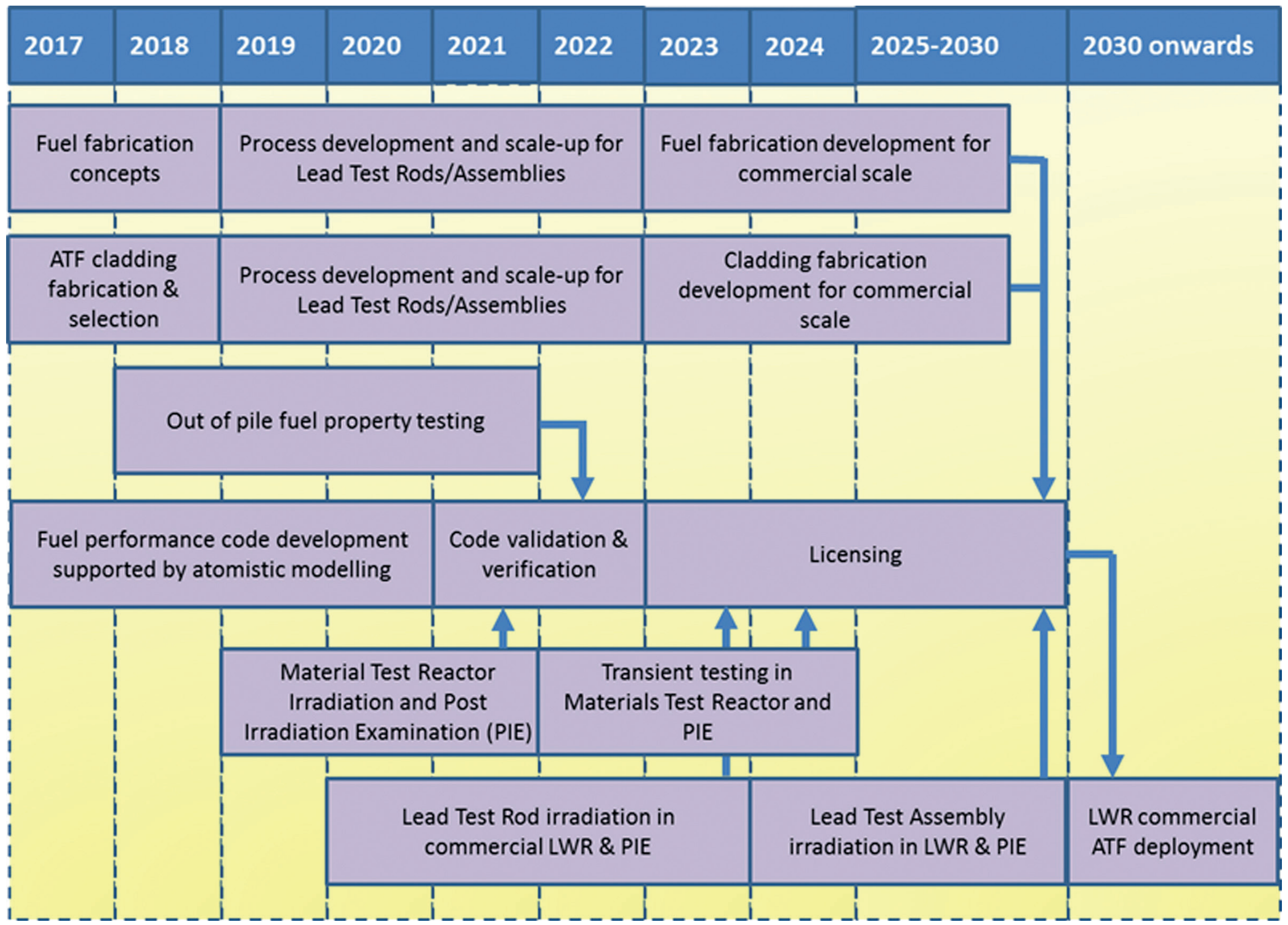

Figure 1: Schematic showing the steps required to qualify new ATF and the timescales involved, assuming no acceleration.

There will be a high expectation on the performance of ATF in normal operating conditions. Since the introduction of Zr alloy clad UO_2 fuel in the 1970s, fuel rod failure rates have decreased by three orders of magnitude, such that they are now a rare occurrence (3). This has been achieved through improvements in fuel assembly design, materials, manufacturing reliability and quality assurance and reactor operation procedures. ATF will be expected to demonstrate operational excellence from its introduction, which will necessitate high levels of manufacturing control and quality assurance of the product.

From an economic perspective one perceived benefit of improving the safety margin of the fuel is that it might allow reactor operators to make a case to reduce the requirements to maintain multiple back-up safety systems or reduce the extent of emergency preparedness arrangements, which could result in significant savings to reactor operation, maintenance and licensing costs. However, these potential economic benefits will only be realised if the cost of ATF remains at around the same level (or lower) than the current cost of UO_2/Zr alloy fuel. Furthermore, the significant cost of developing a new ATF concept through to commercial scale will need to be taken into account. Although some of the early development costs may be supported through government funded initiatives, it will be the fuel vendors who bring these products to market and they will expect to see a return on their investment. The cost of fuel can be separated into the "uranium cost" (including the costs of uranium ore extraction, conversion to uranium hexafluoride and enrichment) and the "manufacturing cost" (including the costs of conversion and pelleting of the fuel material, cladding fabrication, rod loading and assembly fabrication). When considering the cost of a particular ATF concept, special attention needs to be given to changes that may be required to the enrichment of the fuel (which is the largest contributor to the uranium cost) and to the manufacturing processes for the fuel and cladding.

Current UO_2/Zr alloy fuel is a very mature product, manufactured to a very high quality with a high level of automation and established supply chains. Introducing new fuel or cladding types could have a significant impact on the manufacturing process and supply chains and may require new infrastructure investments to be made.

Another important consideration which has both safety and cost implications is what to do with the spent fuel. This will depend on the policy adopted by different countries. If the fuel is to be reprocessed then compatibility with the existing PUREX process, based on dissolution of the fuel in nitric acid, will need to be tested. If this proves to be problematic then alternative processing schemes will need to be developed. If the fuel is to be stored awaiting long term disposal then assurance that the spent fuel will remain stable over long periods of time in the environmental conditions in which it is stored will be required. Decay heat generated by the fuel may also be different to standard LWR fuel, which could necessitate changes in the spacing and ultimately the size of a long term repository. These issues have received little attention to date but will become increasingly important as the most promising ATF candidates progress through fuel qualification.

4 UK Perspective

The UK has only one operating LWR (Sizewell B) and therefore the direct impact of introducing ATF in current generating plant will be small compared to many other countries. However by the time ATF products are licensed for use, the UK can expect to have a new fleet of LWRs, which could benefit from adopting ATF. Furthermore, the UK is investigating the potential deployment of Small Modular Reactors (SMRs), due to the anticipated benefits of lower financing costs and savings resulting from modular manufacturing methods. The lower thermal powers of SMR designs mean that there are less onerous requirements for decay heat removal during an accident than for a large scale LWR. The use of ATF could therefore increase the coping time of SMRs to the extent that it might be possible to eliminate the need for operator action during a severe accident. Such "walk-away safety" could be an important differentiator for SMRs when compared to some large scale LWRs. Whether ATF is deployed in new large scale LWRs (such as Hinkley Point C) or in SMRs it could result in plant which is more resilient in the event of a severe accident and has improved economics, benefiting the UK consumer.

The UK has a proud history of innovation in nuclear fuel manufacture, including the Integrated Dry Route (IDR) process operated by Springfields Fuels Limited, which manufactures UO_2 fuel for the UK fleet of Advanced Gas-cooled Reactors (AGRs), as well as UO_2 fuel and powder products for the overseas LWR market. Historically the UK skill base in fuels has also developed manufacturing routes to supply fuel and cladding materials for a variety of prototype and test reactors. For example, UK researchers investigated the development of an all ceramic fuel, based on a silicon carbide (SiC) clad UO_2 fuel as the proposed next evolution of the AGR. The UK fuel manufacturing sector is therefore ideally placed to play a leading role in international efforts to develop new cladding and fuel materials, and to commercialise their production routes. This connects with the UK Government Industrial Strategy (4) which has a focus on manufacturing and materials of the future with a challenge to ensure that the UK leads the world in the sustainable manufacturing and delivery of the next generation of products and components. It is also important to recognise that other industrial sectors (e.g. automotive, aviation, space) as well as other segments of the nuclear sector (e.g. fusion, GEN-IV reactor concepts) are also looking to develop new materials able to withstand increasingly hostile environments. This could lead to opportunities for technology transfer in both materials development and manufacturing methods between sectors. There is also an opportunity for the UK to take a lead in the evaluation of spent fuel management strategies for different ATF concepts, building on historic strengths in this area.

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The UK could see ATF deployed in new build reactors (including certain SMRs) by 2030. There are significant opportunities for the UK to play a leading role in the development of new ATF concepts, especially in manufacturing, testing and spent fuel management.

5 Comparison of ATF Options

With the importance of both performance and economics of ATF in mind, a comparison has been made (see Table 1) of some of the leading ATF candidates. This is not intended to include all of the ATF concepts that have been described in the literature, but rather concentrates on assessing the candidate materials that are at the forefront of international efforts. The table considers both performance and economic attractiveness of the different fuel and cladding materials. The colour coding shows how each material performs relative to the current UO_2/Zr alloy fuel, with green indicating improvements in performance or economics and red indicating where there are known deficiencies. Not surprisingly, candidate fuel and cladding materials generally show improved performance under severe accident scenarios, since they are designed to be more resilient in those circumstances. However not all candidate materials have acceptable behaviour in normal operating conditions. From a research perspective, tackling the issues that are currently negative relative to UO_2/Zr alloys presents the best chance of bringing ATF concepts to market.
The assessment in Table 1 has been carried out for fuel and cladding materials in isolation. Bringing a fuel together with a cladding provides an opportunity to combine performance and economic benefits, for example by using a high uranium density fuel with a silicon carbide composite or Fe alloy cladding. The assessment does not take into account potential issues concerning the chemical compatibility between fuel and cladding materials, which will need to be considered separately.

In the following sections each of the candidate fuel and cladding materials and the current research issues are considered in more detail.

5.1 ATF Cladding

The cladding provides an important barrier to the release of radioactive fission products in the event of an accident. Therefore approaches which aim to maintain the integrity of the cladding by for example reducing its rate of oxidation are the main focus. By reducing oxidation rates the quantities of combustible gases that are released can also be reduced. Concepts currently under consideration include modifying the existing Zr alloy cladding through a surface treatment, the application of a coating, or changing the cladding material entirely. Each concept varies in the extent of the potential improvement in accident tolerance and the time and cost required to develop and demonstrate the new concept through to licensing its use in reactors. Three of these concepts which are receiving most attention are considered below.

5.1.1 Coated Zr Alloy Cladding

One of the simplest approaches to developing an ATF cladding is to apply a thin coating to the current Zr alloy. Several materials have been proposed as coatings and may be judged according to the protection afforded by the oxide that is formed when exposed to steam at high temperatures, as well as its chemical and mechanical compatibility with the Zr alloy substrate. One promising candidate is a metallic chromium coating which oxidises to form a protective chromia (Cr_2O_3) layer (see Figure 2a). This has been shown to reduce weight gain significantly relative to Zircaloy-4 when oxidised at 1200°C for relatively short periods of time (5,6). Although this may only provide a small increase in coping time, the reduced heat generation and H_2 production from the oxidation reaction could be vital in the recovery of an accident situation.

In addition to the choice of material the coating technology must be tailored to the mass production of ~4m long, ~1cm diameter coated Zr alloy tubes. This technology selection requires a compromise between several factors, including the quality of the coating, its adhesion and wear resistance (which must, at the very least, be sufficient to withstand loading of rods into fuel assemblies), the rate of deposition and the consistency that can be achieved as the process is scaled-up. Physical Vapour Deposition (PVD) techniques (7) produce high quality, almost defect free coatings but at a relatively slow deposition rate, whilst those based on plasma spraying (8) are quick to deposit but tend to be rough and contain porosity.

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Coated Zr alloy claddings are a promising near term option that would be relatively easy to implement, although benefits in accident scenarios are likely to be small.

MATERIAL		PERFORMANCE ATTRIBUTES		ECONOMIC ATTRIBUTES		Other Issues
		Normal Operating Conditions	Severe Accident Scenarios	Uranium Cost (e.g. neutronic / enrichment effects)	Manufacturability	
CLADDING	Coated Zr alloys	Minimal change from existing cladding.	Small increase in coping time compared to existing cladding.	Small neutron penalty depending on coating material and thickness.	Technology to coat full length LWR rods yet to be demonstrated.	Durability of coatings during assembly production.
CLADDING	Advanced Fe alloys	Tritium permeability may require mitigation strategy. Potential embrittlement for high Cr contents.	Good performance at temperatures close to 1500°C.	Higher neutron absorption requiring either thinner cladding or higher enrichment fuels.	Established industry and manufacturing technologies for certain alloys.	Resilience of thin walled cladding tubes during production.
CLADDING	SiC/SiC composites	Hydrothermal corrosion of SiC/SiC in normal operating conditions is concerning.	Excellent high temperature performance with potential for significant safety benefit.	Lower neutron absorption than Zr alloys.	Manufacturing costs currently high. Hermetic cladding-to-end-cap joining technologies need to be proven.	Development of new testing procedures and licensing approach.
FUEL	Advanced UO_2 fuels	Increased thermal conductivity, fission product retention, creep and oxidation resistance with minimal changes to other properties.	Higher thermal conductivity reduces stored energy and improves margin to melting, assuming dopants do not affect melting point.	Lowering of uranium density increases enrichment costs as additive content increases. BeO is possibly an exception due to neutronic behaviour.	Manufacture mostly compatible with existing fabrication processes.	
FUEL	Uranium Nitride (UN)	Requires testing. Swelling behaviour not yet proven. Reaction with water likely to be unacceptable.	Melting point comparable with that of UO_2. Much higher thermal conductivity increases power to melt.	Highest uranium density increase (+40%) providing economic benefit.	Current manufacturing routes not commercially scalable.	Commercially scalable enrichment in ^{15}N not yet demonstrated.
FUEL	Uranium Silicide (U_3Si_2)	Requires testing. Swelling behaviour and reactivity to water not yet proven to be acceptable.	Higher thermal conductivity offsets lower melting point than that of UO_2.	Increase in uranium density (+17%) providing economic benefit.	Current manufacturing routes not commercially scalable.	

Colour scale:

positive			neutral			negative

Table 1: Comparison of performance and economic attributes of ATF candidate fuels and claddings.

5.1.2 Advanced Fe Alloy Cladding

Austenitic stainless steels were used as cladding materials in the early days of LWR deployment. Cladding failures due to stress corrosion cracking, especially in the highly oxidising water chemistries of boiling water reactors (BWRs), combined with higher neutron absorption compared to Zr alloys, led to the phasing out of the use of steels by the early 1980s. However, significant progress has been made recently to evaluate the use of ferritic FeCrAl alloys as potential cladding materials where the high temperature oxidation resistance in steam relies on the formation of an alumina scale (3). Oxidation resistance in these alloys has been shown to extend up to around 1475°C, close to their melting point (9). FeCrAl alloys have also been shown to perform well in normal operating conditions in both pressurised and boiling water coolant chemistries (10). The mixed Cr- and Fe-rich spinel phases that form under these conditions appear to have only a relatively minor detrimental effect on the subsequent formation of the protective alumina layer in high temperature steam (11).
The main issue for Fe alloy cladding is the higher neutron capture cross-section compared to that of Zr alloys, which would require either an increase in the fuel enrichment or a reduction in the thickness of the cladding to offset the neutron penalty. To maintain enrichment below the current 5% 235U limit, a reduction in clad thickness to ~300μm with an associated increase in fuel pellet diameter, would be needed. Whilst the manufacture of thin walled cladding tubes is technically feasible, the overall fuel cost is estimated to be between 15-35% higher than that of current LWR fuel (3). Additional concerns for Fe alloys as a cladding material are the potential for radiation-induced embrittlement in high Cr content alloys and their permeability to tritium. Although tritium is a relatively weak ß-emitter, any significant increase in the inventory of tritium in the primary coolant would increase dose to reactor personnel which might require mitigation, such as the incorporation of a barrier layer on the inside of the clad (12).

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New Fe alloys show promising high temperature behaviour, however the inherent neutron penalty will challenge their economic viability.

5.1.3 Silicon Carbide Composite Cladding

Silicon carbide (SiC) fibres reinforcing a bulk SiC matrix (SiC/SiC) as shown in Figure 2b offer the potential for a low activation, low neutron absorption material capable of withstanding very high temperatures and high doses of irradiation (13). The most radiation tolerant SiC/SiC consists of pure, near stoichiometric, highly crystalline ß-SiC fibres and matrix. These are best produced using Chemical Vapour Infiltration (CVI) or liquid phase sintering techniques, such as the Nano-Infiltration and Transient Eutectic-phase (NITE) process. Of these, CVI is a relatively mature process but is relatively slow and costly, whereas the NITE process is less mature and long thin tubes are more difficult to manufacture, although in principle it could be quicker and cheaper to produce the required quality of product (14).

In most SiC/SiC designs the outer surface consists of a monolithic SiC layer since this has been shown to demonstrate excellent oxidation resistance to steam at temperatures up to 1600°C (15,16). However SiC/SiC does not perform so well in the hydrothermal conditions representative of LWR operation, since under these conditions the SiO_2 layer which forms is not protective. The addition of dissolved hydrogen, as is typical in a pressurised water reactor coolant, has been shown to reduce the rate of dissolution (17). However the formation of reactive species in the coolant due to neutron irradiation is also detrimental to the hydrothermal corrosion of SiC/SiC, such that it is not yet certain whether control through the addition of dissolved hydrogen can reduce the dissolution rate to tolerable levels.

SiC/SiC presents a number of additional challenges compared to metallic claddings, meaning that the timescales for possible implementation are longer. Joining the end caps to the cladding with a hermetic seal is an issue given that the use of welding is not possible. Joining techniques being investigated include diffusion bonding, transient eutectic phase joining, metallic brazing and polymer-derived SiC joining (18). SiC/SiC is also not truly ductile, which is generally undesirable for a cladding material given the thermal stresses and internal pressurisation, coupled with the irradiation damage that the material experiences during normal reactor operations. Defining a failure criterion (a necessary step in the licensing of a cladding material) is difficult, since micro-cracking is likely to occur within the composite at stresses far below the point at which gross failure occurs. Establishing new mechanical testing procedures will probably be needed to allow a failure criterion to be defined.

The use of a new cladding material like SiC/SiC could also impact on fuel rod and fuel assembly designs. The pellet-clad gap, the thickness of the cladding and the fuel pellet diameter may all need to be adjusted to optimise the performance of the fuel. In terms of economics though, SiC/SiC does have a lower neutron absorption than other candidate claddings, providing potential savings. However, manufacturing costs for SiC/SiC are currently significantly higher than for Zr alloys and the extent to which these can be reduced through scale-up and the use of improved manufacturing technology remains uncertain.

NNL View

SiC/SiC composites are an attractive long term option due to excellent accident tolerance and low neutron cross-section. Demonstrating acceptable performance in LWR operating conditions, developing joining technologies and reducing manufacturing costs pose significant challenges.

a) b)

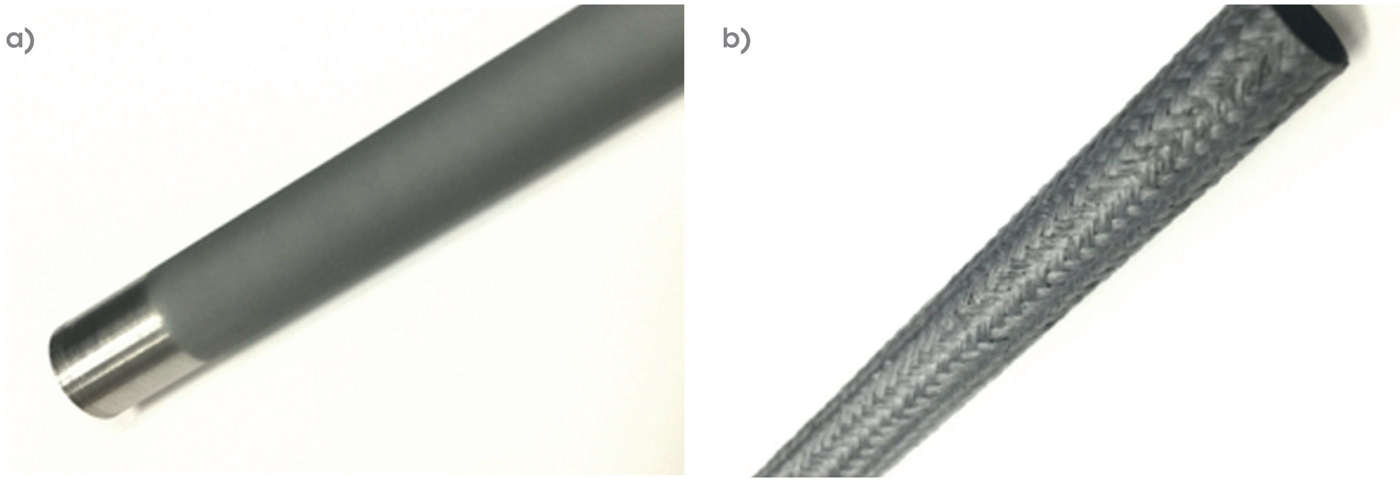

Figure 2: Test specimens of ATF cladding materials: (a) Cr-coated Zr alloy and (b) SiC/SiC composite (images courtesy of Westinghouse Electric Company).

5.2 ATF Fuels

Ceramic UO_2 has been the fuel of choice for LWRs throughout their history (now over fifty years). It boasts a high melting point (2847±30°C) (19), has good resistance to oxidation in water and its use is underpinned by a detailed understanding of its performance under irradiation. However, one drawback of UO_2 as a fuel, is its low thermal conductivity, which decreases with increasing temperature and burn-up. This low thermal conductivity leads to high pellet centreline temperatures and as a consequence the power-to-melt is not as high as it could be by switching to a different fuel material. In the following sections both evolutionary improvements to fuel materials, through the use of additives to UO_2, are considered alongside more revolutionary changes in the form of high uranium density fuel materials, which could also deliver significant improvements in fuel economics.

5.2.1 Advanced UO2 Fuels

Incorporating dopants or additives into UO_2 fuels to improve fuel performance is not new. Indeed fuel vendors have already developed doped fuels incorporating small (<0.2 wt%) amounts of chromia or a combination of chromia and alumina into the fuel, and these fuels are already employed in reload quantities. The benefits of this type of fuel result from increases in grain size and density, leading to better fission product retention, creep and oxidation resistance rather than any changes in thermal conductivity (20).

Higher levels of additives can be incorporated into the UO_2 matrix, resulting in more significant increases in thermal conductivity (21-24), but these fuels have yet to be irradiated in commercial reactors. Figure 3 shows the variation in thermal conductivity as a function of temperature for these materials alongside undoped UO_2 and other high density fuel materials, when unirradiated. Irradiation and the presence of porosity will reduce thermal conductivity, the former due to the accumulation of defects and fission products, which is important to take into consideration when assessing the in-reactor performance of the fuel.
Whilst any improvement in power-to-melt is desirable, there is an economic downside in the reduction of uranium density in the fuel due to the presence of the additive(s). In the case of BeO there is a potentially compensating effect due to a neutron-multiplication reaction of Be with fast neutrons which could lead to a net reduction in uranium cost, provided that any costs associated with the additional safety implications of working with carcinogenic BeO are not too great (25).
The satisfactory performance under irradiation of these additive fuels, including the effect on thermal conductivity, also needs to be demonstrated.

NNL View

The use of additives to improve the thermal conductivity of UO_2 has only a limited potential to improve accident tolerance and is also unlikely to offer benefits to the economics of fuel manufacturing.

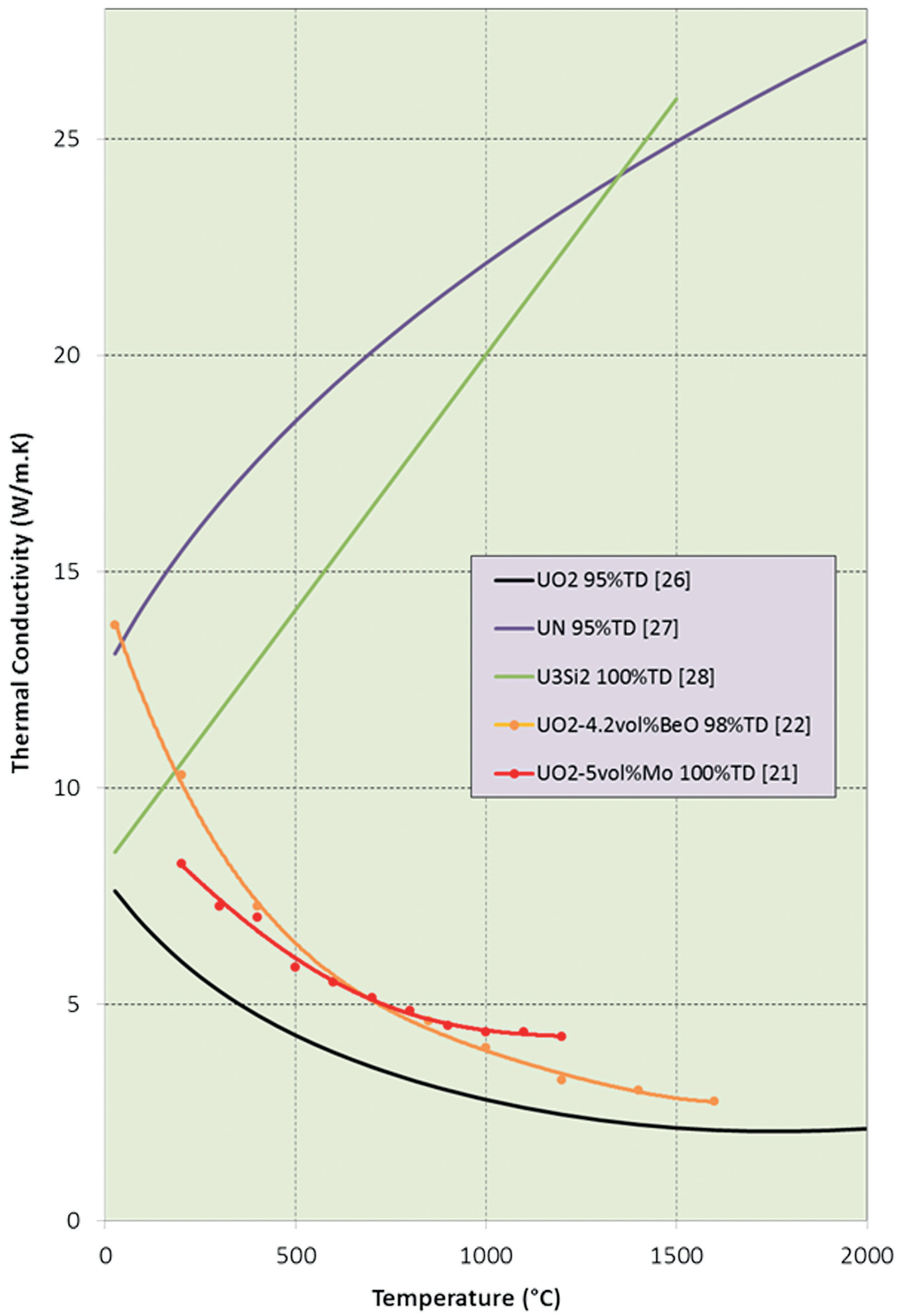

Figure 3: Temperature variation of thermal conductivity for unirradiated candidate ATF fuel materials, with density given as a % of theoretical (%TD).

5.2.2 High Uranium Density Fuels

Uranium compounds with higher uranium density than UO_2 have potential economic advantages by enabling the use of lower enrichment fuel, or by reducing the quantity of fuel that needs to be manufactured while keeping the enrichment level the same. The latter would require fuel to stay in-reactor longer, which would reduce operational costs associated with re-fuelling, but which would be challenging in terms of the increased fuel burn-ups that would be achieved.

Figure 4 shows potential high melting point, high density uranium compounds that might be considered as a replacement for UO_2. Of the four highest density uranium compounds UC is unattractive due to its reactivity with water, which could lead to extensive fuel washout in the event of a fuel rod failure. UN, which in theory would give the largest economic advantage and largest increase in power-to-melt, is better than UC in its water tolerance, but is still inferior to UO_2. Efforts are being made to improve on its water resistance by forming a composite fuel, incorporating a more water tolerant phase such as U_3Si_2 (29). A further difficulty with UN is the formation of ^{14}C via the $^{14}N(n,p)^{14}C$ reaction which presents downstream problems for reprocessing, long-term storage and disposal of the spent fuel. Technology to enrich nitrogen in the ^{15}N isotope has been developed at small scale, but the cost to do this industrially might be prohibitive.

UB_2 has not received much attention and its properties are not well known. Naturally occurring boron contains 19.9% ^{10}B, which has a very high neutron cross-section and is normally limited to parts per million levels in fuel specifications to avoid parasitic neutron absorption. An exception to this is where it is deliberately added to fuel as a burnable absorber to suppress over-reactivity during the early part of irradiation. The cost of boron depletion (reducing the ^{10}B concentration) could be prohibitive unless it is comes as a waste from a ^{10}B enrichment process, as is planned as part of boric acid production for several designs of new build LWRs. The extent of boron depletion could also be limited to allow sufficient residual ^{10}B to act as a burnable absorber.

U_3Si_2 has received considerable interest in the past few years and although it does not provide as large an increase in uranium density as the other compounds mentioned it does not require isotopic tailoring and its stability in water is better than UN (30). It also has a high thermal conductivity which increases with temperature (see Figure 3) which means that, despite its relatively low melting point, the power-to-melt is expected to be higher than UO_2.

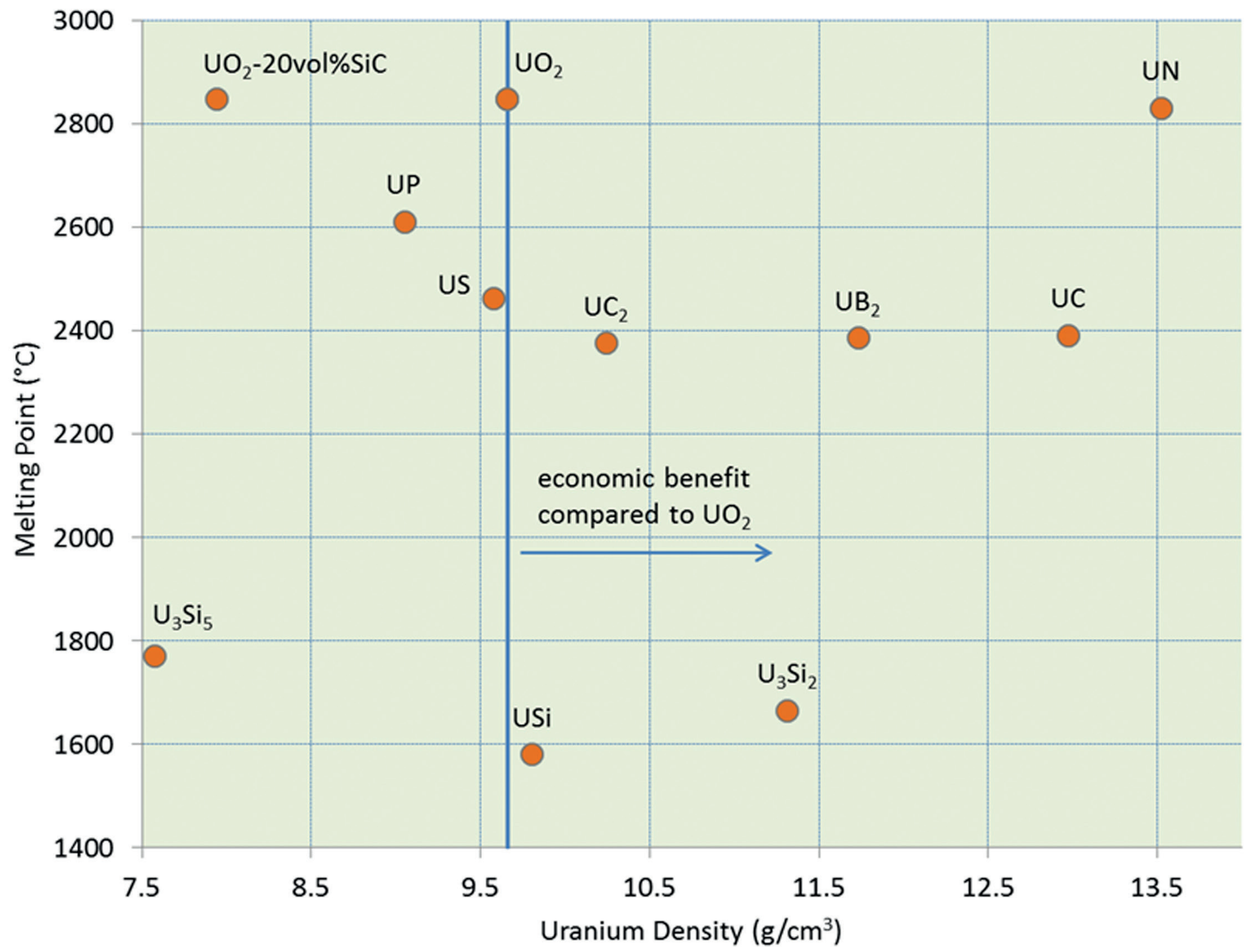

Figure 4: High melting point high uranium density compounds that might be considered as alternative fuels for ATF concepts.

The large scale manufacture of high uranium density fuels is an important consideration since fabrication routes developed at laboratory scale tend to be developed for convenience rather than commercial viability. For example, U_3Si_2 is commonly fabricated by arc melting of uranium metal with silicon. Not only is arc melting difficult to envisage being scaled up, but the uranium metal must first be fabricated by conversion of UF_6 to UF_4 (hydrogen reduction) and then of UF_4 to metal (metallothermic reduction with Mg or Ca) as shown in Figure 5. NNL are currently evaluating the potential for more direct conversion routes from UF_6 or UF_4 which would eliminate the reduction to metal and arc melting processes (30).

Demonstration of satisfactory irradiation performance of high uranium density materials under LWR conditions is also lacking. In particular, it has not yet been demonstrated that the in-reactor swelling of these materials is suitably low. A certain amount of increased swelling relative to UO_2 can be accommodated by a reduction in the pellet outer radius, but too large a fuel-cladding gap will result in unacceptably high fuel temperatures early in life.

NNL View

High density fuels have significant potential to deliver economic benefits to an ATF. However, firstly, commercial manufacturing routes must be developed and uncertainties over irradiation performance and water tolerance resolved.

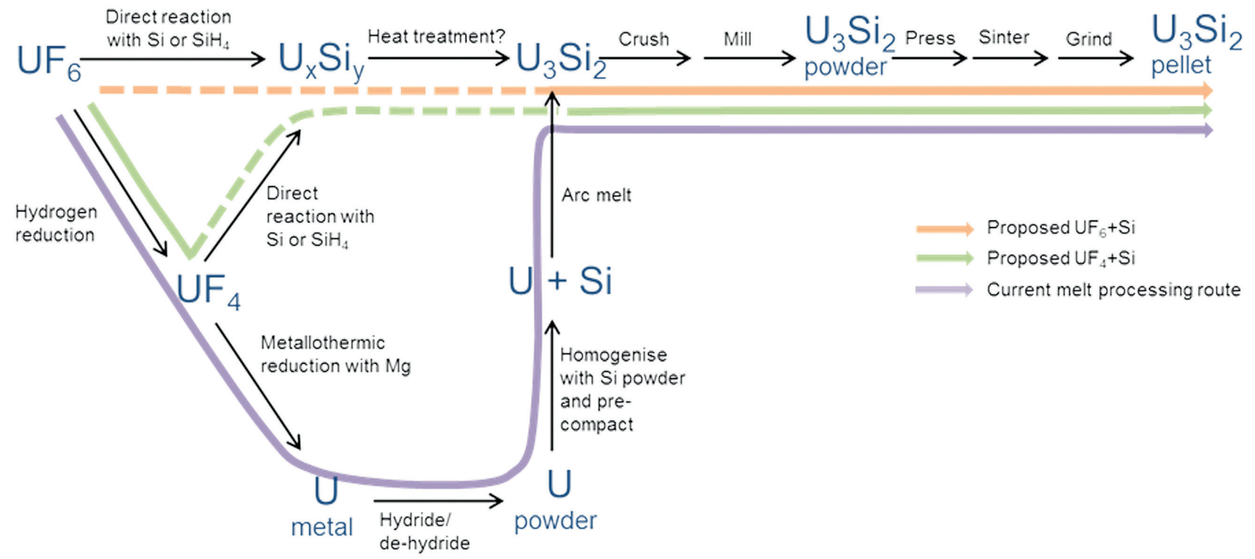

Figure 5: Overview of potential fabrication routes for U_3Si_2 fuel with (inset) a sintered pellet produced by a melt processing route.

6. Summary

Reactor operators are showing great interest in the prospect of new ATF concepts due to the potential combination of economic and safety benefits, whilst fuel vendors are striving to develop new products that will provide them with a market lead. The introduction of a new fuel or cladding material will require extensive testing and qualification, which in turn will require sustained investment from government and/or industrial stakeholders if the full benefits of ATF on existing LWR fleets and new build reactors including certain types of SMRs are to be realised.

A number of candidate ATF cladding and fuel materials have been assessed in terms of their performance in both normal operating conditions and severe accident scenarios together with factors affecting their economics. Table 1 is provided as a guide for researchers interested in this topic to focus on the issues that are likely to have the greatest impact in developing ATF. One of these areas is manufacturing, which links with the UK Government's Industrial Strategy to enhance manufacturing capability in the UK.

Until recently, changing from a UO_2-fuelled and Zr alloy clad fuel design for LWRs would have been unthinkable, but this view has shifted and is reflected in the significant research activities that are underway internationally. The UK should focus on deploying its strengths in manufacturing and seek to play a key role in international collaborations to help develop these concepts through to commercial reality.

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5th Floor
Chadwick House
Warrington Road
Birchwood Park
Warrington
WA3 6AE

T. +44 (0) 1925 289800
E. customers@nnl.co.uk

W. www.nnl.co.uk

@UKNNL

NATIONAL NUCLEAR LABORATORY