An Integrated Portfolio Approach to Plutonium Science: Underpinning the UK's Present and Future Needs

Note for the Record of a Workshop held at the University of Manchester (13/2/2025)

1.Executive Summary.

The UK will need industrial-scale programmes involving plutonium for many years into the future and these have to be underpinned by research and development (R&D). This paper summarises a workshop on UK plutonium science held on 13 February 2025, involving domain experts from both programme owners and the R&D community. While much of the physical infrastructure needed to carry out the necessary R&D in the UK exists or is being developed, the organisational construct and management arrangements could be improved, and the workshop findings have been developed into a *Theory of Change* for UK plutonium science. Five specific recommendations are made to improve collaboration and coordination across civil and defence applications, which would lead to a step change improvement in effectiveness.

Recommendation 1- Strategic. The UK should adopt a portfolio approach to plutonium science overseen by an authoritative, accountable individual or group (a 'Plutonium Scientific Authority'). An urgent review is needed as to the best means to achieve this oversight either through existing or new structures. The portfolio should comprise three programmes which align with the three pillars of activity (Appendix 1), within which specific projects are grouped, and identifying or establishing appropriate mechanisms to manage the portfolio and coordinate across the three pillars. A priority action should be to align different organisations' technical strategies in an integrated technical roadmap for plutonium science in the UK.

Recommendation 2- Strategic. The lifecycle cost savings of a proportionate, flexible approach to low technology readiness level experiments and trials before scale up will be substantial and should be quantified so to allow both capture of efficiency and value, and prioritisation. Researcher access to plutonium facilities therefore needs to be seen as a strategic priority across all stakeholders and the full costs of accessing plutonium facilities for researchers should be identified and recoverable. A co-ordinated, long term financial commitment to resource the plutonium science portfolio adequately across all elements of national capability is essential.

Recommendation 3- Strategic. As part of developing the plutonium science portfolio, a strategic approach to plutonium skills development, drawing on existing good practice in the sector, should be put in place and properly resourced, including provision of a range of facilities with proportionate working arrangements and multi-year programmatic funding. This should be part of the development of the technical roadmap and should cover the needs of academia and industry.

Recommendation 4- Operational. Effective plutonium R&D will de-risk major UK programmes but there are challenges with conducting a plutonium science programme, including safety and security risks. The challenges associated with R&D delivery need to be balanced against the substantial risks arising from not undertaking these activities, and therefore carrying greater uncertainty into major operations. In this context, safety and security arrangements for R&D need to be proportionate and to recognise the need for flexibility in R&D activities. Timescales for industrial deployment should account for necessary R&D activities to reduce overall risks. Using a collaborative approach, a range of models should be developed, for different facilities and operations, both on and off Nuclear Licensed Sites.

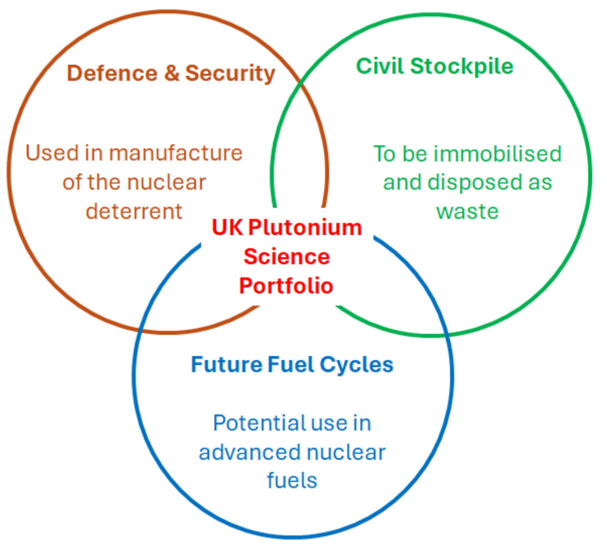
Recommendation 5- Operational. The installation and commissioning of the facilities currently known to be needed at UKNNL and AWE to support national programmes

should be an urgent priority and will be a valuable test of the capacity to change. Again, an integrated, coordinated and collaborative approach (see Recommendation 1) is essential to deliver this.

2. Context

2.1 The UK has exploited plutonium technologically for almost 75 years, both in its nuclear deterrent and in nuclear power. A new generation of deterrent is being developed and past fuel reprocessing has led to accumulation of 141 tonnes of separated plutonium, the World's largest civil stockpile. Government has recently decided that UK-owned materials will be managed as waste subsequent to the identification of a preferred immobilisation technology. The UK's programmes have a high profile internationally and increasing demands cannot be adequately supported by the current R&D arrangements.

2.2 Plutonium has uniquely complex and challenging physical, chemical and nuclear properties (see Box 1, below) which make it valuable but also extremely hard to work with. The UK will be managing and processing plutonium on an industrial scale for at least several decades into the future. After a long period of relative quiescence, policy decisions across civil and defence sectors now require a significant ramping-up in activity which needs to be supported by appropriate R&D and technical skills development capabilities. Three pillars of UK Plutonium Science can be identified (see Graphic below), focussed on the priority national missions in *Civil Stockpile Management* and *Defence & Security*, together with a key need to maintain R&D capability in advanced nuclear technologies and their *Future Fuel Cycle Options*. These pillars are described briefly in Appendix 1.



The Three Pillars of the UK Plutonium Science Portfolio

Box 1: The Unique Properties of Plutonium

Plutonium is made from uranium in nuclear reactors and is valued in nuclear technology because plutonium-239, one of the most easily manufactured isotopes, readily undergoes fission.

However, plutonium's radioactivity, and its complex physical and chemical properties which make it hazardous to work with. These characteristics, together with the political and public sensitivity of plutonium work, mean that such projects require specialist facilities and a highly skilled workforce, and often attract a high level of regulatory and public scrutiny.

3. Challenges in UK Plutonium R&D

3.1 Working with plutonium at scales above a few grams requires highly specialised facilities with stringent radiological and criticality safety cases to control radioactivity. These facilities must be secure, 'Category 1' facilities with rigorous procedures for materials accountancy, safeguards and physical security. Only two UK R&D facilities are capable of working with plutonium at these larger scales – AWE Aldermaston (defence) and UKNNL's Central Laboratory at Sellafield (civil sector). The difficulties in working with plutonium, even at these facilities, are substantial and there are some common problems faced by both organisations. However, these facilities are facing a step change in demand over the next 10 years and, with the limited capacity available for plutonium R&D, the UK must make best use of its plutonium infrastructure.

3.2 Academia should also play a role in supporting the UK's plutonium missions and its national laboratories. Two UK universities (Manchester and Sheffield) have capabilities for small scale (*ca* 1 g) plutonium research, a quantity where security and safety constraints are less demanding. Additionally, universities provide the training ground for the next generation of plutonium scientists and engineers, can be more flexible in their approach, can promote publication of results in the scientific literature, and can provide access to specialised equipment that does not need to be housed in the limited space in Category 1 facilities.

3.3 At a workshop hosted by the University of Manchester's Dalton Nuclear Institute on 13 February 2025, the participants (listed in 6 below) collectively identified a number of key challenges that, if resolved, would both massively accelerate delivery and reduce the costs of the plutonium R&D needed to underpin UK policy decisions and mitigate technical and engineering risks to industrial programmes with values in the £ tens of billions.

3.4 Recent and planned capital programmes (e.g. National Nuclear User Facility; Royce Institute; AWE recapitalisation; UKNNL) have created or should create much of the physical infrastructure required to support current activities and initiation of further programmes of work. However, the barriers to installing, commissioning and operating new facilities for plutonium research are substantial and growing and, together with working across organisational boundaries, are leading to increasing costs and timescales and putting industrial programmes scheduled to deliver in the 2030s at risk. Some specific capability gaps also remain (e.g. pilot scale capability; topics in 3.6 and 3.7 below) which will need to be addressed in future.

3.5 Additionally, compared to historic approaches to R&D, modern instruments and techniques offer both opportunities and challenges which should be exploited:

- it is possible to work with very small samples (e.g. lift-outs prepared by focussed ion beam milling), which should ease movement of material from Nuclear Licensed Sites to specialist off-site facilities;
- it is possible to bring techniques which previously required specialist off-site infrastructure on to Nuclear Licensed Sites (e.g. 'Benchtop' synchrotrons); and
- experience (e.g. with electron microscopes) has shown that modern instruments may be very fragile when exposed to the radiation levels encountered with plutonium samples.

To deliver effective research programmes at pace, it is essential to share practical experience, allowing us to establish a suite of available, reliable and maintainable instruments and ensure we have the right tools in the right places across national labs and universities to deliver state of the art plutonium science.

3.6 While much useful information can be obtained from very small samples, some essential studies (e.g. integrity, mechanical properties) still require representative samples (potentially tens of grams and upwards). Upscaling and industrialisation of processes, for example proving process flowsheets or innovative plant engineering, require trial/pilot scale facilities to raise technology readiness and minimise technical risks to delivery. Complementary computational modelling and simulation tools are also needed to accelerate progress and provide fundamental understanding. An analysis of needs and their owners, based on an in-depth review of programmes, should be part of the UK's plutonium technical strategy.

3.7 There are particular challenges in researching some important topics, for example i) carrying out ageing studies, particularly of bulk items, and ii) defining the effects of specific materials on processes and outcomes (e.g. impact of isotopic composition of plutonium; effects of processing and storage history).

3.8 There is an acute and growing plutonium skills need at all levels. Such skills can only be developed by working with authentic materials and an effective plutonium R&D infrastructure would be an excellent vehicle for attracting and training new entrants. A range of proven collaborative training models already exists in the sector (e.g. the SATURN Centre for Doctoral Training) and new initiatives such as the NDA Plutonium Ceramics Hub are welcome. The investment in these schemes has had significant successes and have been invaluable and necessary in attracting and retaining the talent required to deliver ongoing UK programmes. However, the current schemes are insufficient to deliver the required step change. It is equally important that career pathways, and R&D programmes, exist to develop early career scientists into the next generation of UK plutonium subject matter experts (SMEs) across both academic and national laboratories. It typically takes more than a decade of post-doctoral experience to develop an SME and there is a real risk of losing the UK's SME base without urgent action.

3.9 The Alpha Resilience and Capability (ARC) scheme has good intentions for developing the technical skills base in plutonium science. However, the practical implementation of these aims was difficult due to the complexity of the arrangements for the plutonium R&D communities in both civil and defence sectors. The reasons for this should be analysed and understood to enable more effective future outcomes. Indeed, the restructuring and relaunching of a properly funded and scoped ARC programme could be a key lever to deliver the plutonium science skills needed by industry. It is important to note that 'skills' are best delivered through mission-orientated R&D; hence the focus should be around the three pillars listed in 2.2.

3.10 'Projectisation', on-off funding and a strongly commercial/competitive approach has proved inefficient for plutonium R&D and this approach will not be able to deliver the increased demands from the growing industrial programmes. Partnership working is more appropriate for such complex R&D with its intrinsic uncertainties. It will prove far more cost-effective for the UK taxpayer in the long run.

3.11 Most importantly, organisational arrangements (e.g. liability, safeguards, security, safety case, design processes, transport, supply of material, waste routes, funding) currently present substantial barriers to the effective use of UK facilities. While restrictions will always remain because of the unique safety and security implications of working with plutonium, addressing these barriers to enable the (safe and secure) movement of people and samples between the small number of key facilities would be transformative.

4. Workshop Findings and A Theory of Change

4.1 The principal workshop findings are:

4.1.1 There are many R&D requirements which are common to the three pillars of activity identified in Appendix 1, and the civil and defence needs are converging. There are some funding gaps in the Future Fuel Cycles pillar that should be addressed. There is a need to share capability and expertise, and to prioritise access to facilities and training, which requires coordination and integration.

4.1.2 Current arrangements for academic access to national lab facilities are inadequately resourced and hence present substantial challenges to host organisations which have higher priority programmes to deliver. They do not cover the (usually large) full economic cost of hands-on plutonium work, imposing substantial burdens on the facility operator. For example, accommodating or hosting a researcher in a facility will require some or all of training, medical surveillance, radiation protection, supervision, technical support, safety case modification, waste management, all drawing on scarce, specialist resource, on top of the costs to access the secure facilities, and much of it is presently unfunded. Furthermore, stop-start activity leads to inefficiencies through repeated learning of processes and procedures, and re-establishment of access arrangements. Continuity and consistency of programmes will greatly reduce time and cost burdens relative to current arrangements.

4.1.3 The scale of demand for plutonium skills and the cost and difficulty of developing them require a coherent approach. A properly resourced partnership model, making best use of UK capabilities, would allow training in cohorts, which has already proved successful in other areas, for example the broad-based nuclear Centres for Doctoral Training led by Imperial College or the University of Manchester. Flexibility at all stages of an individual's career path, working across industry, national labs, academia, regulators, is essential.

4.1.4 Many arrangements (e.g. safety case) have been developed for routine industrial production processes involving large amounts of material and lack the flexibility needed for R&D activities where quantities of material are often much smaller and operations are not routine and predictable. A different mindset is needed to (as well as safely and securely) deliver vital R&D programmes to time, cost and quality.

4.1.5 There are many interfaces both within and between organisations which currently present barriers to efficient working, for example the matters listed in 3.10 and 3.11 above. The sharing of experience, good practice and development of common approaches and procedures would reduce these barriers. This should build on progress made through ARC, the civil-defence nuclear discussions and existing collaborations and relationships between key R&D organisations.

4.2 A *Theory of Change* is a method which explains how a given intervention, or set of interventions, is expected to lead to specific change, drawing on a causal analysis underpinned by the available evidence. Based on the workshop findings, a Theory of Change for UK plutonium science has been devised. This is shown below and has been used to develop a set of recommendations (see 5 below).

The UK Plutonium Science Portfolio- Theory of Change

Root Causes	Needs	Resources (inputs)	Activities (outputs)	Implementation Outcomes	Mechanisms of Change	Outcomes
30+ years of low effort leading to ageing facilities, inadequate skill base, fragmentation Silos within Government lead to lack of coordination, duplication, pseudo-competition Lack of proportionality in arrangements Arrangements designed for large scale production processes are unsuitable for R&D activities Recent policy changes require a sharp ramp-up from a low base	Equipment Coordination Organisation Skills	Existing Cat 1 facilities (AWE, NNL) Existing off-site facilities (Manchester, Sheffield) Currently planned recapitalisation Limited new facilities at some future time Pilot scale Ageing Others from gap analysis Portfolio owner on behalf of Government ('Plutonium Scientific Authority') Portfolio governance arrangements Funding for portfolio transformation	Portfolio management of three programmes (Civil Stockpile Management; Defence; Future Fuel Cycle Options) Gap analysis to identify future facility needs Partnership approach, not projectisation (avoiding pseudo-competition, short-termism, poor decisions...) Proportionality in safety, security, commissioning Efficient arrangements (liability, safeguards, security, safety case, transport, supply of material, waste routes....)	Integrated technical roadmap aligning individual organisational strategies Schedule of activities Coordination; prioritisation; quick, clear decision-making Better delivery- pace, flexibility, efficiency, lower risk Better visibility in Government	Better decision making Working in a single UK plutonium R&D ecosystem Effective R&D derisks national programmes Myth-busting- nuclear need not be slow, expensive and risky Regenerated skills pipeline	Effective response to generational challenges (deterrent, civil stockpile, net zero) Critical long-term programmes delivered at faster pace, more safely, at lower risk and for lower lifetime cost

5. Recommendations

Recommendation 1- Strategic. The UK should adopt a portfolio approach to plutonium science overseen by an authoritative, accountable individual or group (a 'Plutonium Scientific Authority'). An urgent review is needed as to the best means to achieve this oversight either through existing or new structures. The portfolio should comprise three programmes which align with the three pillars of activity (Appendix 1), within which specific projects are grouped, and identifying or establishing appropriate mechanisms to manage the portfolio and coordinate across the three pillars. A priority action for the Plutonium Scientific Authority should be to align different organisations' technical strategies in an integrated technical roadmap for plutonium science in the UK.

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6. Participants and Process

6.1 Based on their roles, experience and domain knowledge, participants were invited in a personal capacity to a one day, professionally facilitated, in-person workshop. Identities and affiliations are listed in 6.2 below. Draft output was developed and approved by all participants, then independently checked. This note reflects the consensus views of the individuals based on the discussions at the workshop. It does not reflect the views of the organisations to which the attendees are affiliated not is it intended to be an in-depth review of plutonium science and research strategies or needs. Rather, it is solely intended to highlight some of the key concerns of the UK's plutonium R&D community and identify potential efficiency improvements that should be considered by those responsible for delivering the UK's plutonium missions.

6.2 Workshop Participants

Name	*Affiliation*
Hayley Green	Sellafield Ltd
Robert Harrison	University of Manchester and Henry Royce Institute
Paul Heath	Nuclear Waste Services
Matthew Higginson	Atomic Weapons Establishment
Zara Hodgson	Director of the Dalton Nuclear Institute, University of Manchester
Lewis Blackburn	RAEng Fellow at University of Sheffield and Henry Royce Institute
Francis Livens	Professor of Radiochemistry, University of Manchester; Non-Executive Director of NDA
Paul Roussel	Atomic Weapons Establishment
Robin Taylor	UK National Nuclear Laboratory

Checked by: Sandra Clarke (NDA)

Appendix 1. Summary of the UK's Plutonium Science Needs

Civil Stockpile Management. Since the 1950s, the UK has accumulated separated plutonium from nuclear fuel reprocessing. This stockpile now stands at about 140 tonnes, and is safely and securely stored, mostly as plutonium dioxide powder, at Sellafield. The original rationale for separating plutonium was its energy potential, since it can be reused as fuel in nuclear reactors, and was essential for the envisaged fast reactor programme. Although the instability of Magnox fuel meant this fuel had to be reprocessed as a waste management route anyway. With the hiatus in UK nuclear build after the Chernobyl accident and the ending of the UK fast reactor programme in 1994, the likely demand for plutonium fuels decreased and material was stockpiled. In 2013, Government adopted the position that all suitable material should be fabricated into mixed oxide fuel (MOX) for thermal reactors, with material unsuited to use in fuel being declared as waste for immobilisation and disposal. In 2025, however, Government decided that the entire stockpile should be immobilised for disposal as waste, in the form of either a 'disposal MOX' or a ceramic wasteform produced by Hot Isostatic Pressing. While the manufacture and through-life behaviour of MOX fuel is well understood, the specification, manufacture and disposability of either disposal MOX or ceramic wasteforms is much less well underpinned and extensive R&D is needed to support process development and scale-up. Government is now initiating the necessary R&D. More background information can be found in references [1]-[3] below.

Defence & Security. Plutonium materials are essential components of nuclear warheads. Metallic materials are most important, often made from plutonium alloyed with other metals. Moreover, military plutonium is usually different in isotopic composition from civil material, with a higher content of plutonium-239, giving a lower specific activity and a higher fissile content. There are thus specific R&D requirements associated with the warhead programme. The current generation of warheads has been in service since 1994 and an upgrade programme has recently been completed, which should extend their lifetime until the 2040s. In 2020, Government decided to proceed with a new, sovereign warhead for a future generation of submarines. This will be the first UK warhead to be designed and manufactured without full scale testing. AWE is responsible for the design and manufacture of the UK warhead and maintains the necessary plutonium capability. AWE therefore has to carry out any R&D necessary to maintain the current Trident warhead and simultaneously that required to manufacture the replacement. AWE is also the UK's national capability for nuclear threat reduction and nuclear forensics. In addition, supporting activities such as treatment and packaging of plutonium-containing defence wastes will also require R&D. More background information can be found in references [4]-[5] below.

Future Fuel Cycles. Throughout the 75 years of its nuclear programme, the UK position on plutonium has evolved as the need for military material and the proposed role of nuclear power in the energy mix have changed. At the time of writing (February 2025), Government is supporting multiple initiatives to develop future nuclear power in support of its Net Zero by 2050 ambition, including large Pressurised Water Reactors, Small Modular Reactors (both Pressurised and Boiling Water designs), a Lead-cooled Fast Reactor, High Temperature Gas-cooled Reactors, and Molten Salt Reactors. While it is highly unlikely that all of these technologies will be deployed, the UK needs to be able to underpin deployment of any candidate technology, which requires maintenance of capability in the full supporting fuel cycles. In addition, while the UK has switched from a closed to an open fuel cycle over the last few years, it is quite plausible that, for energy security, economic and sustainability reasons, it may want to return to a closed cycle at some point in the next decades. The UK still has globally significant and scarce capability in recycling nuclear fuel and, given the timescale required to re-establish it, and the challenge of doing so once the capability is lost, Government has invested in R&D activities to maintain it. Maintenance of the R&D capability in future fuel cycles also maintains the UK's involvement and influence internationally as well as enabling other strategic materials or waste management process development for defence, nuclear security, space and decommissioning applications. The management of plutonium is integral to, and sometimes a very large part of, all the fuel cycle activities outlined here. More background information can be found in reference [6] below.

References

[1] Plutonium Disposition Strategy, HM Government. https://questions-statements.parliament.uk/written-statements/detail/2025-01-24/hcws388

[2] Progress on Plutonium Consolidation, Storage and Disposition, Nuclear Decommissioning Authority. https://assets.publishing.service.gov.uk/media/5c9e3e0140f0b625e1cbd851/Progress_on_Plutonium.pdf

[3] Managing the UK Plutonium Stockpile, Dalton Nuclear Institute, The University of Manchester. https://documents.manchester.ac.uk/display.aspx?DocID=68958

[4] Delivering the UK's Nuclear Deterrent as a National Endeavour, Defence Nuclear Enterprise CP1058. https://assets.publishing.service.gov.uk/media/671b8641956d9b52e8c6d276/Defence_Nuclear_Enterprise_Command_Paper.pdf

[5] Replacing the UK's Nuclear Deterrent: The Warhead Programme, House of Commons Library Research Briefing No 9777. https://commonslibrary.parliament.uk/research-briefings/cbp-9777/

[6] Fuelling Net Zero: Advanced Nuclear Fuel Cycle Roadmaps for a Clean Energy Future, Department of Business, Energy & Industrial Strategy and National Nuclear Laboratory. https://afcp.nnl.co.uk/wp-content/uploads/sites/3/2021/06/AFCP-Advanced-Nuclear-Roadmaps.pdf