Radioactive Waste Burning by Nuclear Transmutation: Considering 'Waste Burner' Nuclear Reactors for the UK

Introduction

This paper considers the case for 'waste burner' nuclear reactors in the UK. It is underpinned by the accompanying detailed report Radioactive Waste Burning by Nuclear Transmutation: Technical Report, which considers in depth the drivers behind the concept, summarises the academic literature on the topic, and discusses knowledge gaps and challenges in relation to relative benefit.

It is UK Government policy that the most hazardous radioactive waste should be disposed of deep underground in a geological disposal facility (GDF). A GDF isolates and contains the waste deep underground in a suitable rock formation to ensure that no harmful quantities of radioactivity ever reach the surface environment. This is achieved through the use of multiple barriers that work together to provide protection over hundreds of thousands of years. The operator of the GDF will have to develop an environmental safety case to demonstrate that the facility will meet strict radiological protection criteria to protect people from harm during the operation of the facility and after it is closed.

Some of the radioactive waste destined for a GDF is made up of isotopes that will take many hundreds of thousands of years to decay to background levels. Some of the isotopes in the waste also generate heat which needs to be managed.

Some vendors argue their waste burner technology could potentially treat this long-lived radioactive waste to shorten the timescale over which it is radioactive and reduce its heat generation.

Proponents of most fast reactor designs, where the primary objective is to generate electricity rather than treat long-lived waste, also make the case that their spent fuel would contain a reduced amount of the longest-lived isotopes compared to spent fuel from conventional (thermal) reactors, and that this in turn could result in savings for the GDF. However, this would only be the case if plutonium was not considered a waste, and is extracted from the spent fuel for subsequent use.

The above notwithstanding, in theory, widespread use of 'waste burner' reactors, and associated fuel cycles, could reduce the footprint of the GDF and the length of time some wastes would have to be isolated and contained in it, making the safety case easier to achieve and the GDF less costly.

However, it should be noted the UK already has a significant inventory (2,500 tonnes[1]) of vitrified high level waste destined for a GDF, which would be impossible to treat by waste burning. This high level waste requires vaults in the GDF with a safety case demonstrating this waste can be safely isolated and contained for 100,000 years.

[1] UK Radioactive Waste and Materials Inventory (2022), Waste Report

Waste burning: the theory

Radioactive waste *burning,* or *transmutation* as it is often referred to, describes treatment of long-lived radioactive waste to shorten the timescale over which it is radioactive. Long-lived, high-level radioactive waste begins life as a component of spent nuclear fuel discharged from nuclear reactors.

Spent nuclear fuel typically comprises residual uranium, plutonium, and other isotopes such as long-lived fission products and minor actinide species present aside from uranium and plutonium. The long-lived fission products and minor actinides are created as a result of reactions in the nuclear reactor, and both are considered radioactive waste, as they have no future use. The uranium and plutonium in the spent fuel can either be disposed of as waste or recycled.

The long-lived fission products typically decay away by around 300 years, with most of their heat having dissipated within 60 years. By contrast, the minor actinides take around 100,000 years to decay if not treated.

Therefore, there is potentially more to gain by 'burning' minor actinides than the long-lived fission products, most of which decay relatively quickly anyway.

For any waste burning scheme, the waste targeted for burning needs to be separated chemically from the rest of the spent fuel. This is necessary to prevent the inadvertent generation of further long-lived waste isotopes aside from those targeted by the waste burning process.

Two broad classes of potential waste burning technologies are discussed in this paper:

- schemes where waste burning is carried out as part of a broader closed fuel cycle which involve fast reactors; and
- accelerator-driven systems where the primary purpose would be to treat or burn the waste, rather than generate electricity.

Proponents of fast reactors argue they produce waste that is less radiotoxic and shorter-lived, as more minor actinides are consumed during reactor operation than conventional 'thermal' reactors. Separated minor actinides from the spent fuel of other reactors can also be added to some fast reactors to be 'burned'. In order to do this, the minor actinides that are separated from spent fuel during reprocessing would be added to the fast reactor fuel.

The primary purpose of accelerator driven systems would be for waste treatment. This system involves using a particle accelerator, possibly in association with a reactor, to transmute the isotopes so they become shorter-lived and generate less heat. This involves chemical separation of waste from the spent fuel and creating a 'target' of concentrated minor actinides to be irradiated. This process is untried on an industrial scale.

Waste burning: the practicalities

Waste burning as part of a broader fuel cycle

The UK operates an open fuel cycle in which nuclear fuel is manufactured from mined uranium and which, once burned in a reactor, constitutes spent fuel. Under UK Government policy the decision on whether to reprocess spent nuclear fuel is up to its owner. However, at present there are currently no reprocessing facilities in the UK; industrial scale reprocessing ceased in

2022. At present there is no economic or commercial driver to reprocess uranium. It is more cost-effective to manufacture fuel from freshly mined uranium than from uranium and/or plutonium that is extracted through reprocessing. In the absence of any proposals from industry for reprocessing, UK Government policy states that new nuclear power stations should proceed on the basis that spent fuel will not be reprocessed.[2] In addition, Government policy is to immobilise the UK's civil separated plutonium inventory, placing it into a long-term stable form suitable for geological disposal.

Undertaking waste burning as part of a closed fuel cycle would involve significant investment in new waste management infrastructure. It would also require the development of a plant to manufacture the fuel containing concentrated minor actinides. Unlike uranium used for fresh fuel, or uranium or plutonium recycled for use as fuel, the minor actinides are highly radioactive and manufacturing them into fuel would involve a higher degree of remote operation, which to date has not been demonstrated at scale.

Furthermore, in order to reduce the lifetime of the minor actinides from 100,000s years to 100s years, at least three cycles of separation, refabrication and burning would be required, dependent on the specific process. Significant pause periods, likely decades, would be required after each burning step to allow heat, radiotoxicity and the presence of a number of specific problematic isotopes to reduce such that fuel manufacture is possible, even with advanced remote handling techniques.

New reprocessing and fuel manufacture facilities would also generate new challenges in the form of secondary radioactive wastes during operations, and wastes arising from decommissioning when operations cease. Based on experience of reprocessing in the UK, it is likely that some of these wastes would themselves require disposal in a GDF, themselves being incompatible with waste burning.

Waste burning through an accelerator driven system

Similarly, waste burning through an accelerator driven system would require new infrastructure – a particle accelerator and/or reactor specifically to transmute the minor actinides and/or long-lived fission products into less radiotoxic waste. As with waste burning as part of a fuel cycle, it would also require a facility to chemically separate the minor actinides and long-lived fission products from the spent fuel.

Conclusions

This review of radioactive waste burning by transmutation indicates that realising any practical benefits could be achieved only with significant capital investment in new waste management and fuel fabrication infrastructure. The UK already has a significant inventory of vitrified high level waste, which would be impossible to burn and which would need to be safely isolated and contained in a GDF for 100,000 years. These factors combined call into question the material and economic benefit of waste burning in the UK context.

Furthermore, although it may be technically feasible to transmute some isotopes in radioactive waste to reduce their radiotoxicity and heat, this is as yet untried on an industrial scale and would require considerable R&D investment to overcome the significant challenges involved in:

[2] Managing Radioactive Substances and Nuclear Decommissioning: UK policy framework

- the chemical separation of the isotopes to be burnt or transmuted from bulk quantities of radioactive waste;
- the manufacture of fuel that incorporates separated minor actinides given their highly radioactive nature;
- understanding the nature, hazard and radioactivity of the additional secondary wastes that would arise from such activities.

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