NUCLEAR INNOVATION AND RESEARCH ADVISORY BOARD

Prioritisation of UK Nuclear Innovation and Research Programme Recommendations

NIRAB–124-1

Purpose

The purpose of this paper is to advise of the outcome of the prioritisation of the NIRAB UK Nuclear Innovation and Research Programme Recommendations carried out using prioritisation principles agreed by NIRAB members.

Background

NIRAB has published a series of recommendations[1] which identify the publicly funded civil nuclear R&D required to inform and underpin Government policy; particularly energy and industrial policy. The UK Nuclear Innovation and Research Programme Recommendations report sets out a number of five year aims and objectives and identifies the specific publicly funded R&D activities needed to deliver them.

It is estimated that approximately £250m would be required over the period 2016-2021 to deliver these recommendations in full. In the Spending Review and Autumn Statement 2015[2] the Chancellor announced the allocation of at least £250m to fund an ambitious nuclear R&D programme as part of the Department for Business, Energy and Industrial Strategy (BEIS) Energy Innovation Budget. This funding will need to deliver:

- an R&D programme to revive the UK's nuclear expertise and position the UK as a global leader in innovative nuclear technologies, and
- a competition to identify the best value Small Modular Reactor (SMR) design for the UK.

The budget has not been apportioned between these two tasks. The working assumption is that the budget will be shared equally between these two overlapping tasks, leaving approximately £125m to fund an R&D programme over the five year period. Some prioritisation of the NIRAB recommended programme will therefore be necessary to determine which R&D tasks should be commissioned as a priority. Until the outcome of the SMR competition is known there will remain uncertainty over the actual allocation of funds. There is therefore the potential for the sum allocated to R&D to vary, for example by ±£25m, leaving a budget of between £100m and £150m.

In parallel with the Spending Review it was announced that the UK and China will invest in a Joint Research and Innovation Centre (JRIC) to invest in nuclear R&D. Each country committed £5m per year during this same five year period[3]. The UK contribution will be paid from the nuclear R&D part of the BEIS Energy Innovation budget. If NIRAB's recommendations are used to set the JRIC priorities this would have the effect of allocating the Chinese funds to the research recommended by NIRAB; effectively increasing the R&D budget by £25m (to £150m ± £25m).

This paper describes how the prioritisation principles agreed by NIRAB (see below) have been applied to establish the initial R&D priorities. Three funding scenarios have been considered for the 5 year period beginning in the 2016/17 financial year, as follows:

- Low case - £125m
- Reference case - £150m
- High case - £175m

1 NIRAB-75-10, UK Nuclear Innovation and Research Programme Recommendations (http://www.nirab.org.uk/media/6233/uk-nuclear-innovation-and-research-programme-recommendations.pdf)

2 Spending Review and Autumn Statement 2015, Cm 9162, November 2015 (https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/479749/52229_Blue_Book_PU1865_Web_Accessible.pdf)

3 https://www.gov.uk/government/news/chancellor-announces-major-progress-in-civil-nuclear-partnership-between-the-uk-and-china-at-7th-economic-and-financial-dialogue

Prioritisation criteria

The principles agreed by NIRAB for use in prioritising R&D recommendations are as follows:

Sustaining Skills and Capability – Critical to delivering the Government's nuclear energy agenda is the availability of the nuclear qualified high level skills and subject matter experts. Much of the UK's current world-class scientific and engineering capability, developed through previous nuclear programmes, is at risk of being irretrievably lost. R&D activities that sustain the key skill groups the UK will need to deliver future programmes should be given priority.

Targeting Specific Market Opportunities - Where possible activities that target specific time critical market opportunities or enable international research collaborations should be given priority.

Prioritising Existing Capability - Developing and sustaining existing areas of UK expertise in the short term should be prioritised, especially where capability would otherwise be at risk.

Supporting Government's SMR Mission - Government has indicated their intent to potentially invest in an SMR programme and to support building one of the world's first small modular reactors in the UK. R&D activities which support this mission should be prioritised, especially where they would support multiple SMR designs or concepts.

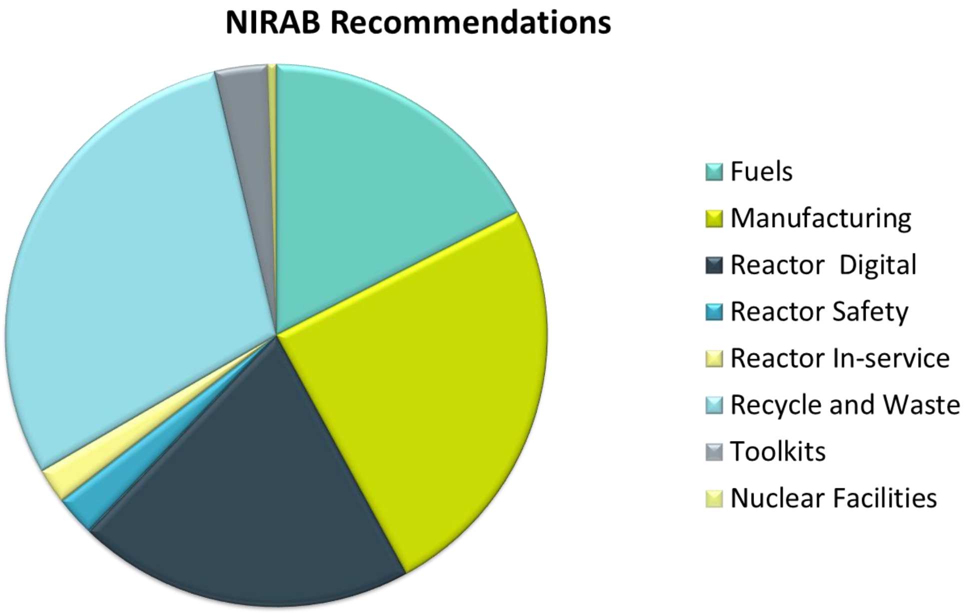
Maintaining a Balanced Programme - Carrying out research across all aspects of the nuclear fuel cycle is an important factor in maintaining global credibility as a nuclear nation and enabling UK industry to access future opportunities across the nuclear sector.

Prioritisation outcome

The prioritisation principles have been applied to the NIRAB recommendations in order to classify the recommendations as follows:

- R&D activities which should be regarded as a priority and addressed without modification
- Those which may need to reduce in scope to accommodate funding constraints (including both the level of funding and the rate at which it is made available)
- Those which may need to be postponed to accommodate funding constraints
- Those which may need to reduce in scope and be postponed

Tables 1 to 6 summarise how the prioritisation principles have been applied to the NIRAB recommendations using the same work breakdown structure as used in the NIRAB UK Nuclear Innovation and Research Programme Recommendations document. Figure 1 shows the impact of the prioritisation on the overall distribution of funds between the project areas. Following prioritisation the fuels and materials and manufacturing areas comprise a slightly larger share of the total (+5% and +3% respectively) at the expense of recycling, waste management and decommissioning (-8%).



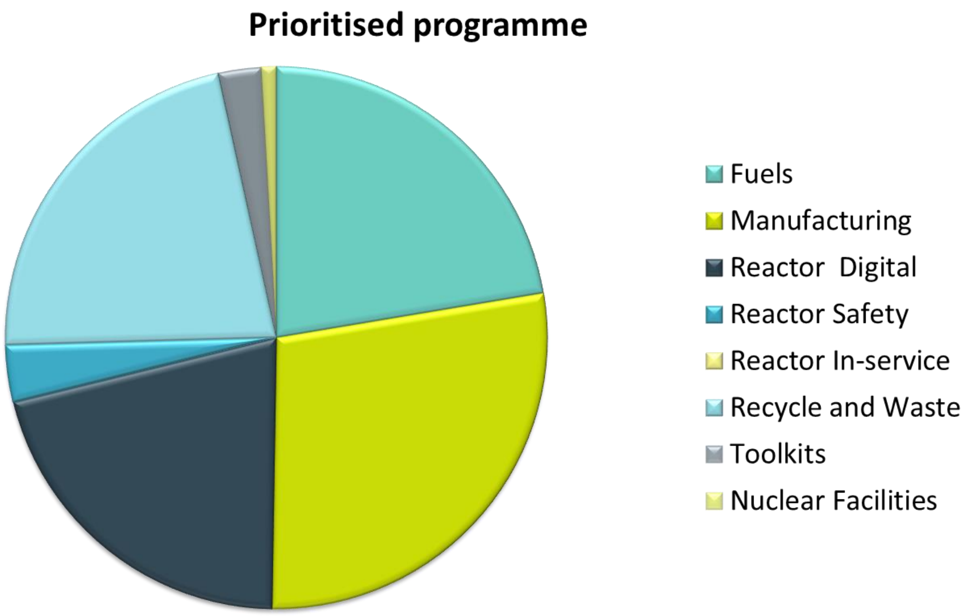


Figure 1 Comparison of the distribution of funding between project areas in the NIRAB recommended programme before and after prioritisation

Fuel research prioritisation and programme

Table 1 summarises how the prioritisation principles have been applied to the recommendations relating to fuel research. Figure 2 illustrates how the research may be grouped into three phases during the five year period. Figure 3 compares proposed spending on the prioritised programme to that recommended by NIRAB, in the UK Nuclear Innovation and Research Programme Recommendations, over the next five years.

Advanced materials and manufacturing research prioritisation and programme

Table 2 summarises how the prioritisation principles have been applied to the recommendations relating to advanced materials and manufacturing research. Figure 4 illustrates how the research may be grouped into 2 phases of activity during the 5 year period. Figure 5 compares how spending on the prioritised programme compares to that recommended by NIRAB over the next five years.

Reactor design research prioritisation and programme

Table 3 summarises how the prioritisation principles have been applied to the recommendations relating to reactor design research. Figure 6, Figure 7 and Figure 8 illustrate how the research on three aspects of reactor design may be grouped into phases during the five year period. Figure 9, Figure 10 and Figure 11 compare proposed spending on the prioritised programme to that recommended by NIRAB over the next five years.

Spent fuel recycle and waste management research prioritisation and programme

Table 4 summarises how the prioritisation principles have been applied to the recommendations relating to spent fuel recycling and waste management research. Figure 12 illustrates how the research on recycling and waste management may be grouped into three phases during the five year period. Figure 13 compares proposed spending on the prioritised programme to that recommended by NIRAB over the next five years.

Strategic toolkit research prioritisation and programme

Table 5 summarises how the prioritisation principles have been applied to the recommendations relating to the development and application of elements of a strategic toolkit. Figure 14 illustrates that research on the strategic toolkit could be delivered in a single phase. Figure 15 compares proposed spending on the prioritised programme to that recommended by NIRAB over the next five years.

Access to international facilities prioritisation and programme

Table 6 sets summarises how the prioritisation principles have been applied to the recommendations relating to maintaining access to international data and facilities. Figure 16 illustrates how that this research could be delivered in a single phase. Figure 17 compares proposed spending on the prioritised programme to that recommended by NIRAB over the next five years.

Table 1 Fuel research prioritisation considerations

Key

	No significant change to the scope and timing of the reference case from work recommended by NIRAB
	Some reduction in scope or delay in commencing research in the reference case
	Prioritisation results in significant delays in the reference case

WBS[1]	TITLE	Description	Variance from NIRAB recommendations	Prioritisation considerations	Summary prioritisation outcome
Fuel					
F1.1a	Accident Tolerant Fuel (ATF)	Carry out initial stages of ATF fuel development.		**Opportunity**: There is significant international interest in this area including in the US where the Department of Energy (DoE) is funding a research programme being delivered by an international multi-disciplinary team including UK universities. ATF development is also a priority topic in the Horizon 2020 programme. If participation is delayed the opportunity will be lost. US and European collaboration opportunities offer the potential to collaborate internationally and leverage funding. **Sustaining skills and capability:** New fuel development work will help to maintain key skills in the fuels area.	No delay or reduction proposed
F1.1b	ATF Cladding	Initial research should be carried out to determine the critical to quality features necessary to make cladding for ATFs. This should include issues that are likely to limit the capability and capacity of economic industrial scale fuel production.		**Sustaining skills and capability:** New fuel development work will help to maintain key skills in the fuels area. **Opportunity:** ATF development presents an opportunity to collaborate with the US DoE on a significant research package. **Enabling:** Early work in the ATF cladding materials will identify the key challenges in ATF production and will set the scope and direction of future ATF work. In particular determining if silicon carbide is a viable cladding material for ATFs or whether other cladding material solutions (such as MAX Phase) should be considered. This initial work is likely to identify key areas of IP that can be leveraged into future ATF collaborations and ultimately ATF production.	No delay or reduction in any option

WBS[1]	TITLE	Description	Variance from NIRAB recommendations	Prioritisation considerations	Summary prioritisation outcome
F1.2	Coated Particle Fuels	Preparatory work for future research into Coated Particle Fuels (CPF) understanding the latest worldwide development in the technology and applications. This will direct future research, including the commissioning of lab-scale production equipment.		**Enabling:** This activity will determine the future direction on CPF research, most notably whether there is a case for re-commissioning existing facilities that have been mothballed. This is an enabling activity that will inform a subsequent decision on whether to make new capital investments. **Opportunity/SMR Mission:** CPFs are the fuel used in High Temperature Reactors (HTRs) and UK based research in this area would indirectly support this development. This presents an opportunity for UK industry.	Coated particle fuel research to be scaled down from NIRAB baseline in the reference case to reflect the fact that the market opportunity is not as early as that for ATF. Scaled down further in the low case reflecting the same driver. High scope reinstates the full scope recommended by NIRAB. Fuel priority order: 1. ATF 2. CPF 3. Pu 4. Thorium
F2.1	Plutonium Fuels	Base research into the latest developments in Plutonium based advanced reactor fuels to understand specific challenges and determine future areas for UK development.		**Enabling:** This activity will determine the future direction of Plutonium based fuel development and the need for any additional equipment in existing research facilities that may be needed to support development. **Opportunity:** Research into Plutonium based fuels will support the UK's reengagement with international nuclear research programmes such as the Gen-IV International Forum and the ASTRID Project.	Pu fuel research postponed beyond this 5 year timeframe in the low scenario on the grounds that we don't currently have a route to market for fast reactor fuel. This assumption would need to be revisited if a strategic agreement is reached e.g. an potential with France to support the development of fuel for ASTRID
F2.2	Thorium Based Fuels Evaluation	Evaluation of thorium based fuels in the broader context of the fuel cycle will give the UK a greater understanding of the potential benefits, timescales and implications of deploying thorium fuel technology.		Not an existing skill base, no route to market identified, no current supply chain and no immediate link to an SMR mission	Delay until at least 2020. Any Th fuel development would only commence after strategic fuel cycle assessments have been completed if these show that a Th fuel cycle could deliver significant benefits to the UK. Lowest priority of fuels work.

WBS[1]	TITLE	Description	Variance from NIRAB recommendations	Prioritisation considerations	Summary prioritisation outcome
F3.1	Reactor Physics Modelling	Carry out a requirements capture exercise for advanced physics modelling to establish the research activities needed to analyse the SMR and Gen-IV reactor types that may be deployed within the UK. This will include identifying overseas programmes for collaboration in regard to nuclear data availability and activities in model developments and validation.		**Enabling:** This activity will determine the areas of research that the UK need to carry out to verify the physics performance of new reactor systems and new fuel types (including, but not limited to, ATF for use in current reactors). This will determine the scope and scale of future research in this area. **Sustaining skills and capability:** Physics modelling is part of the wider fuels and reactor development where it is important to sustain a UK indigenous capability.	Reference case and low case reduced from the NIRAB baseline to assume a slower rate of attack and/or the development of fewer models (with a focus on the highest priority needs). The high case is increased to match the NIRAB baseline and would result in a wider range of reactor / fuel models in line with the increased level of fuel research.
F3.3a	Nuclear Data	Programmes are required to re-engage with international nuclear data programmes, including both data generation and evaluation to enhance the data for advanced fuels and to retain the skills base in this important area.		**Sustaining skills and capability:** Nuclear data underpins the modelling of the nuclear physics aspects of simulation to calculate whether a reactor will operate with a specified fuel design and reactor configuration, what power it will generate and the composition and properties of the irradiated fuel.	No delay or reduction in any option – this meets a fundamental need for data which is currently not available. This activity is needed to support all advanced fuel development programmes.

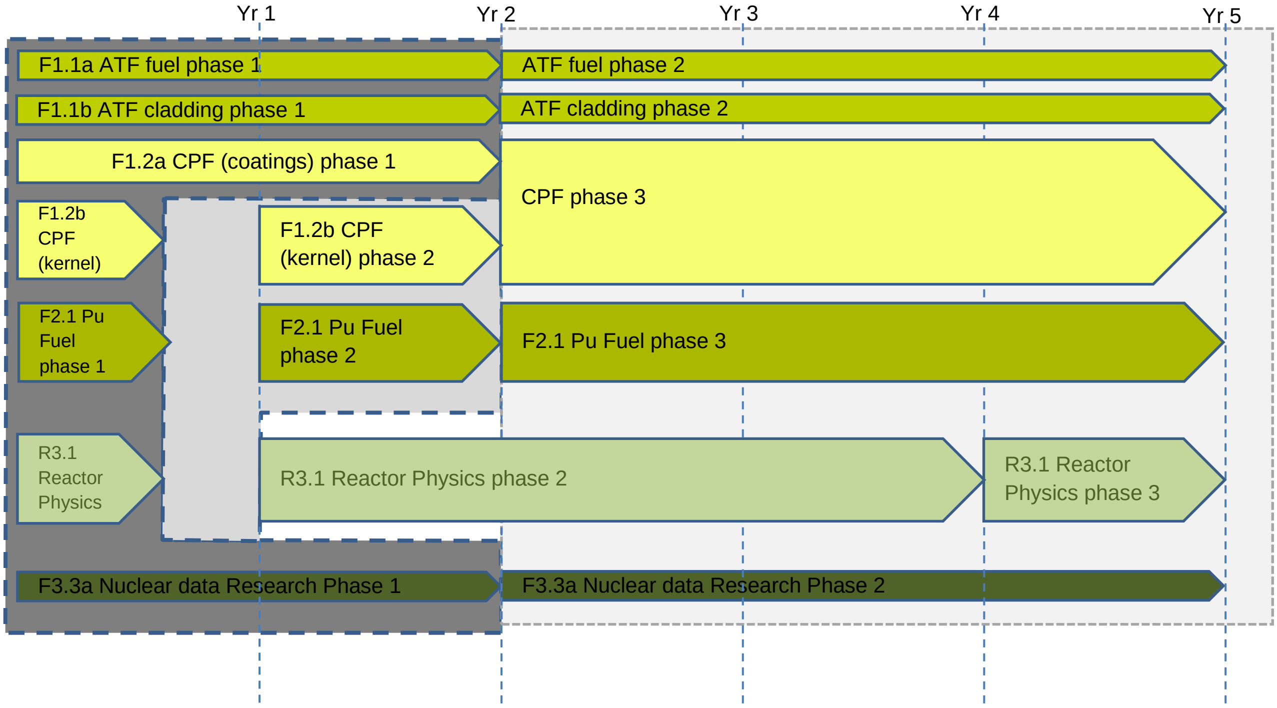


Figure 2 Outline fuel programme proposal

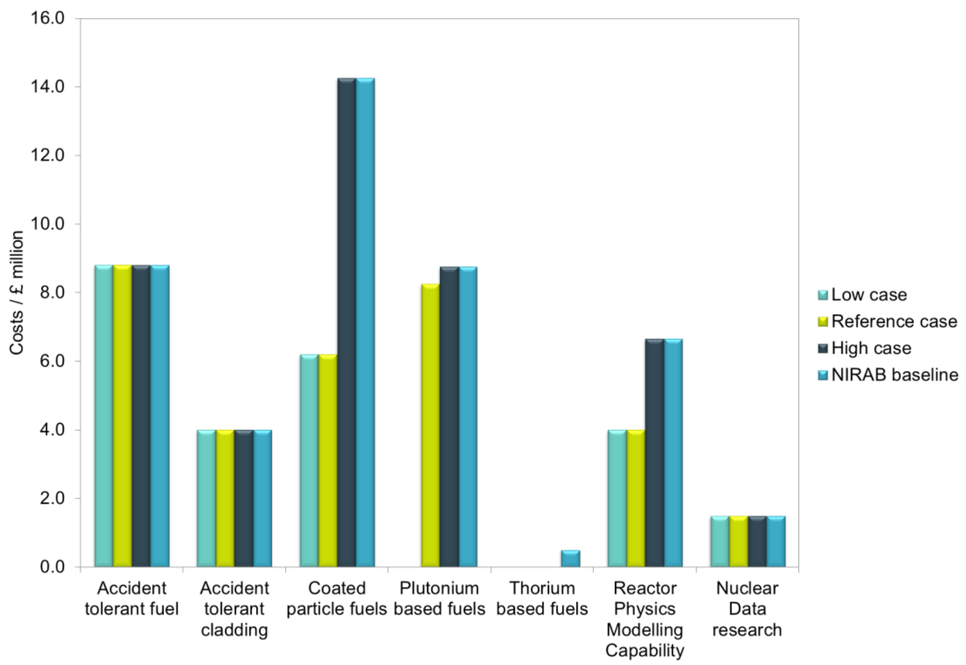


Figure 3 Comparison of NIRAB recommendations and prioritised fuel programme

Table 2 Advanced materials and manufacturing research prioritisation considerations

Key

Green	No significant change to the scope and timing of the reference case from work recommended by NIRAB
Yellow	Some reduction in scope or delay in commencing research in the reference case
Red	Prioritisation results in significant delays in the reference case

WBS[1]	TITLE	Description	Variance from NIRAB recommendations	Prioritisation considerations	Summary prioritisation outcome
Manufacturing					
M1.1	New Nuclear Material and manufacturing developments	Fundamental research into new materials and manufacturing processes. This should be based on the likely material property requirements of reactors such as Gen-IV reactors (including Sodium Fast Reactors (SFRs) and HTR/Very High Temperature Reactors (VHTRs)).	Yellow	**Sustaining skills and capability:** This work would sustain the UK's nuclear materials research capability (for example that currently provided by the New Nuclear Manufacturing (NNUMAN) programme). This would provide a link into the research that will be the focus of the Sir Henry Royce Institute into new materials.	NIRAB recommended a substantial programme of materials and manufacturing development and testing and assigned a high priority. This reflects the fact that there is an identifiable route to market on a short timeframe. This would have been sufficient to develop a number of manufacturing techniques. Some cuts to the scale of materials work to meet funding constraints, but significant programme retained, resulting in the development of fewer materials and manufacturing techniques. The work will need to focus on materials and manufacturing processes with potentially the greatest value or impact.

WBS[1]	TITLE	Description	Variance from NIRAB recommendations	Prioritisation considerations	Summary prioritisation outcome
M2.1	Advanced Manufacturing Component mechanisation and automation	Investigate the manufacturing techniques and issues that will be crucial to solve in order to support economically viable SMR manufacture in the UK. This should take a lead from the SMR Techno-Economic Assessment and any Generic Design Assessment (GDA) challenges highlighted for the UK deployment of SMRs.		**SMR Mission:** Teasing out these issues will give a clear set of challenges that will determine the direction and scope of future advanced manufacturing development work in years 3-5. Solutions to the challenging areas will highlight areas in which the UK can generate IP. This will also underpin the business case for SMRs. **Sustaining skills and capability:** This research will make use of and help sustain the UK's manufacturing research base including the Nuclear Advanced Manufacturing Research Centre (NAMRC) facility. **Opportunity:** This work aligns with significant international and commercial collaboration opportunities for UK Industry, showcasing the UK's capability to overseas SMR Vendors.	There is only a small differential in the level of ambition between the baseline NIRAB recommendations and the reference case programme. It is expected that opportunities will be presented in this area from BEIS future SMR focussed work that could make up for this reduction.
M2.2	Large Scale Component Manufacture and Assembly	Investigate the critical to quality features and issues that will be crucial to solve in order to support economically viable SMR assembly and deployment in the UK. This should take a lead from the SMR Techno-Economic Assessment and any GDA challenges highlighted for the UK deployment of SMRs.		**SMR Mission:** Teasing out these issues will give a clear set of challenges that will determine the direction and scope of future advanced manufacturing development work in years 3-5. Solutions to the challenging areas will highlight areas in which the UK can generate IP. This will also underpin the business case for SMRs. **Opportunity:** This work will also present opportunities that are applicable to large reactor assembly and IP that the UK could exploit during the second phase of the nuclear new build programme.	No delay or reduction. A key area for cost reduction in reactor build.
M2.3	Assembly Process/ Manufacturing Modelling	Research into process flow modelling to inform the design of nuclear factories of the future, particularly the kind of assembly plants required to manufacture SMRs.		**SMR Mission:** The increase in throughput required to underpin the economic case for SMRs will require both a reduction in specific manufacturing process time but also a rethink in how assembly plants are sited, arranged and operated. **Enabling:** Carrying out this research will determine the scope and future direction of innovation programmes to address the issues identified with factory processes and flows.	There is a very modest reduction in the level of ambition from the baseline NIRAB recommendations. It is expected that opportunities will be identified in this area from BEIS future SMR focussed work that could make up for this reduction.
M3.1	Pre-Fab Module Development Phase 1	Develop solutions to enable off-site modular construction of significant elements of nuclear facilities.		**SMR Mission/Opportunities:** The outputs of this work will be aimed at increasing the certainty of the cost and programme for constructing nuclear facilities, reducing risk and strengthening the case for financial investment.	No reduction in the reference case, but delayed in the low case

WBS[1]	TITLE	Description	Variance from NIRAB recommendations	Prioritisation considerations	Summary prioritisation outcome
M3.2	Module Transportation	Address the challenges of manufacturing, transporting and installing modules of up to 1000 Tonnes in weight. Underpinning R&D and verification will develop large scale concrete plant modules.		**SMR Mission/Opportunities:** The outputs of this work will be enable the implementation of modularisation of reactor modules and generate UK IP for the transport of large nuclear loads.	No reduction in the reference case, but delayed in the low case
R1.3	Codes and Standards	Determine a pathway that will allow the necessary codes and standards to be updated to enable new advanced manufacturing processes to be implemented.		**Enabling:** Determining the pathway to providing new or augmented code and standards will determine the level of evidence and research required to support new manufacturing techniques. It will also help to establish a schedule for when new techniques are likely to be capable of being implemented. This will support the integration of research and development work with future reactors build programmes and determine the scope, scale and direction of future research activities.	No delay or reduction. Opportunity to leverage experience of developing codes for current reactor to future designs such as VHTR
R1.4	Coolant Chemistry	Evaluate coolant chemistry/materials compatibility issues (including effects of radiation) relating to candidate water-cooled SMR designs.		**SMR Mission/Enabling:** This work will inform the R&D required to support opportunities for UK to contribute to future SMR developments. **Sustaining skills and capability:** It is important for the UK to have a nuclear chemistry capability to act as an intelligent customer for SMR technologies.	The start of the programme has been delayed by 2 years to match anticipated funding levels in the first 2 years. Development of a novel chemistry regime for a future reactor delayed. Not possible to use new chemistry regime for an existing SMR design, need to target new SMR offering or Gen IV plants.

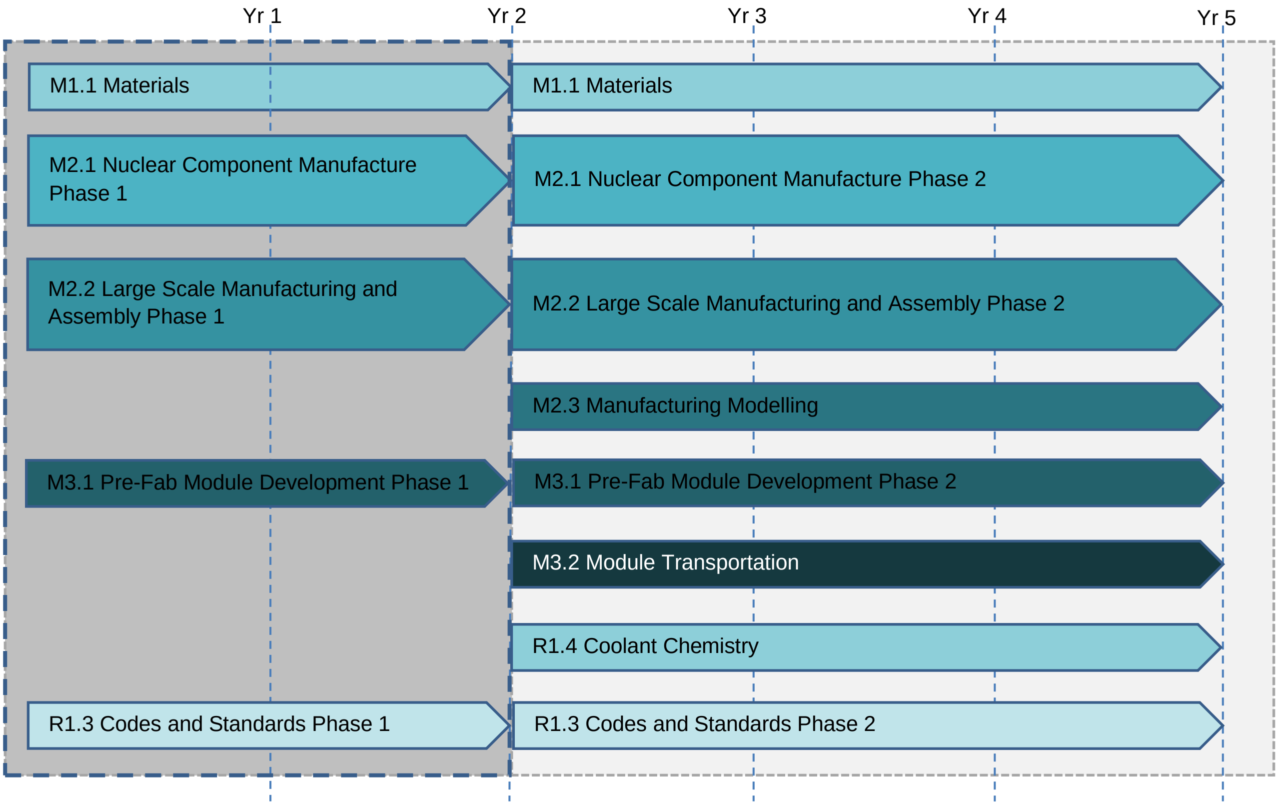


Figure 4 Outline manufacturing programme proposal

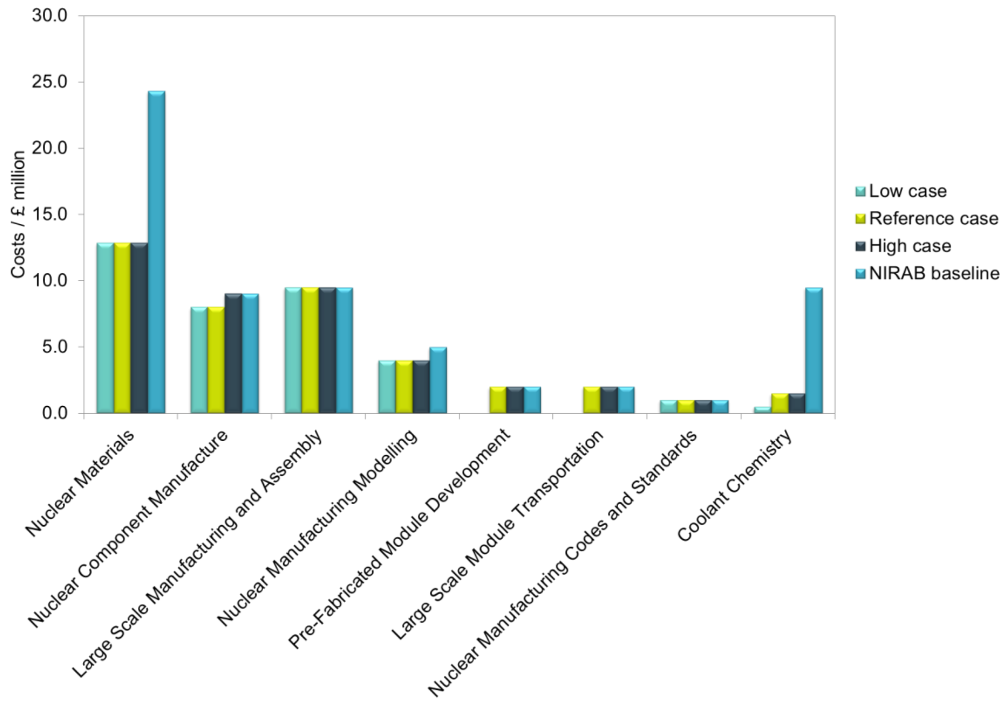


Figure 5 Comparison of NIRAB recommendations and prioritised materials and manufacturing programme

Table 3 Reactor Design research prioritisation considerations

Key

Green	No significant change to the scope and timing of the reference case from work recommended by NIRAB
Yellow	Some reduction in scope or delay in commencing research in the reference case
Red	Prioritisation results in significant delays in the reference case

WBS[1]	TITLE	Description	Variance from NIRAB recommendations	Prioritisation considerations	Summary prioritisation outcome
Reactor design – digital					
R1.1	Innovative Reactor Architectures and Components	A number of technical challenges will form the basis of an R&D programme to deliver innovative reactor architecture and components for SMRs and Gen-IV reactors. International programmes exist in these areas and the UK will engage via appropriate routes.	Red	**Opportunity:** UK could develop new products that could support Gen-IV reactor design.	Delayed. Assume that design specific work for SMRs is funded through the SMR budget.
R1.2	Nuclear Virtual Engineering Centre	Develop a nuclear focussed Virtual Engineering Centre to demonstrate how virtual engineering technologies can be employed and deliver real benefits to reactor design and manufacturing. This includes research into the application of 'big data' management techniques to nuclear technologies.	Green	**Opportunity:** Virtual engineering and its associated technologies are widespread across many other high-tech industries and bringing these into the nuclear sector will enable collaborative design, increase productivity and deliver a step change in the way that nuclear design and development programmes are delivered. **Enabling:** Demonstration of the capabilities of virtual engineering and overcoming the inevitable challenges of implementing such technology in a security and safety led industry will be a catalyst to increase the widespread uptake of modern digital engineering practices within the nuclear industry. It will also be the first steps towards a broader UK capability in nuclear computing.	No delay proposed for the reference case. However a more limited approach may be necessary in the low case giving a proportionally smaller impact on digital engineering with the nuclear industry.

WBS[1]	TITLE	Description	Variance from NIRAB recommendations	Prioritisation considerations	Summary prioritisation outcome
R2.1a	Thermal Hydraulics Rig	One of the most significant facilities in NIRAB's baseline programme is a large rig that can be used to validate new thermal hydraulics codes and investigate passive flow regimes. Priority work would be to carry out requirements capture for the thermal hydraulics rig to allow a procurement specification to be completed and rig siting options to be evaluated.		**Enabling:** Delivery and commission of this rig is unlikely to be completed in time to allow the necessary validation testing to be carried out in years 3-5 if the specification does not start until year 3. Based on experience of delivering similar facilities elsewhere a period of 2 years will be required to specify and build the rig. In addition a host site needs to be determined early as it is likely that building work will be required to accommodate the rig. **SMR Mission:** The thermal hydraulics work is applicable to the SMR mission allowing the UK to validate SMR designs.	A thermal hydraulics rig is regarded as a high priority. However a reduced budget is assumed. Assumed lower capital cost for rig through **either** reduced functionality **or** cost sharing. Also assumed a delay to the start of measurement programmes on the rig (start in year 5) as rig may not be complete earlier than this (-£5m).
R2.1b	Thermal Hydraulics Modelling	Develop computer models for new flow regimes, focusing on passive flows. Verification of these models can be carried out using new thermal hydraulics rigs in subsequent years.		**Sustaining skills and capability:** The UK has a long successful history of innovation in thermal hydraulic code development and this is an area currently at risk from underinvestment. **SMR Mission:** The thermal hydraulics work is applicable to the SMR mission allowing the UK to validate SMR designs.	No delay or reduction proposed
R2.2	Verification Innovation	Develop the next generation of rig instrumentation for nuclear verification facilities.		**New Capability:** Will complement the system design and design verification capabilities. **Opportunity**: New V&V products that can be used in a nuclear sector present an opportunity for UK businesses, in particular SMEs.	No scope reduction or delay proposed in the reference case. This is the development of a new capability to exploit future market opportunities. Scope delayed in the low case

WBS[1]	TITLE	Description	Variance from NIRAB recommendations	Prioritisation considerations	Summary prioritisation outcome
R2.3	Modelling and Simulation	A number of modelling and simulation research and innovation activities have been identified to address specific challenges in the nuclear sector. This includes: • Multi-scale structural performance modelling • Develop digital twins • Code integration techniques		**Opportunity:** Advances in modelling and simulation capability for the UK will generate IP and skills that can be applied to a number of future opportunities including SMR verification and Gen IV reactor design and development.	No delay or reduction proposed. A possible area of international collaboration.
Reactor design – in service					
R3.1	Fuel Handling	Develop innovative concepts for potential refuelling systems to optimise the economics in terms of trade-off between capital cost and outage duration, whilst being cognisant of the core mechanical behaviour, safety and operator dose.		**SMR Mission/Opportunity:** Engineering solutions that turn refuelling into a simple routine operation will provide improved plant capacity factors that will lead to an improvement in the overall economics of reactors.	Delayed in reference and low cases. Could be implemented through SMR budget - i.e. Government SMR mission may include development of fuel handling system for a UK SMR. May only be possible for a given design / concept.
R3.2	In-Service and Repair Technologies	Development of innovative in-service and repair technologies, including remote handling and robotic systems.		**Opportunity:** R&D will develop new inspection and repair technologies to put the UK at the forefront of this market and become a key player in future collaboration.	Delayed in reference and low cases. No specific time based opportunities identified.
R3.3	Robotic Test Asset	Develop an asset at a nuclear licensed site that will give developers a training ground which presents some of the challenges faced in providing robotic products into such locations.		**Enabling:** Enables the implementation and exploitation of robotics technologies.	Delayed in reference and low cases. Others are investing in an initiative in this area that would provide similar benefits and capabilities.

WBS[1]	TITLE	Description	Variance from NIRAB recommendations	Prioritisation considerations	Summary prioritisation outcome
R3.4	Equipment Health Monitoring	Innovation is required to adapt sensing technologies for use within the nuclear sector and specific health analysis technologies to position UK at the forefront of this market and become a key player in future reactor development collaborations.		**Opportunity:** Developing a capability to characterise the equipment in nuclear plants will be significant in enabling the widespread uptake of EHM within the nuclear industry. This programme will develop valuable IP and solutions from industry will highlight the UK as a route to collaboration in future reactors developments and the in-service market.	Delayed in reference and low cases. No specific opportunities have been identified. Not critical to the implementation of SMRs or nuclear in the UK. No specific advantage over innovation in any other sector.
Reactor design - safety					
R3.5	Reactor Design for Security and Safeguards	Develop methodology to deliver nuclear safety, nuclear security and safeguards through the design process and new approaches to design substantiation for an integrated safety case.		**Opportunity/SMR Mission**: Capability will provide expertise to support SMR deployment in the UK.	No reduction to the very modest recommendations
R3.6	Security Modelling	Develop new approaches and tools to evaluate the effectiveness of nuclear security measures.		**Opportunity/SMR Mission**: Capability will provide expertise to support SMR deployment in the UK.	No reduction to the very modest recommendations
R3.7	Safety Engineering Specification	Carry out a review of current UK licencing arrangements including lessons learnt from recent GDA applications, SMR phase 1 study and the techno-economic assessment to identify priority activities to advance the UK's safety engineering capability and establish international collaboration. This would include work on incorporating security and safeguards into design activities.		**Enabling:** This review will determine where the UK's strengths and weakness are in Safety Engineering and identify a programme of safety case methodology development to deliver new capability. This will determine the scope and scale of future research in this area. **SMR Mission:** Safety case development will be one of the UK's key contributions to an SMR mission, delivering the GDA and subsequent full justification to support any SMR manufacturing facility and plant deployment. **Opportunity:** Safety production and consultation for major worldwide nuclear safety campaigns offer a significant opportunity for the UK industry. **Sustaining skills and capability:** There are a reducing number of people in the UK with an in-depth knowledge of the application of nuclear safeguards. This work will contribute towards sustainment of this important skill-set.	No reduction to the very modest recommendations

WBS[1]	TITLE	Description	Variance from NIRAB recommendations	Prioritisation considerations	Summary prioritisation outcome
R3.8	Safety Centre of Excellence			This is a method of implementation and exploitation of the safety work in R3.7 so the justification applies here.	No reduction to the very modest recommendations
R3.9	C&I Safety	Develop a framework to allow successful regulation of C&I technologies for implementation within nuclear plants.		**Opportunity:** UK opportunity to deliver a larger portion of reactor i.e. I&C systems/software. **SMR Mission**: UK capability to deliver/assess software for SMR.	Modest reduction in scope in comparison to NIRAB recommendations. Opportunity to pursue through SMR funding

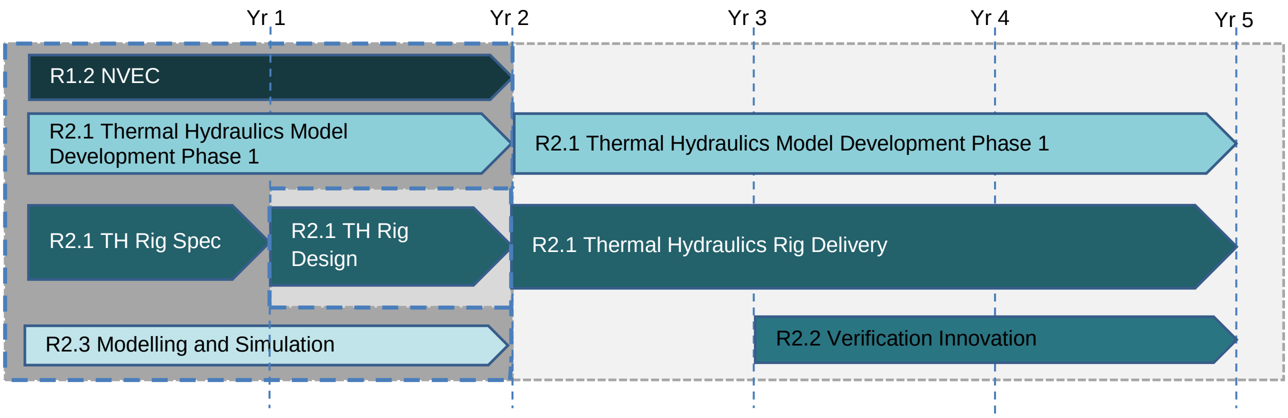


Figure 6 Outline reactor design (digital engineering) programme

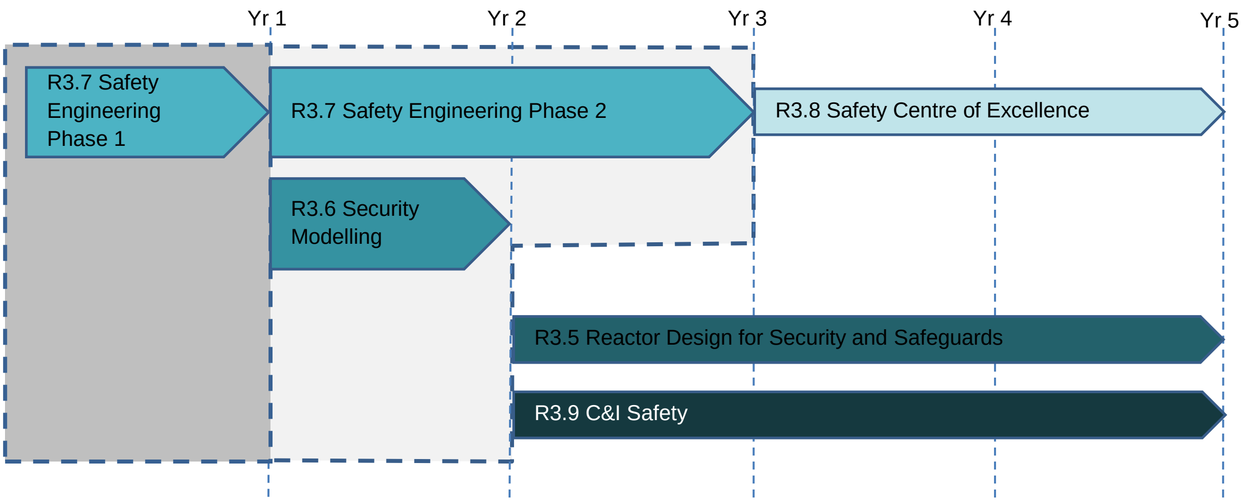


Figure 7 Outline reactor design (safety engineering) programme

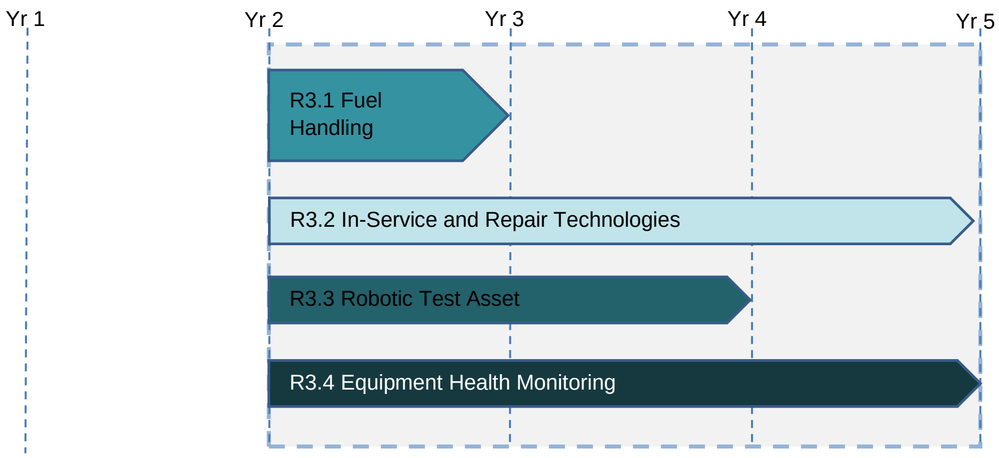


Figure 8 Outline reactor design (in service design) programme

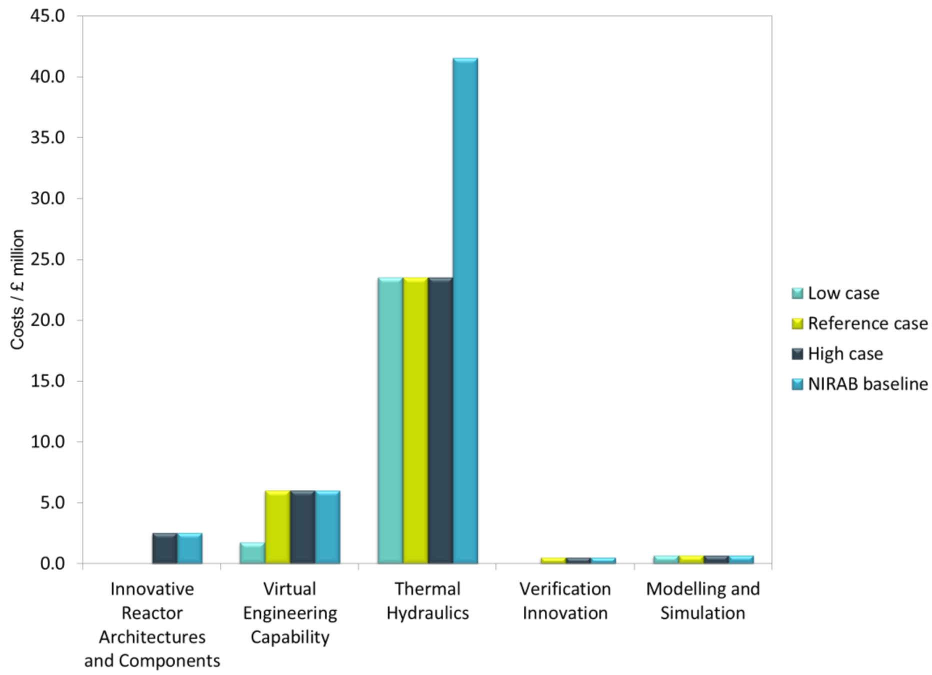


Figure 9 Comparison of NIRAB recommendations and prioritised reactor design (digital engineering) programme

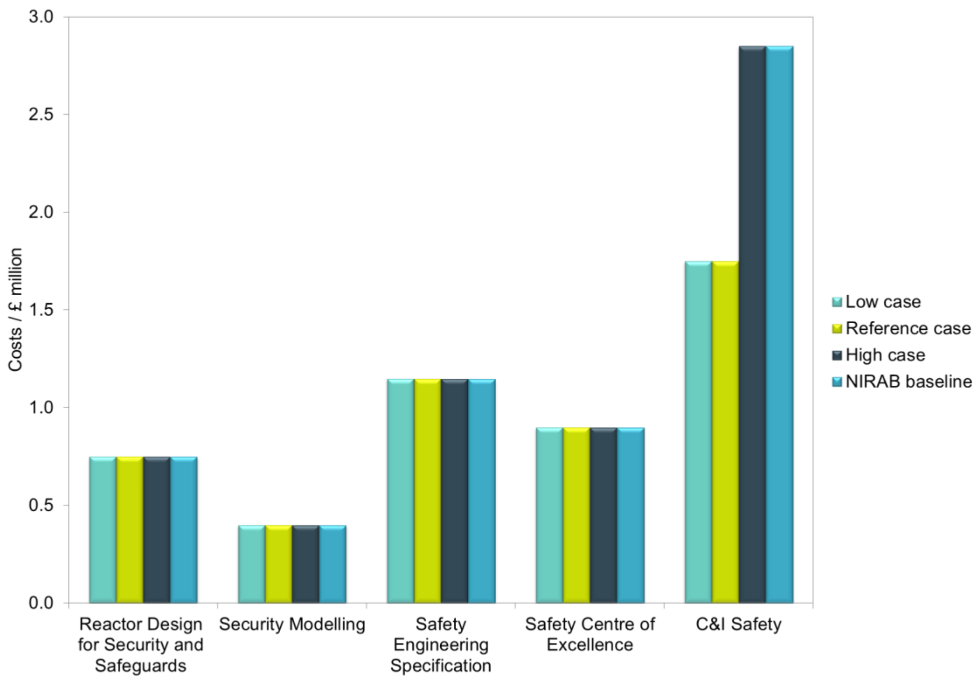


Figure 10 Comparison of NIRAB recommendations and prioritised reactor design (safety engineering) programme

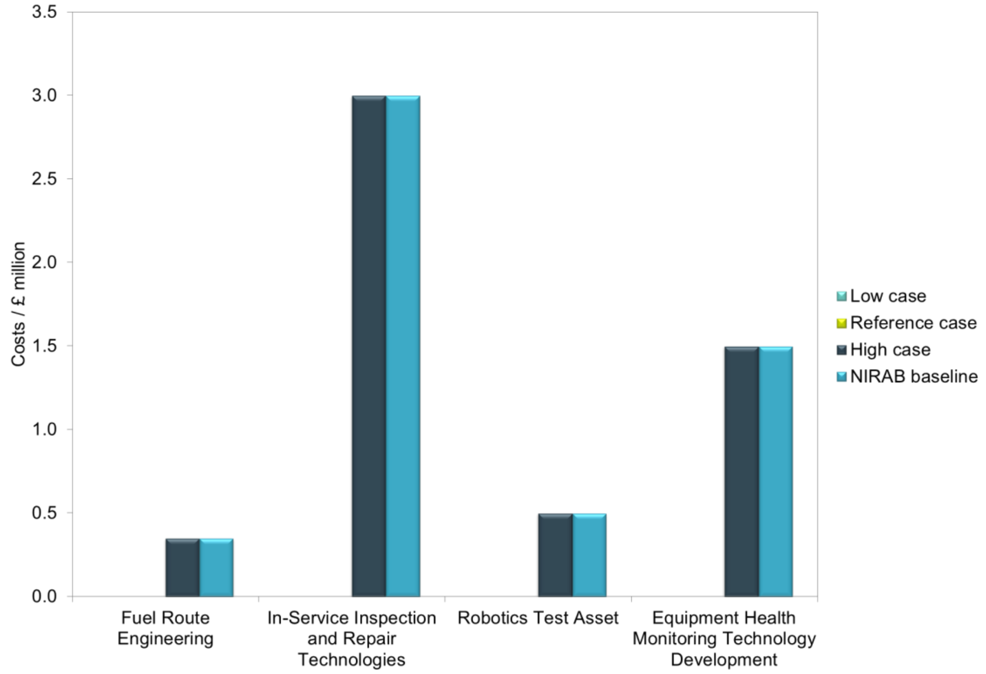


Figure 11 Comparison of NIRAB recommendations and prioritised reactor design (in service) programme

Table 4 Recycle and waste management research prioritisation considerations

Key

Green	No significant change to the scope and timing of the reference case from work recommended by NIRAB
Yellow	Some reduction in scope or delay in commencing research in the reference case
Red	Prioritisation results in significant delays in the reference case

WBS[1]	TITLE	Description	Variance from NIRAB recommendations	Prioritisation considerations	Summary prioritisation outcome
Recycle					
E1.1	Advanced Aqueous Recycling Studies	Carry out basic chemistry research into aqueous recycling based on limitations and issues with current process. Aim to define the steps for an advanced recycling technology (dissolution, separations and conversion).	Green	**Sustaining skills and capability:** Carrying out research into recycling technology will help to sustain a key resource that the UK is in danger of losing, in particularly with the closure of commercial scale recycling facilities. This capability will be key to support some future energy scenarios and support key decision making. This project was highlighted as the highest priority recycling and waste management task as it allows the existing world class skill base to be maintained. **Enabling:** This work will identify the scope and direction of the future research in this area and in particular will allow the scope of the facilities needed for future recycling development to be determined.	Recommended as the key priority for spent fuel recycling. Build on existing work to maintain a world leading capability.
E2.1	Fast Reactor Fuel Recycle Phase 1	Develop, test and commercialise an innovative flowsheet for fast reactor fuel recycling.	Yellow	**Opportunity:** Opportunity for international collaboration in R&D, supporting Gen-IV programmes. The international nuclear research community recognises aqueous reprocessing as an area in which the UK has expertise and can add value to collaborative projects.	Delay the start of the programme by 2 years to match anticipated funding levels in the first 2 years. Not an **urgent** priority as the UK is not engaged in fast reactor research. Subsequently carry on at the recommended rate of attack. Postponed in the low case as a consequence of more severe funding constraints.

WBS[1]	TITLE	Description	Variance from NIRAB recommendations	Prioritisation considerations	Summary prioritisation outcome
E2.2	Pyroprocessing Phase 1	Carry out fundamental research into pyroprocessing to regenerate UK capability in pyroprocessing and use this experience to show how it can be deployed at industrial scales.		**Enabling:** Understand future direction and possibilities of pyroprocessing.	The start of the programme has been delayed by 2 years to match anticipated funding levels in the first 2 years. Not an **urgent** priority as the UK is not engaged in fast reactor research. Subsequently carry on at the recommended rate of attack. Postponed in the low case as a consequence of more severe funding constraints. Delay to start will not affect end point as not targeting specific market opportunity.
E3.1	Off Gas Capture	Develop and demonstrate an integrated off-gas capture process to entrain iodine species, carbon-14, tritium and semi-volatile fission products proposing enhanced processes relevant to aqueous recycle		This is an enabling activity that supports and complements the development of advanced aqueous recycling technology. Current reprocessing technologies generate gaseous effluents which need to be managed. This is likely to remain the case for advanced technologies. There is also a trend to progressively reduce gaseous and liquid effluent discharges which will increase the level of challenge.	The start of the programme has been delayed by 2 years in all cases to match anticipated funding levels in the first 2 years. Not an **urgent** priority and has been allowed to lag behind separation process development. The scale of the programme is also reduced to meet budget constraints.
E3.2	Advanced Solvent and Effluent Treatment	Develop a suite of interconnected processes for the management of medium active liquid effluents, including solvents, arising from new recycling techniques.		This is an enabling activity that support and complements the development of advanced aqueous recycling technology. Current reprocessing technologies generate liquid effluents which need to be managed. This is likely to remain the case for advanced technologies. There is also a trend to progressively reduce gaseous and liquid effluent discharges which will increase the level of challenge.	The start of the programme has been delayed by 2 years in all options to match anticipated funding levels in the first 2 years. Not an **urgent** priority and has been allowed to lag behind separation process development. Once it starts the scale of the programme is also reduced to meet anticipated budget levels.

WBS[1]	TITLE	Description	Variance from NIRAB recommendations	Prioritisation considerations	Summary prioritisation outcome
E3.3	Processing of Aqueous Waste Forms	Develop waste management processes for the various wastes arising from aqueous flowsheets.		**Enabling:** need to be confident that the wastes and effluents generated by advanced recycling technologies (E1.1 and E2.1) can be immobilised into a form compatible with geological disposal.	The start of the programme has been delayed by 2 years in all options to match anticipated funding levels in the first 2 years. Not an **urgent** priority and has been allowed to lag behind separation process development which should identify the waste management challenges. Once it starts the scale of the programme is also reduced to meet anticipated budget levels. In general the waste management skill base is well exercised by the NDA estate. Can be carried out in next period. Follows on from detail development within E1.1. Delay to start will not affect end point as not targeting specific market opportunity
E3.4	Processing of Pyroprocessing Waste Forms	Develop new processes to manage new wastes loaded with fission products and salts arising from pyroprocessing recycling techniques.		**Enabling:** We will need to be confident that the wastes and effluents generated by advanced recycling technologies (E3.1) can be immobilised into a form compatible with geological disposal.	The start of the programme has been delayed by 2 years in all options to match anticipated funding levels in the first 2 years. Not an **urgent** priority and has been allowed to lag behind separation process development. Once it starts the scale of the programme is also reduced to meet anticipated budget levels. The waste immobilisation skill base is well exercised by the NDA estate. If necessary this could be cut or delayed further. Opportunity to fund pyroprocessing research through RCUK in the short term. Mid-TRL development of pyroprocessing (assuming EPSRC pick up fundamentals in phase 1) carried out in next period. Delay to start will not affect end point as not targeting specific market opportunity. Needs to be carried out after initial stages of pyroprocessing have been carried out.

WBS[1]	TITLE	Description	Variance from NIRAB recommendations	Prioritisation considerations	Summary prioritisation outcome
E4.1	Recycling Facilities	Develop a networked series of world class recycle and waste management research facilities		Enabling: Additional facilities may be needed to deliver tasks E1.1 to E3.4.	Tasks E1.1 to E3.4 already assume development of some facilities and will focus on those critical to the delivery of the recycle research programmes. Need to specify exactly what the need is.

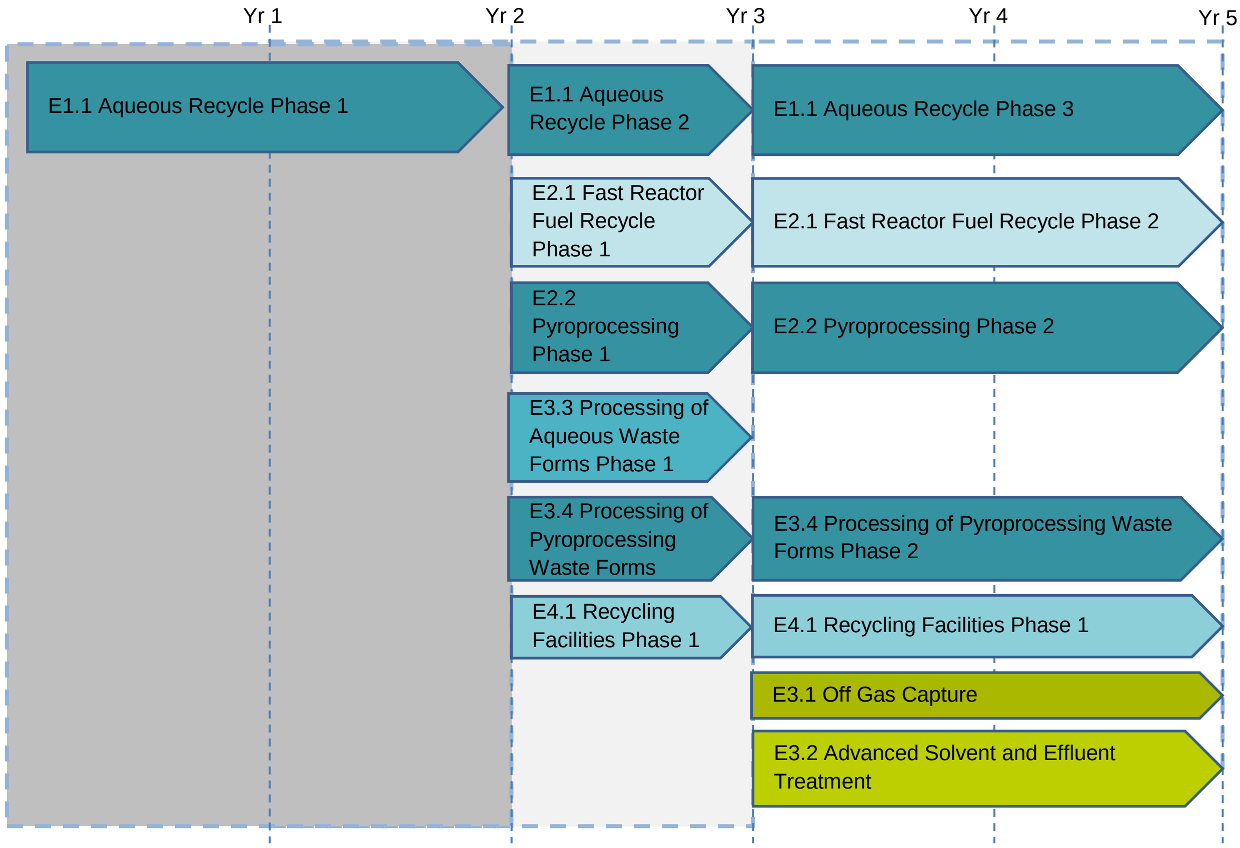


Figure 12 Outline Recycle and waste management programme

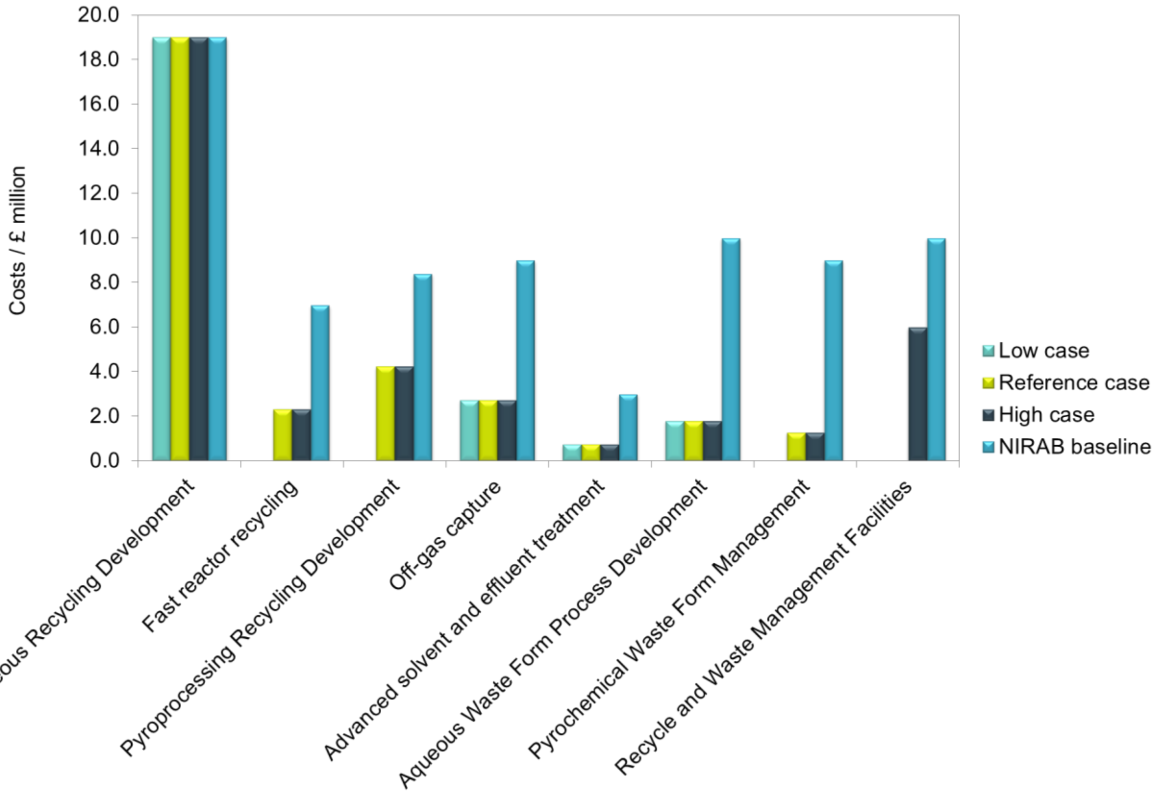


Figure 13 Comparison of NIRAB recommendations and prioritised spent fuel recycle and waste management programme

Table 5 Strategic toolkit research prioritisation considerations

Key

Green	No significant change to the scope and timing of the reference case from work recommended by NIRAB
Yellow	Some reduction in scope or delay in commencing research in the reference case
Red	Prioritisation results in significant delays in the reference case

WBS[1]	TITLE	Description	Variance from NIRAB recommendations	Prioritisation considerations	Summary prioritisation outcome
Toolkit					
S1.1	Strategic Assessments	Deliver strategic assessment tools that can inform key decisions within the UK nuclear sector.	Yellow	**Enabling:** Delivering the strategic assessment toolset within the first part of the programme will allow the main R&D programme (delivered in Years 3-5) to be better scoped and directed. The key research required to support future decisions can be determined along with a schedule of when key decisions need to be taken.	The scope has been reduced in all options. Some work has been delivered in 2015/16 (GFA development). Reduced funds should be able to deliver a significant improvement in capability. Some possible overlap with reactor physics and nuclear data.
S2.1	Public Engagement	Develop evidence-based tools to inform and enhance the delivery of a national strategy on public engagement in nuclear energy and embed these within the delivery programme for the NIC communications strategy. Develop new understanding of the underlying reasons for public attitudes to nuclear energy at national, regional and individual level, how these have emerged over time and how these are shaped by events.	Yellow	**Enabling:** Public engagement is a key enabler to the widespread deployment of nuclear technologies in the UK. The part that nuclear research and development programmes can play is managing perceptions needed to be determined. This could influence the scope and direction of much of the UK's future R&D programmes. **SMR Mission:** Give the perception of SMRs as a new technology and the opportunity to site them in new locations successful public engagement is a key enabler to the deployment of SMRs in the UK.	NB it is expected that all science and engineering projects should carry a requirement for public engagement.

WBS[1]	TITLE	Description	Variance from NIRAB recommendations	Prioritisation considerations	Summary prioritisation outcome
R1.5	Fast Reactor Knowledge Capture	Carry out a structured knowledge capture of the knowledge around the fast reactor programmes at Dounreay. Organise and disseminate the knowledge within the UK to allow access as required to support future research and Gen-IV programmes.		**Sustaining skills and capability:** The UK has developed a wealth of knowledge on the design, manufacture, operation and decommissioning of sodium cooled fast reactors from the implementation of the Dounreay fast reactor projects from the 1960s to the present day. This knowledge is a valuable asset to the future development of Gen-IV reactors and much of the "front end" knowledge is now in danger of being lost through the retirement (in some cases many years ago) of key individuals. Carrying out a knowledge capture from remaining available data and individuals will allow it to be organised and disseminated as appropriate to the UK industry, maximising its value.	No delay or reduction in any funding scenario.

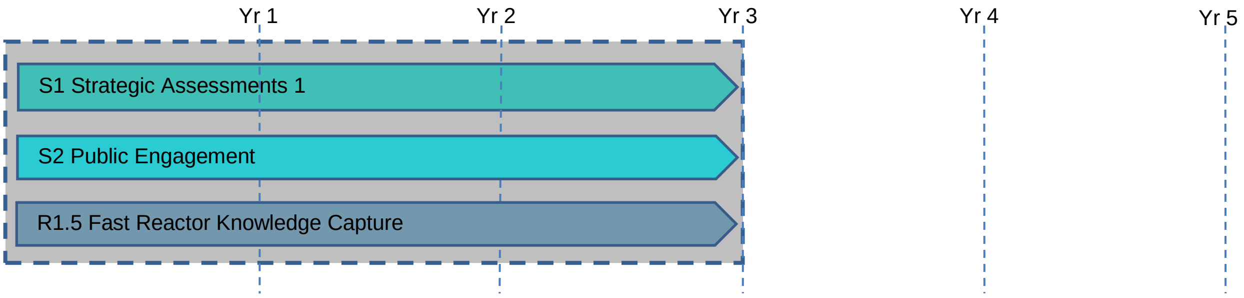


Figure 14 Outline Strategic toolkit programme

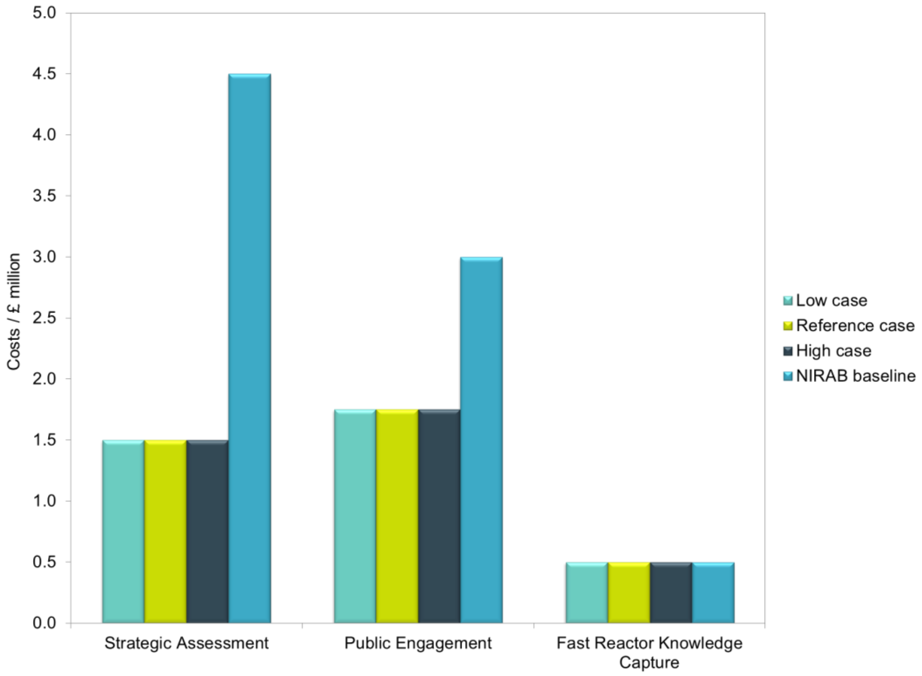


Figure 15 Comparison of NIRAB recommendations and strategic toolkit programme

Table 6 Nuclear Facilities research prioritisation considerations

Key

Green	No significant change to the scope and timing of the reference case from work recommended by NIRAB
Yellow	Some reduction in scope or delay in commencing research in the reference case
Red	Prioritisation results in significant delays in the reference case

WBS[1]	TITLE	Description	Variance from NIRAB recommendations	Prioritisation considerations	Summary prioritisation outcome
Nuclear facilities					
F3.2	Access to irradiation facilities	UK subscription to the OECD Halden Reactor Project and JHR representation	Green	**Enabling:** Access to a materials test reactor such as the OECD Halden Reactor Project is essential to delivering the development programmes for new fuels. Performance testing and validation of prototype fuels will be carried out under both normal operating conditions and transient conditions.	No delay or reduction in any option – these are basic enabling capabilities. The UK has a long history of participation.
F3.3b	Nuclear data (NEA Data Bank)		Green	The UK was a founder member of the NEA in 1958 and continues to be a member of the data bank. It is proposed that membership is funded through the R&D programme in year 1 and costs recovered from end users on a rolling basis.	No delay or reduction in any option.

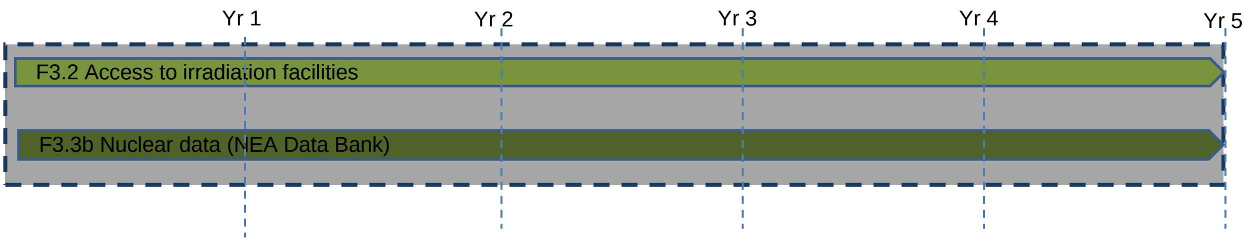


Figure 16 Outline international facilities programme

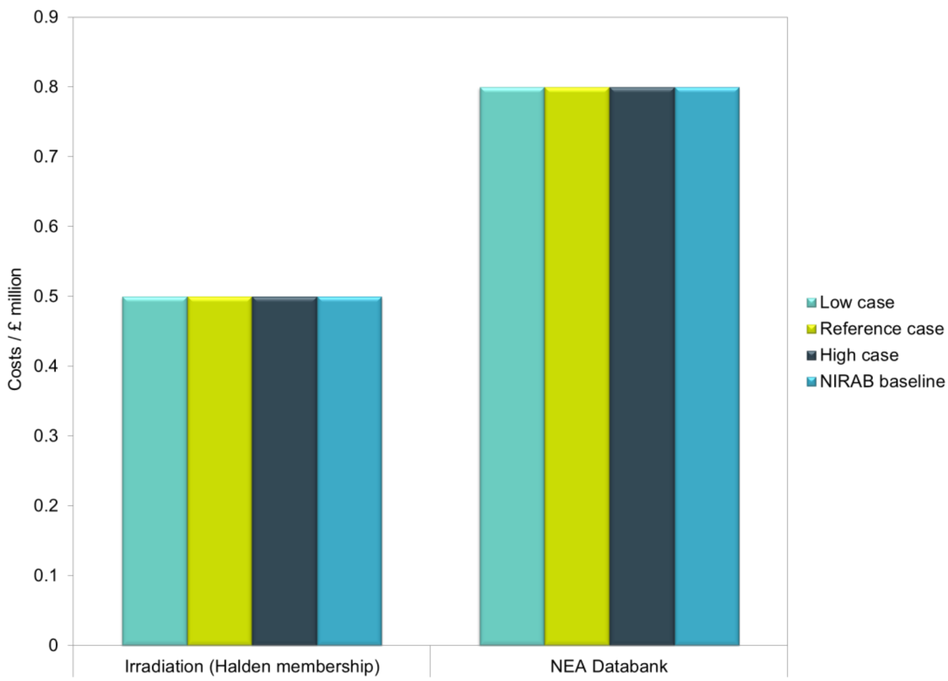


Figure 17 Comparison of NIRAB recommendations and prioritised facilities access programme