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Integrated waste management and R&D at the National Nuclear Laboratory

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Summary. — Integrated waste management is a strategy adopted in the UK to minimise the waste arising from nuclear operations. The application of the waste hierarchy, that prioritises waste prevention, minimisation, reuse and recycle in preference to waste disposal is central to the minimisation of waste and ultimately the development of a circular economy. This paper describes the waste hierarchy approach and illustrates through examples, how R&D at NNL is supporting this approach and developing and demonstrating new technology to underpin its application to environmental restoration and clean energy programmes.

1. – Introduction

The UK was one of the first countries to develop a nuclear industry. The Calder Hall Magnox reactors first came on-line in 1956, generating electricity in Cumbria in the North-West of England. Indeed, the nuclear industry in the UK has covered most of the nuclear fuel cycle, including Research and Development (R&D), fuel fabrication, enrichment, nuclear generation (with Magnox, Advanced Gas Cooled Reactors (AGRs) and a Pressurised Water Reactor (PWR)), prototype reactors, fuel reprocessing, waste management and decommissioning.

Whilst generation continues with the AGR fleet and the PWR at Sizewell, many legacy facilities are now entering a decommissioning phase. The UK's Nuclear Decommissioning Authority (NDA) estimated in its 2021 strategy [1] that the discounted lifetime plan for Decommissioning and Clean-up costs of its civil legacy sites was greater than £130bn, including circa £11bn for a geological disposal facility and a programme duration of over 100 years to complete decommissioning and waste management activities.

Looking forward, the UK has set the challenge to reach net zero by 2050. Whilst the exact pathway is undefined, nuclear has the potential to play a significant role in achieving this goal through new generating capacity and potential future use of SMRs, AMRs and Advanced Fuel Cycles.

The UK's National Nuclear Laboratory (NNL) for fission, is harnessing nuclear science to benefit society, addressing issues of critical national importance, through work in four focus areas;

- Clean Energy,
- Environmental Restoration,
- Health and Nuclear Medicine, and
- Security and Non-Proliferation.

This paper focuses on the importance of an Integrated Waste Management approach and is illustrated with examples of how NNL's R&D supports this aim in its Environmental Restoration and Clean Energy missions.

2. – Integrated waste management: The Waste Management Hierarchy

World leaders adopted the United Nations (UN) 2030 Agenda for Sustainable Development in 2015 [2], with aims expressed as 17 Development goals. Nuclear can contribute to achieving these goals but must do so whilst considering the sustainable consumption of resources.

One approach that can help to achieve this in the context of integrated waste management is the application of the waste hierarchy methodology, to both the management of legacy waste from historic operations (Environmental Restoration) and by applying the principles of the hierarchy to the design and development of new facilities, fuel cycles and new energy systems (Clean Energy). Figure 1 illustrates the basis of the hierarchy, which provides a framework to strive to minimise the use of resources and minimises the

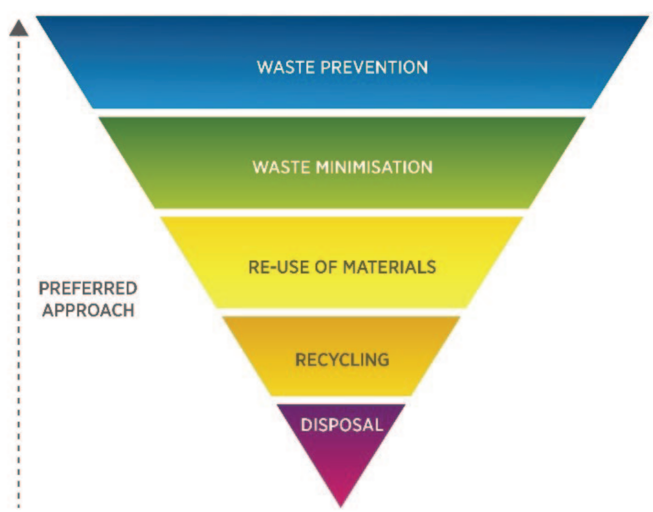

Fig. 1. – Visualisation of the waste hierarchy.

amount of waste requiring disposal. It is worth noting that this approach is not specific to the nuclear sector and its principles are codified in law in many countries. An overview of the framework is described below, however its broad application is described by the UK Government's Department for Agriculture and Rural Affairs (DEFRA) in 2011 [3].

The hierarchy comprises 5 themes for managing waste, ranging from the most preferred strategy of Waste Prevention to the least preferred strategy of disposal.

2˙1. *Waste prevention*. – The preferred option is to prevent the production of waste. This question is best addressed at the design stage, through minimising the usage/wastage of raw materials, designing for extended use (lifetime) and planning for through-life maintenance of equipment and facilities.

One example in a nuclear context is the adoption of the principle of "Designing for Decommissioning" [4], where consideration is now given to how a nuclear reactor (or other nuclear facility) will be dismantled and decommissioned, as part of the initial plant design phase and subsequent approvals. This is a significant step forward for the industry and a lesson learned from the challenge of legacy facilities of the early days of the industry.

Design for Decommissioning is a cross-sector issue with relevance to many different industries. It is also a timely issue, as many early nuclear plants, oil and gas facilities, and wind turbines, are coming to the end of their operational lives and will be decommissioned. Lessons can be learnt from these decommissioning programmes which can then be used to inform the design of future systems to prevent waste generation. To this end, NNL and NDA facilitated a Design for Decommissioning Workshop, drawing together participants from multiple industries across the energy sectors in 2021. A "Cross Sector Learning Report" was subsequently published [4], to share the learning insight openly.

2˙2. *Waste minimisation*. – Where it is impossible to prevent waste completely, the next best strategy is to minimise the amount of waste generated by a process. In the case of industrial processes, this may be through optimising the process / flowsheet to minimise the waste arising by good design practice and by optimising the process once operational. This is typically done using a range of tools from flowsheet modelling and simulation, to environmental assessments including Life Cycle Assessment (LCA). LCA and other tools are used to evaluate the environmental impact of "production" generally. This approach was applied by Wallbridge [5] to assess the impacts of decommissioning Magnox reactors, with the aim to identify the key environmental impacts, which could then be minimised. Manufacturing process improvement techniques such as Six Sigma are also often used to reduce wastage and optimise production.

2˙3. *Re-use of materials*. – Nuclear facilities, be they fuel manufacture, fuel cycle, reactors or other activities, are large capital infrastructure industrial processes, carried out at scale, and often on sites with multiple facilities. The scale of these operations brings the possibility that the waste arising from one process may be reusable within the complex. For example, cooling water discharge from one process may have a potential use as cooling water or diluent for another process. Effective reuse of materials requires careful monitoring and characterisation but can reduce raw material demands and the volumes of waste generated.

2˙4. *Recycling*. – If the waste cannot be prevented, minimised or reused, the challenge is to process the waste in a way to recover valuable components. This could be in the form of recovering chemical species from an effluent stream. In the case of nuclear waste management and decommissioning specifically, a relevant approach is to consider decontamination technologies. If there is a way to decontaminate materials (*e.g.*, pipes, vessels, concrete, etc.) by removing the radioactive contamination to allow the base materials to be recycled, then this may have significant benefits both environmentally and in terms of sustainable development. For this reason, decontamination science is a key area for research at the National Nuclear Laboratory.

There are multiple drivers to develop effective and efficient decontamination processes;

- To remove a radiological hazard from an environment, to allow safe human access for maintenance or for decommissioning activities,
- To reduce the volume of waste requiring specialist disposal; thereby optimising the use of critical storage/disposal capacity and reducing costs, and
- To enable recycling of the clean base material, in line with the principles of sustainable consumption and to enable a sustainable future through the circular economy.

One recent development is the Electrolytically Assisted Surface Decontamination Technique or EASD^{TM} which was developed in collaboration with C-Tech Innovation (a Small- Medium Enterprise in the UK) [6]. This patented process accelerates the removal of contamination from metal surfaces when treating with nitric acid. Effective and efficient decontamination of metals from nuclear facilities and their subsequent recycling would have significant environmental benefits.

2·5. *Disposal*. – Disposal is the least preferred strategy in the waste hierarchy, which effectively consumes materials putting them beyond future use. However, some waste could become valuable resources of the future. This is illustrated by the increased recent

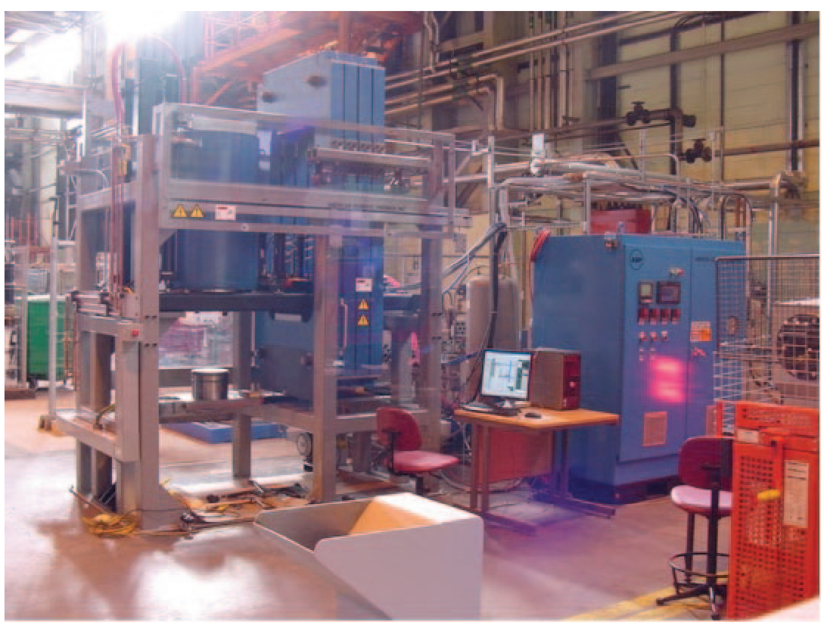

Fig. 2. – Hot Isostatic Pressing (HIP) Rig, at the NNL Workington Laboratory (UK).

policy focus on the management of future critical resources. One non-nuclear example of this is the noticeable increasing drive to recycle used electronic goods which contain valuable materials that can be recovered for recycle as raw materials for new products.

However, industrial processes do sometimes generate hazardous waste that must be disposed of safely to protect the environment, the population, and future generations. This is the case in the nuclear sector where some materials must be disposed of due to their radioactive nature, often in an immobilised waste form and then emplaced in an engineered facility. Whilst the nuclear industry has immobilised waste in different forms, notably intermediate level waste in cemented waste forms and high-level waste in glass, research and development in this area continues, nationally and internationally, with the drive to reduce the volume of waste and develop alternative durable waste forms.

NNL are investigating alternative cement formulations to underpin the ongoing operation of encapsulation processes and to potentially reduce the carbon footprint of future processes using different raw materials. The potential use of geopolymers is also under investigation for some wastes. Ongoing work is investigating the performance of geopolymers for the immobilisation of organic liquid wastes, and is linked to the current Euratom collaborative research project PREDIS [7].

Vitrification has been deployed successfully in the UK to treat high-level waste for decades. Building on this, NNL has been active in developing and evaluating the use of thermal treatment technologies for other wastes. Figures 2 and 3 show two thermal treatment demonstrators, a Hot Isostatic Press (HIP) process at the NNL Workington facility and an "In Container Vitrification Process" at NNL's Central Laboratory on the Sellafield site respectively.

Research, development and demonstration activities are ongoing to evaluate the potential feasibility and benefits of thermal treatment for specific intermediate level waste

Fig. 3. – In container vitrification (Thermal) Treatment Rig, at the NNL Central Laboratory (UK).

types. Thermal technologies have the potential to passivate the waste and achieve significant waste volume reduction. Volume reduction is significant as it has the double benefit of reducing size (or even number) of stores that are needed prior to disposal and reducing the volume required in the final repository for these specific wastes.

Internationally, the potential of thermal treatment led to the development of the EURATOM collaborative THERAMIN project that pooled experience and demonstrators to evaluate a wider range of different thermal technologies including facilities in Finland, France and the UK. THERAMIN established an international community of expertise in thermal treatment which is underpinning future developments through collaboration.

3. – Clean energy: Advanced fuel cycles

The previous sections have focussed on legacy facilities, however research and development is now underway into future energy systems. As part of the (UK) Department for Business, Energy, and Industrial Strategy's (BEIS) £505 million Energy Innovation Programme (EIP), the Advanced Fuel Cycle Programme (AFCP) was initiated as a collaboration between BEIS and the National Nuclear Laboratory (NNL). AFCP represents the largest (UK) public investment in future fuels and fuel cycle research and development in a generation and was tasked with redefining the feasibility and potential of advanced nuclear science in a future low-carbon society [9]. A holistic and integrated approach to waste management was considered alongside future fuel and fuel cycle research. This holistic approach and application of tools such as the waste hierarchy identified many opportunities to prevent and minimise waste and promote a more sustainable fuel cycle for the future [10].

4. – Conclusion

The UK has been at the forefront of the development of the nuclear industry since the 1950's, and many of the legacy facilities are now awaiting decommissioning. Therefore, an integrated approach to waste management is crucial to optimise this process. The application of the waste hierarchy is fundamental to achieving this goal, both for legacy facilities and in the design of future nuclear fuel cycle systems. This approach can also target R&D to develop innovative approaches to maximise the value of resources and minimise waste disposal.

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