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UK fuel cycle R&D in Advanced Nuclear Fuels

Nuclear energy is a mature, reliable and low–carbon technology and is viewed by many as an essential contributor to a sustainable energy mix. In many countries, policy concerning the back end of the fuel cycle has yet to be resolved and many have yet to finalise their plans for geological disposal. Decisions on open vs closed fuel cycles will be dependent on the speed at which new fuels and reactor technologies are developed and on ultimate power generation requirements. As such, advanced reactor and fuel cycle research has an important role to play in setting out the most appropriate scenarios for nuclear energy deployment for the remainder of this century.

The depth and breadth of ceramic fuels manufacture R&D capability within the UK is based on decades of support to UK industry programmes together with involvement in international programmes over the longer term. With the closure of the final UK programme in this area (i.e. SMP support), these skills are likely to diminish without other programmes being implemented to sustain them.

In the UK, the R&D baseline has focused on mixed plutonium and uranium oxide (MOX) fuels. While it is important to protect knowledge and experience gained to date, this does not fully represent the boundaries of future research direction(s). Fuel cycle R&D to safeguard advanced ceramic fuel skills needs to be cognisant of the large nuclear materials management programme. Stocks of civil uranium and plutonium arising from reprocessing of spent fuel are being managed according to the UK policy of safe and secure storage, while maintaining options for future use of potentially valuable materials.

Fuel cycle R&D could augment this programme to:

- Keep a range of nuclear generating options open for the future;
- Enable the UK to make informed decisions on future policy and strategy;
- Support work that will be required on plutonium disposition;
- Open up the opportunity to leverage UK investment through international commercial work and collaboration on international programmes for example in the EU;
- Develop opportunities for exploitation of reactor demonstrators to be built in the EU.

Within Europe the Sustainable Nuclear Energy Technology Platform (SNETP) is focused on developing Gen IV reactors which will require the manufacture of test fuels. The very high costs and long lead times of building skills, expertise and new manufacturing facilities in terms of safety and licensing, infrastructure and security represents a significant hurdle in addition to those of delivering test reactors and next generation fleets. The UK already has key nuclear research facilities in place to lead on nuclear fuel research and is developing a Nuclear Fuel Centre of Excellence to equip these facilities to undertake research and development (R&D) for advanced nuclear fuels.

A vision for nuclear fuel research in the UK

The UK Government has published an R&D Roadmap [1] (Nuclear Energy Research and Development Roadmap: Future Pathways) which sets out a vision for nuclear research and development and the research outcomes that would be needed to support future energy policy decisions. It also makes the case that Government will need to take action to maintain an agile and flexible R&D capability to ensure that informed decisions can be made.

The Government's R&D roadmap cites research objectives for the short and long term including; protecting and developing nuclear fission skills and knowledge, development of organisational infrastructure and re-engagement with international collaborative programmes.

Priority research and development to fulfil these include:

- Deploying the UK's fuel cycle R&D facilities;
- Developing a rational basis for selecting a preferred UK future nuclear energy fuel cycle;
- Developing a rational basis (data bank and analysis) for selecting a preferred recycling technology, if a closed fuel cycle is to be adopted;
- Developing new, international nuclear energy links to develop complementary goals and symbiotic relationships.

Fuel technology is an area where the UK can demonstrate significant and advanced knowledge, and with the right infrastructure investment can play a major role in developing fuels for current and future generations of reactors.

Part of the Government's long term vision is to equip the UK to supply the fuel needs for Generation III+, Generation IV and Small Modular Reactor reactors globally. The figure below of the UK's public nuclear R&D facilities includes the facilities of the Nuclear Fuel Centre of Excellence (NFCE), for housing this fuel R&D equipment. These facilities will need to handle quantities of active materials including alpha active materials and house the required material performance testing and analysis equipment.

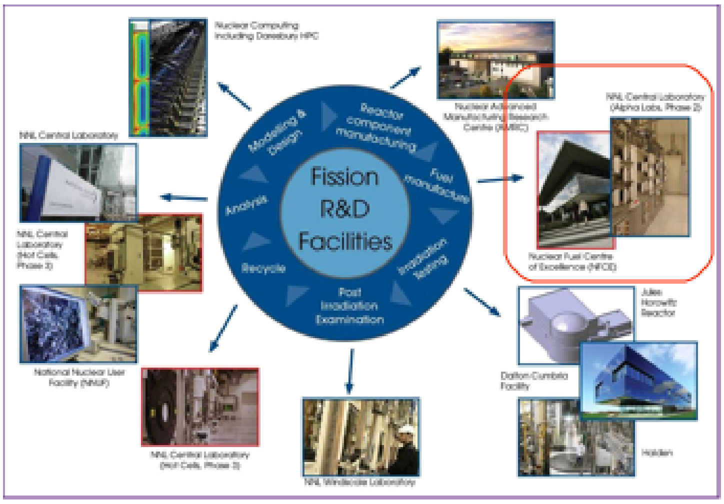
To attain a world-leading fuel manufacturing status will require fundamental research into fuel material performance and new and improved fabrication technology, and this research will need to be conducted by subject matter experts who have access to world-leading facilities. The establishment of a UK Nuclear Fuel Centre of Excellence would provide this, and see industry, NNL and academia engage in national and international collaborative research in advanced fuel manufacturing technology. The NFCE will be open to international partners,

[1] Nuclear Energy Research and Development Roadmap: Future Pathways, 2013

offering world-leading capability and facilities in advanced fuel fabrication R&D, complementing international facilities such as the Halden and Jules Horowitz Test Reactors.

The benefits of establishing a NFCE will be significant and include:

- Enabling development of advanced fuel and cladding leading to safer and more efficient fuels, subsequent lifetime extension and improved performance for post irradiation storage and waste disposal;
- Developing capability which will facilitate the potential for commercial fuel manufacture of Generation III+, Generation IV and Small Modular Reactor fuel;
- The ability to leverage investment through collaboration on international research programmes;
- Delivering test fuel for international reactor demonstrators, including Halden and the Jules Horowitz Reactor;
- Enabling access to high cost R&D facilities and equipment;
- Maintenance and advancement of critical nuclear skills.



UK's public nuclear fission R&D facilities (from the Nuclear Industrial Strategy)

In order to be world leading in nuclear fuel R&D, the UK will need to make use of the UK's significant underpinning academic strengths in materials science, combined with the facilities and capability of the Nuclear Fuel Centre of Excellence (NFCE). Collaboration through other centres of excellence such as the National Nuclear User Facility (NNUF), the Nuclear Computing Centre of Excellence (NCCE) and the Nuclear Advanced Manufacturing Research Centre (NAMRC) would enable this.

In the UK, the R&D baseline in recent times has focused on mixed plutonium and uranium oxide (MOX) fuels. While it is important to protect knowledge and experience gained to date, particularly since the closure of SMP and decommissioning of the MOX powder processing R&D rig and related equipment, this does not fully represent the boundaries of future research direction(s).

Fuel cycle R&D to safeguard advanced ceramic fuel skills needs to be cognisant of the large nuclear materials management programme while maintaining options for future use of potentially valuable materials. Stocks of civil uranium and plutonium arising from reprocessing of spent fuel are being managed according to the UK policy of safe and secure storage. Future treatment and storage options are being developed along with options for potential use of Pu and U stocks as MOX for disposition in Light Water Reactors (LWRs), Heavy Water Reactors (HWRs) or metal fuel for disposition in a fast reactor. The vision for the NFCE envisages additional areas of fuel research including in Accident Tolerant Fuels (ATF) for Generation III/III+ technologies, fuel-like targets for radioisotope production and fuels for Generation IV technology such as fast reactors.

The benefits of undertaking research in fuels will be derived from developing and deploying the skills and expertise in fuel manufacture that the UK needs to:

- Keep a range of nuclear generating options open for the future;
- Enable the UK to make informed decisions on future policy and strategy;
- Support work that will be required on plutonium disposition;
- Open up the opportunity to leverage UK investment through international commercial work and collaboration on international programmes for example in the EU;
- Develop opportunities for exploitation of reactor demonstrators to be built in the EU.

Engagement and close collaboration with industrial organisations will be important to gaining long term benefits from R&D in nuclear fuels. However, an Industry focus on R&D can be parochial which means that it will not sponsor very long term R&D on advanced fuels of the type that might be required to meet the large nuclear energy needs identified in some Government energy scenarios. Government action is therefore required to prevent market failure and to ensure that a skill base is developed to provide the advice that will be needed to support future energy strategy decisions. Therefore development of skills in advanced fuels will need to be backed by a Government funded R&D programme which if successful will:

- Ensure that there is a healthy R&D capability of both programmes and facilities and a pool of experts with the skill, knowledge and experience derived from international collaboration to identify the most appropriate nuclear energy options for the UK;
- Produce valuable results so that industry recognises the value of the R&D, sees opportunities for exploitation and is increasingly willing to fund R&D; and
- Put the UK back at the top table of nations carrying out nuclear R&D.

Research and Development Programmes for Advanced Nuclear Fuels

A wide range of nuclear power systems and fuel cycles are being evaluated worldwide. It is essential that enough knowledge, skill and experience is attracted, nurtured and/or retained across a range of possible future nuclear systems to enable accurate and timely advice to be provided to Government as to which of these systems are compatible with UK needs.

These future nuclear systems feature different fuel options for various reactor designs within open fuel cycles and additionally various fuel types resulting from recycle schemes for closed systems. Advanced systems of interest to the UK could include systems which maximise UK benefits, including developing existing skill strengths and IP in advanced systems with similarities to systems developed in the UK. These advanced systems include Small Modular Reactors (SMRs), Sodium-cooled Fast Reactors (SFRs) and High Temperature Reactors (HTRs). R&D in these systems would utilise UK experience and data in sodium coolant systems, graphite moderation and gas cooling, advanced ceramic fuel such as MOX and steel cladding.

The various fuels for these advanced systems include a range of chemical forms (metal, oxide, carbide, nitride) containing a range of fissile materials (uranium, plutonium) and thorium as well as combinations of these materials with or without the addition of minor actinides. Cladding technology ranges from metal alloys, ceramics and coatings.

It is important to maintain an understanding of how this range of fuels and cladding can be manufactured and whether fuel manufacture could be a constraint in selecting future fuel cycles. Further to this, the UK's fuel cycle facilities would be deployed to test, analyse and evaluate the performance of candidate fuel and cladding types. Fabricating small quantities of non-standard fuel for test irradiation in UK facilities such as the Dalton Cumbria Facility will provide important underpinning nuclear data. Fabrication for testing in research and test reactors is also potentially a significant source of revenue for the UK and an important contribution to international collaboration on developing future nuclear technology.

These fuel options are currently developed to varying degrees of maturity as indicated by the Technology Readiness Levels (TRLs) in the diagrams below. Figure 2 compares the development of various fuels for reactor systems. Standard uranium oxide fuels are highly developed whereas fuels containing new compounds have a low TRL across the spectrum of reactor technologies. Opportunities exist for the UK to leverage its facilities and lead in developing fabrication routes for evolutionary fuel (UOX, MOX, metals) and new fuel compounds e.g. uranium silicide and new elements in fuels such as Thorium, combined with taking a lead on understanding nuclear fuel material properties and behaviour.

Ordered by approximate increasing maximum operating temperature	**Generation**	**II**	**II–III+**	**IV**					
	Reactor	**AGR**	**L/HWR**	**SFR**	**SCWR**	**LFR**	**MSR**	**GFR**	**HTR / VHTR**
Advanced cladding categories	**Outlet temperature (°C)**	650 [73]	~325 [73] (PWR)	550 [24]	510 – 625 [24]	480 – 800 [24]	700 – 800 [24]	850 [24]	650 – 1000[24]
Standard	UO_2	10	10	9	3	5		3	8
	MOX		10	8	2	3		3	6
New geometries	Annular pellets in non-VVER		5	Grey indicates that the fuel is not relevant to the reactor type					
	Dual Cooled Fuel (DCF)		5		1			1	
Evolutionary	Advanced UO_2	3	9 – 2	3	1	2		1	2
	Advanced MOX		7 – 2	3	1	4		2	2
	Advanced Metal		3	7		2			
New compounds	Carbide		2	7	2	4		3	8 (oxy)
	Nitride		3	7	2	4		3	
	U_3Si		4		2				
	U_3Si_2		3		2				
New elements	Thorium		8 – 5	4	2	2	2	2	7
	Minor Actinides (MAs)		2	4	2	2	3	2	2
Including other materials	Inert Matrix Fuels (IMFs)		5	5	2	3		3	
	Dispersion		4		2				
	Zirconium hydride-based		3		2				
	Coated particle-based		4		2			3	8 – 2
Liquid-based	U in FLiBe molten salt						4		

Figure 2 TRL assessments of advanced fuels vs reactor systems

Figure 3 compares the development of various claddings for reactor systems - noting that, non standard cladding technologies have a low TRL. Opportunities exist for the UK in cladding including material performance studies and developing fabrication routes for ceramic based materials.

Ordered by approximate increasing maximum operating temperature	Generation	II	II–III+	IV					
	Reactor	**AGR**	**L/HWR**	**SFR**	**SCWR**	**LFR**	**MSR**	**GFR**	**HTR / VHTR**
Advanced cladding categories	**Outlet temperature (°C)**	650 [73]	~325 [73] (PWR)	550 [24]	510 – 625 [24]	480 – 800 [24]	700 – 800 [24]	850 [24]	650 – 1000[24]
Zirconium	Standard alloys		10				Grey indicates that the cladding is not relevant to the reactor type		
	Surface treated		3		2				
	Advanced alloys		8		3				
Steels	F/M			7		4			
	RA F/M			3	3	3			
	F/M surface treated				2	3			
	Standard austenitic	10	8 (former standard)	6	3	4		3	
	Austenitic surface treated	8							
	Advanced austenitic		6	8	3	4		3	
	ODS F/M			4	2	3		3	
Semi-refractory alloys	Advanced Fe		3	2	2	2	2		
	Ti and Ti/Al intermetallic		1	1	1	1			
	Ni			7	3			3	
	Hastelloys						5		
	V			4		2		3	
	Cr		2	2	2	2		2	
Refractory alloy liners	Nb, Mo, Ta & W			4		3		3	
Ceramic-based	MAX phase		2	2	2	2		2	
	Cermets			2		2		2	
	SiC particle coatings							3	8
	SiCf/SiC		3	3	2	3		3	
	Cf/C		1	1	1	1		2	
	ZrC particle coatings							2	6

Figure 3 TRL assessments of advanced claddings vs reactor systems

The background to the following programme areas of key nuclear fuel and cladding research is outlined further below including:

- Accident tolerant fuels and cladding / more efficient fuels and cladding,
- Plutonium containing fuel and cladding,
- Minor actinide fuels and cladding,
- Metal fuels and cladding.

Accident tolerant fuels and cladding / more efficient fuels and cladding (ATF)

Following the Fukushima accident there is a new interest in developing accident tolerant fuels. These fuels (e.g. oxide, nitride, carbide) and claddings (e.g. metal, ceramic) have the potential to be deployed in Generation III/III+ reactor designs such as those currently being considered for UK new build. They offer potential benefits in safety (through for example improved fuel and cladding properties such as thermal conductivity) and also in economics (for example, fuels with a greater energy density or simplified fabrication processes) compared to those utilised in today's fuel plants and reactors. The economic benefits are important given that both fuel vendors and reactor operators would need to invest in alternative fuel management strategies and infrastructure should this fuel be desired. The programme would develop models to predict improvements in fuel cladding performance and develop fabrication routes for integrated accident tolerant fuels and cladding systems for subsequent material irradiation testing.

Plutonium containing fuel and cladding

It is important to include development of Pu containing ceramic fuel for Generation III+ and IV systems to enable informed technology choices to be made. Pu ceramic fuels are currently utilised in closed or open fuel cycle systems (e.g. to recycle Pu (as MOX) from reprocessed LWR fuel) and represent the favoured route for deposition of the UK's civil Pu stocks. This theme of Pu containing fuel and cladding incorporates ceramic fuels produced through dry powder metallurgy or wet sol-gel routes and advanced cladding technology. It is important that advanced fabrication technologies such as sol-gel and use of remote handling systems are considered here due to the potential requirements for advanced fabrication processes that enable improved product quality control and reduced operator dose. The programme would develop lab scale technology for fabrication of Gen IV fuels via a stepping stone through Gen III MOX technology.

Minor actinide bearing fuels and cladding

Any option to close the fuel cycle in the future will need consideration of Minor Actinides (MAs) in fuels. Present day reprocessing operations separate out MAs such as neptunium and americium from spent fuel to enable the refined Pu and U to be recycled into fresh fuel using powder metallurgy fuel fabrication technologies. MAs are diverted along with fission products to High Level Waste stores for cooling prior to repository disposal. However, inclusion of MAs in waste contributes greatly to the long term heat loading of the vitrified waste product sent to a repository. This places a challenge on the repository heat limits which is solved by dispersed spacing of these higher temperature waste packages – effectively reducing the capacity of the repository. Gen IV reactor technologies can be developed to burn these MAs if they are recycled into fresh fuel with consequent benefits to repository capacity. There are several recycling flow sheets being developed which co-extract various MAs from spent fuel (i.e. extracting along with Pu and U). A favoured approach is to co-extract americium as a minimum because it has the greatest impact on repository heat. Other schemes are being developed to extract other MAs for subsequent fabrication into fresh fuel to variously enhance proliferation resistance, safety, economics and plant operational performance. Americium is also present in the UK's aged stocks of reprocessed Pu (through radioactive decay) and therefore fuel technology using these stocks will need to cope with this higher dose material if it is to be recycled.

Metal fuels

Metal fuel was deployed in the UK's Magnox reactor fleet and is the fuel choice for research reactor driver and target fuels designed to produce specific isotopes through nuclear fission for subsequent extraction and use in the medical sector (e.g. cancer treatment). Metal fuel is also considered an option for next generation fast reactor technology and has been shortlisted as an option for disposition of UK Pu stocks.

Figure 4 outlines how nuclear fuel research programmes could develop through Technology Readiness Levels through different lead organisations and funding routes currently available in the UK.

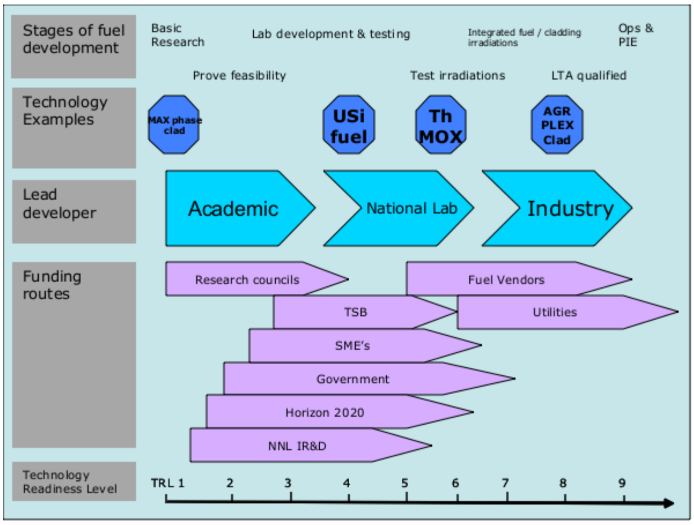


Figure 4 Stages of fuel development, lead developers and funding routes

Areas of fuel fabrication research and development

Equipment will be required to develop fabrication routes for nuclear fuels and cladding at a lab scale in order to undertake material performance studies including testing under conditions of higher temperatures and pressures, irradiation and various chemical environments. These studies would be developed in combination with modelling studies to enable improved mechanistic understanding of material behaviour and underpinned by developments in nuclear data for advanced system materials.

This lab scale activity will, if successful (i.e. demonstrate the required material performance parameters), need to be developed further to enable the production of reliable flow sheets to underpin the design of commercial scale fuel plant manufacturing routes. For example, to develop and underpin a reliable flow sheet for Pu/U ceramic fast reactor fuel, knowledge of MOX fuel production routes needs to be developed further, including using knowledge of powder flow, recycle (and residue) additions, and improvements such as reverse running, recycle scouring and early Conpor addition.

The underpinning of manufacturing process feasibility and optimisation could, in part, be tackled using surrogate as well as active materials. This would broaden the contribution to fuel R&D through use of low and non active laboratories which house unique fabrication and analysis equipment. For example, these laboratories and equipment could aid in development and processing of fuels requiring low oxygen content (e.g. carbide, nitride fuels) and wet fuel production processes. These fabrication routes are novel and not well understood but open up a different range of fuels which can potentially offer significant advantages.

Example areas for advanced ceramic fuel production route developments include:

- New fuel qualification standards. There have been significant developments in microscopy/image analysis tools in recent years (e.g. greater automation, computational power, image analysis tools) that could be introduced to the fuel qualification process. Potential areas to investigate include grain size measurement, pore size distribution, defect and impurity (i.e. as opposed to doping) identification/classification. There is also the potential for high-temperature Environmental SEM in fuel manufacture. This could enable in-situ observations of fuel sintering (e.g. grain growth/pore elimination) to understand the effect of sintering atmosphere and dopants etc;

- Pellet production. Advanced tooling requirements for the manufacture of novel pellet designs need to be identified. Combined modelling and experimental R&D is needed to understand and improve strong green and sintered pellet production through slow pressing and the effect of sintering atmospheres;

- Glove box welding. Ability to weld in glove boxes and in low oxygen environments are required for the fabrication of advanced test fuels such as nitrides.

- Understanding powder flow and mixing is vital to ensure good fuel quality and reduced recycle and waste production. UO_2 and PuO_2 are cohesive powders which can lead to difficulties during handling/processing. A better understanding of effects caused by moisture uptake, thermal cycling and static charging can be obtained through a combination of inter particle force measurements using Atomic Force Microscopy (AFM) and flow ability testing devices. Use of advanced multi-scale modelling tools would help in predicting powder behaviour;

- Furnace control. Optimisation of pellet quality, surface interaction, fission gas release and coatings. This would also include the condition of residues for long-term storage and pressurisation avoidance;

- Design of scrap recovery and recycling flow sheets is required to suit evolutionary and revolutionary fuel manufacture processes. This is also needed to build on the experience of best in class fuel plants where incorporation levels of 35% are achieved;

- Fuel stocks age over time and/or are affected by storage conditions, the quality of dry fuel feed stocks is a key input to production but there is no standard method of evaluating these feed stocks;
- Proving stocks of already-manufactured PuO_2 will make suitable MOX or fast reactor fuel, incorporating aged PuO_2 with varying isotopic specifications. There is also the wider NDA-legacy MOX materials that might be incorporated into new MOX production if the isotopic specifications could be met;
- Inspection and metrology of fuel element components is needed for evaluation of test fuel assemblies.

Technology and capability required to deliver fuel research programmes

To deliver these programmes, NFCE facilities need to be equipped with the following technology and capability including:

1. Ceramic fuel fabrication technology for U, Pu, Inert Matrix (e.g. blend, mill, press, sinter, grind),

2. Surrogate pellets (for example for Th, Pu and minor actinide fuels),
3. Annular pellets (e.g. AGR, fast reactor fuel),
4. Higher enriched uranium (e.g. radioisotope targets),
5. Reprocessed uranium (Rep U),
6. Waste recycling (e.g. U scrap recovery, Pu scrap recovery),
7. Large scale furnace technology (e.g. for cladding treatment),
8. Joining technology (e.g. metals and ceramics),

9. U and Pu fuel sample preparation suites,

10. Physical property testing (e.g. mechanical and thermal),

11. Microstructure examination of materials (OM, SEM, TEM),

12. Spectroscopic analysis (Optical Emission, Energy Dispersive x-ray analysis, portable x-ray fluorescence, EBSD),

13. Oxidising furnace (a non standard pellet sintering route),

14. Fuel performance modelling (e.g. fuel qualification and licensing, core design, multi scale applications),

15. Material properties modelling (e.g. fundamental studies of fuel, cladding behaviour),

16. Nuclear data for materials to be used for advanced systems,

17. Zirconium alloy and coating development,

18. Inert gloveboxes and furnace for non standard gas atmospheres (e.g. for nitride, carbide fuel),

19. Wet fuel production (particle and coated particle fuels),

20. Advanced fabrication technology (e.g. spark plasma sintering, 3D Printing),

21. Melting, casting and machining (for metal fuels and cladding),

22. Electro-refining (for development of metal fuels),

23. Powder metallurgy routes (USi fuel, UAl fuel),

Conclusions

Decisions on open vs closed fuel cycles will be dependent on the speed at which new fuels and reactor technologies are developed and on ultimate power generation requirements. As such, advanced reactor and fuel cycle research has an important role to play in setting out the most appropriate scenarios for nuclear energy deployment for the remainder of this century.

The UK Government has published an R&D Roadmap (Nuclear Energy Research and Development Roadmap: Future Pathways) which sets out a vision for nuclear research and development and the research outcomes that would be needed to support future energy policy decisions. It also makes the case that Government will need to take action to maintain an agile and flexible R&D capability to ensure that informed decisions can be made.

A wide range of nuclear power systems and fuel cycles are being evaluated worldwide. It is essential that enough knowledge, skill and experience is attracted, nurtured and/or retained across a range of possible future nuclear systems to enable accurate and timely advice to be provided to Government as to which of these systems are compatible with UK needs.

These future nuclear systems feature different fuel options for various reactor designs within open fuel cycles and additionally various fuel types for recycle schemes for closed systems. Advanced systems of interest to the UK include systems which maximise UK benefits including developing existing skill strengths and IP in advanced systems with similarities to systems developed in the UK (i.e. High Temperature Reactors, Sodium-cooled fast reactors and Small Modular Reactors).

The benefits of undertaking research in fuels will be derived from developing and deploying the skills and expertise in fuel manufacture that the UK needs to keep options open, support work on Pu disposition and develop opportunities for UK industry in advanced nuclear systems.

Fuel technology is an area where the UK can demonstrate significant and advanced knowledge, and with the right infrastructure investment can play a major role in developing fuels for current and future generations of reactors.

To attain a world-leading fuel manufacturing status will require fundamental research into fuel material performance and new and improved fabrication technology, and this research will need to be conducted by subject matter experts who have access to world-leading facilities. The establishment of a UK Nuclear Fuel Centre of Excellence would provide this, and see industry, NNL and academia engage in national and international collaborative research in advanced fuel manufacturing technology. The NFCE will be open to international partners, offering world-leading capability and facilities in advanced fuel fabrication R&D, complementing international facilities such as the Halden and Jules Horowitz Test Reactors.

The benefits of establishing a NFCE will be significant, and include:

- Enabling development of advanced fuel and cladding leading to safer and more efficient fuels, subsequent lifetime extension and improved performance for post irradiation storage and waste disposal;
- Developing capability which will facilitate the potential for commercial fuel manufacture of Generation III+, Generation IV and Small Modular Reactor fuel;
- The ability to leverage investment through collaboration on international research programmes;
- Delivering test fuel for international reactor demonstrators, including Halden and the Jules Horowitz Reactor;
- Enabling access to high cost R&D facilities and equipment;
- Maintenance and advancement of critical nuclear skills.

The background to the following programme areas of nuclear fuel and cladding research has been outlined, including:

- Accident tolerant fuels and cladding / more efficient fuels and cladding,
- Plutonium containing fuel and cladding,
- Minor actinide fuels and cladding,
- Metal fuels and cladding.

Areas of fuel fabrication R&D have been outlined and additionally the technology and infrastructure that will be required to develop fabrication routes for nuclear fuels and cladding at a lab scale through to industrial plant prototyping.

Engagement and close collaboration between academic, national laboratory and industrial organisations and involvement of international programmes will be essential to delivering the long term benefits from R&D in nuclear fuels and R&D will need to be backed by a Government funded programme.