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DOI:
IAEA-CN-199/379

Link to publication record in Manchester Research Explorer

Citation for published version (APA):
Gill, M., Abram, T., & Butler, G. (2013). Options for UK plutonium in SFR fuel cycles: Overview of current work. In *International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13)* (Vol. 8). International Atomic Energy Agency. https://doi.org/IAEA-CN-199/379

Published in:
International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13)

Citing this paper
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OPEN ACCESS

Download date:09. Jun. 2022

Options for UK plutonium in SFR fuel cycles
Overview of current work

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Presented by Matthew Gill

Abstract. The current study examines potential long-term options for stockpiled plutonium use in a UK fast reactor (FR) programme and the situations where FRs could become more advantageous than current options proposed by the NDA. This paper consists of a review of initial considerations and outlines the approach to be taken for further work. The UK has more than 90 tons of separated plutonium stockpiled due to its 1960s commitment to reprocessing. Originally intended for use in FRs, which never became economically viable, it is now labelled as a "zero value asset". Present NDA options aim to reduce the stockpile through irradiation of MOX in thermal reactors; direct disposal; or disposal following a period of storage. Recently, the UK's consideration of GE-Hitachi's PRISM reactor for plutonium burning suggests that different uses of FRs could, in the future, become advantageous with changing political and economic circumstances. These include: reducing dependence on resources; minimising long-term radio-toxicity of waste; proliferation concerns, or a combination of these factors, which will be reviewed.

1. Introduction

The basis of this study is to consider likely fast reactor (FR) fuel cycles in the UK and assess their relative benefits in terms of five high order metrics: (1) Impact on UK stored material and requirements for imported fissile material; (2) Technology readiness level; (3) Repository requirements; (4) Proliferation resistance; (5) Economic competitiveness. This paper sets out the initial considerations for the study and a review of relevant materials, which will form the main body of work and its analysis. Previous studies in this area have not considered the UK with its unique position – owning a large stockpile of civil plutonium.

FR fuel cycles are of little use at present due to the low cost of thermal reactor systems and abundance of uranium. Given time, this may no longer be the case. Future needs for a more sustainable base-load electricity generator could make FRs an obvious choice, and subsequently make plutonium a valuable commodity. Equally, given the evolution of technology and changes in public opinion, the opposite could happen and the need for nuclear power may vanish, making plutonium a liability.

1.1. The UK

At present, the UK is continuing down the nuclear route, with 16 GWe of new nuclear power expected by 2025. The Department of Energy and Climate Change's (DECC) reasons for supporting new nuclear power is based on it being ”the UK's most significant source of low carbon energy” and that prices do not fluctuate greatly with raw material prices[1]. However, past this round of new build it is uncertain what may happen and, at present, stock piled plutonium is classed as a ”zero value asset”[2]. If the UK decides to move away from nuclear, disposing of this plutonium would be advantageous, eliminating any storage costs. However, if nuclear electricity generation continues in the UK and worldwide in the long-term, this stock of fissile material could become valuable as a substitute for dwindling uranium resources. With there being no ”cost nothing”[3] option and uncertainty in the future of nuclear power, three high level options for plutonium have been outlined by the Nuclear Decommissioning Authority (NDA):[2][3][4]

- Long-term storage before disposal;
- Reuse of plutonium in thermal reactors as MOX before disposal or
- Immobilisation and disposal.

Recently, alternatives have been suggested and are being considered by the NDA. One option, which has made significant progress, is the reuse of plutonium in GE-Hitachi's PRISM Sodium Fast Reactor (SFR) prior to disposal[5]. This plan irradiates all plutonium in metallic fuel to the spent fuel standard before reloading it into the reactor to achieve the maximum burnup and thus generating as much electricity as possible. This increases the rate of return on initial investment. This option's consideration shows that there are situations where FRs could be considered in the UK, whether they be based on public opinion; international pressure or economically favourable solutions provided by the private sector.

All NDA options focus on the UK's large civil stockpile and methods to reduce it. Despite stockpile reduction being part of the study, a lot of options outlined focus on drivers other than this, considering long-term aspects such as sustainability. All options consider the use of SFRs rather than thermal reactors. Whilst thermal reactor fuel cycles have been extensively assessed in the UK and are suitable for comparison, they do not form part of this work.

2. Technical barriers

2.1. Sodium fast reactors

Only SFRs are considered as they are the most commercially developed, have more experience (both in the UK and internationally) and a reasonable timescale. Two reactor types will be compared throughout the study. One will be a more commercially developed, large scale MOX reactor like that of the CDFR and EFR project, which the UK has experience with in terms of the fuel cycle and reactor technology. The other will be a smaller, modular reactor with metallic fuel like that of GE-Hitachi's PRISM reactor: the associated fuel cycle and reactor technology have significantly less operational experience. The fuel cycles for each reactor will be considered. For the MOX reactor, the more common approach of aqueous reprocessing and pelletised fuel at centralised facilities will be used. For the smaller metallic fuelled reactor type, on-site fuel cycle facilities will be considered using pyro-reprocessing techniques. The purpose of this comparison is to see if developing a less experienced fuel cycle that has intrinsic advantages over current technology is worth developing over a more "off the shelf" approach with lower development costs.

2.1.1. Reactor experience and barriers

Worldwide there is significant FR experience and the UK has extensive experience as part of the DFR (metallic fuel); PFR (MOX fuel) and input on the CDFR and EFR projects. One of the main barriers is technical expertise and a large skills gap exists if the UK was to manufacture and operate facilities. These would be significant and limiting factors in the time scale of deployment.

Despite such operational experience, the construction and running of a number of reactors has highlighted several reliability issues with SFRs. Some demonstration reactors, such as PFR; MONJU and Superphenix suffered prolonged shutdowns as a result of a number of problems: refuelling issues; sodium leaks and reactivity spikes, to name a few. As such, advances in materials; components and safety analysis would be highly useful before large scale deployment.

Table 1. Cumulative load factor of demonstration SFR reactors [6].

Reactor	PFR	BN-600	Phenix	Superphenix
Cumulative load	20.57%	71.51%	33.72%	6.6%

Examining the cumulative load factor of demonstration reactors, only BN-600 has a reasonable cumulative load factor. The reason for BN-600's high cumulative load factor is its ability to operate despite sodium fires. By engineering around issues such as this, with materials advances and improved component design, it should be possible to achieve consistent reliabilities for future SFRs. Considerations such as oxide dispersion strengthened steels; pumps; welding and leak detection, amongst others, are very important. A key area identified for UK research comes under the umbrella of power conversion systems. Advances in steam generators or alternative power conversion systems can reduce the probability and severity of sodium-coolant interactions, which cause reactor outages. Alternative power conversion systems such as helium or supercritical CO2 Brayton cycles could be employed and the UK is particularly well placed to use printed circuit heat exchangers, for example[7].

2.1.2. Fuel cycle barriers

Metallic fuel experience is limited to EBR-II development as part of IFR. UK has experience with U-Mo fuel but this is unlike modern zirconium-TRU fuel design. Therefore, fabrication experience and reprocessing experience is very low.

Worldwide there has been considerable experience of fabricating thermal MOX. As of 2000, there had been: Belgium-BN/Desse 467 tHM; Germany-Siemens 158 tHM; France-CFCa 248 tHM; France-Melox 455 tHM, India-BARC 3 tHM, Japan-PFFF 120 tHM, UK-MDF 14 tHM, UK-SMP 5.5 tHM (2007). There has also been a lot of fast reactor MOX: Germany-Siemens 5.9 tHM; France-CFCa 110 tHM; Japan-PFFF 4 tHM; Japan-PFPF 10 tHM; UK-MDF/Sellafield 13 tHM; Russia-Paket 1.4 tHM and Russia-ERC 4.3 tHM[4][8][9][10]. Despite considerable experience there have still been issues with production. In the UK, the SMP never reached its name plate capacity and was shut down without fulfilling its contractual obligations. The large scale and complexity of such plants makes the failure of such large scale centralised facilities very expensive and impossible for private industry to finance alone, due to risk.

Despite considerable reprocessing experience there has only been a small quantity of MOX fuel being reprocessed. As of 2006, less than 171 tHM of MOX has been reprocessed in large scale purex plants: France-UP2/3 150 tHM; France-APM 2.8 tHM; and Japan-TRP 18 tHM. Fast reactors even less: France-UP2/3 100 tHM (diluted with thermal MOX); France-APM 10.7 tHM; France-AT1 1 tHM; Russia-RT1 450 tHM; Russia-RIAR 7 tHM and UK-UKAEA-RP 14 tHM[9][11][12]. As a result the assumption that these operations can be scaled up, may not be true and the building of plants which under perform or go over budget has the potential to make them economically unfavourable at first and have a knock on effect in terms of public acceptance.

The UK has experience of aqueously reprocessing metallic fuel (not zirconium based fuel). The B205 Magnox reprocessing plant operated successfully with a capacity of 1500 t/year of Magnox fuel and later suffered outages and required refurbishment before finishing its planned run. Reprocessing oxide fuel has been done in the Thorp plant with a capacity of 1200t/year. Unfortunately it has never been reliable, with changing throughput due to outages, major accidents and required modifications[13].

2.2. Partitioning and transmutation (P&T)

P&T scenarios have been widely considered due to their impact on long-lived radiotoxicity of waste and how this reduces the burden on a geological repository. Thermal loading in a repository is significantly reduced so more material can be stored[14]. Due to inefficiencies, transmutation schemes cannot remove the need for TRU disposal, instead it reduces repository requirements[15]. In a study considering Yucca mountain, the capacity could be increased by a factor of 4.4-5.7 with all minor actinides removed (depending on separation efficiency)[16]. However, it is not possible to remove the need for a repository. As a result it is worth considering long-lived isotopes, which have higher thermal loadings, or alternatively, the more easily transmuted and fissioned TRUs.

3. Assessment criteria

Below are the criteria which were used to assess fuel cycles:

(1) Sustainability – Considers the impact on UK material over time, depending on the system doubling time of different fuel cycles. It also includes the requirements for imported fissile material;

(2) Technology readiness level – There is significantly more experience with some facilities, which have been demonstrated on a commercial scale. Some techniques, such as advanced reprocessing methods or metallic fuels, have only been demonstrated on a small or lab scale, which greatly affects deployment timescale and cost;

(3) Repository requirements – The size of a repository and the length of time that waste must be kept secure and out of the environment is significant. This is assessed in terms of the time it takes for waste toxicity to reduce to the levels of natural uranium and the heat generated by waste over time. It has repercussions in terms of cost and burden to future generations and the public acceptance of nuclear power;

(4) Proliferation resistance – Systems which are more diversion resistant with higher intrinsic barriers to production/diversion of material are preferable (through minimising onsite materials; time to produce significant quantities; time to detect diversion and detection methodologies). In the UK this is, to a certain extent, less of a concern being a weapons state. However, the development of a fuel cycle which is deployable everywhere is a key factor;

(5) Economic competitiveness – Certain fuel cycles will be more economically favourable than others. Whilst it is understood that a lot of the above criteria cannot all be met in one system, there is the potential for a more ideal system, based on the UK requirements and public/political opinion. However, this may not prove cost effective and the most technologically ready systems might be the only economically effective route.

4. UK Fuel-Cycle-Options (FCO) for consideration

The UK's stance on nuclear power and plutonium disposition has been very changeable. With this in mind, and from a review of literature, common criteria for fuel cycle options (FCOs) became apparent. As such, six logical options and their justification have been outlined for further investigation:

- (FCO-1) Sustainability – Meet the requirements of limited uranium resources and the potential for large growth in terms of nuclear capacity;
- (FCO-2) Sustainability with high proliferation resistance – As above but with high intrinsic barriers to proliferation. Large growth in sustainable nuclear power could include insecure, non-weapons states. As a result, any fuel cycle deployed in the UK should be deployable in other states without fear of separated plutonium being easily diverted;
- (FCO-3) Proliferation resistance and minimising fissile stock – FRs to minimise the proliferation risk of any separated, weapons usable material;

- (FCO-4) Waste minimising – Reduce the burden on geological repositories and minimise the lifetime of all SNF so the burden of nuclear waste on future generations is minimised;
- (FCO-5) Sustainability with minimum waste – A sustainable FR system that keeps the lifetime of waste produced to a realistic minimum;
- (FCO-6) Feasibility – Whilst multiple FR systems have inherent advantages, there are issues with under developed technology. Therefore, if FRs become advantageous over thermal reactors in the near term, the most deployable route will be favourable.

Multi-attribute decision analysis methodologies were used to determine fuel cycle scenarios that best meet the above options. This was done by applying weightings, based on personal consideration of literature and previous studies, in terms of: proliferation; sustainability; waste and feasibility. These weightings were applied to aspects such as: the initial fuel stream; fuel constituents (whether higher actinides are included), and how fuel cycles are setup (to be self sustaining; breeding or net consumers of fissile material). Different permutations of these were considered and the scorings gave the following results for each fuel cycle option (shown in figure 1):

- FCO-1 – Breeding with only plutonium and uranium fuel and both LWR and FBR fuel is reprocessed;
- FCO-2 – Stockpiled plutonium has been through LWRs as MOX once (reducing the stockpiled mass and storing it in an active matrices). FRs use this as an initial driver fuel and actinides are homogeneously included (and potentially some lanthanide for self shielding purposes) in the fuel and set up for breeding;
- FCO-3 – No reprocessing, only use stockpiled plutonium as fuel to achieve very high burnup before disposal;
- FCO-4 – Multiple recycle of all TRUs from LWR and FBR fuel, with all MAs in target assemblies;
- FCO-5 – Same set up as FCO-1, but with americium homogeneously mixed in with the fuel in relatively small quantities to reduce one of the major components of long-lived waste;
- FCO-6 – The same as FCO-1 but with the potential (given a long deployment timescale) that some plutonium has been recycled in LWR MOX.

There is also the option to mix some of the sustainability and waste minimising scenarios in an equilibrium system to meet certain requirements. However, despite these being outlined as sensible routes to study, time constraints may require limiting these to a few of the more relevant fuel cycles for comparison. Similarly, some scenarios can be considered more relevant due to public opinion. There is also the potential for further analysis to remove some FCOs from the study for not being realistic. However, they are included here for completeness. The multi-attribute analysis was based on weightings given by the user and, despite material in previous studies supporting this assessment, it is important to realise that others may weight aspects differently.

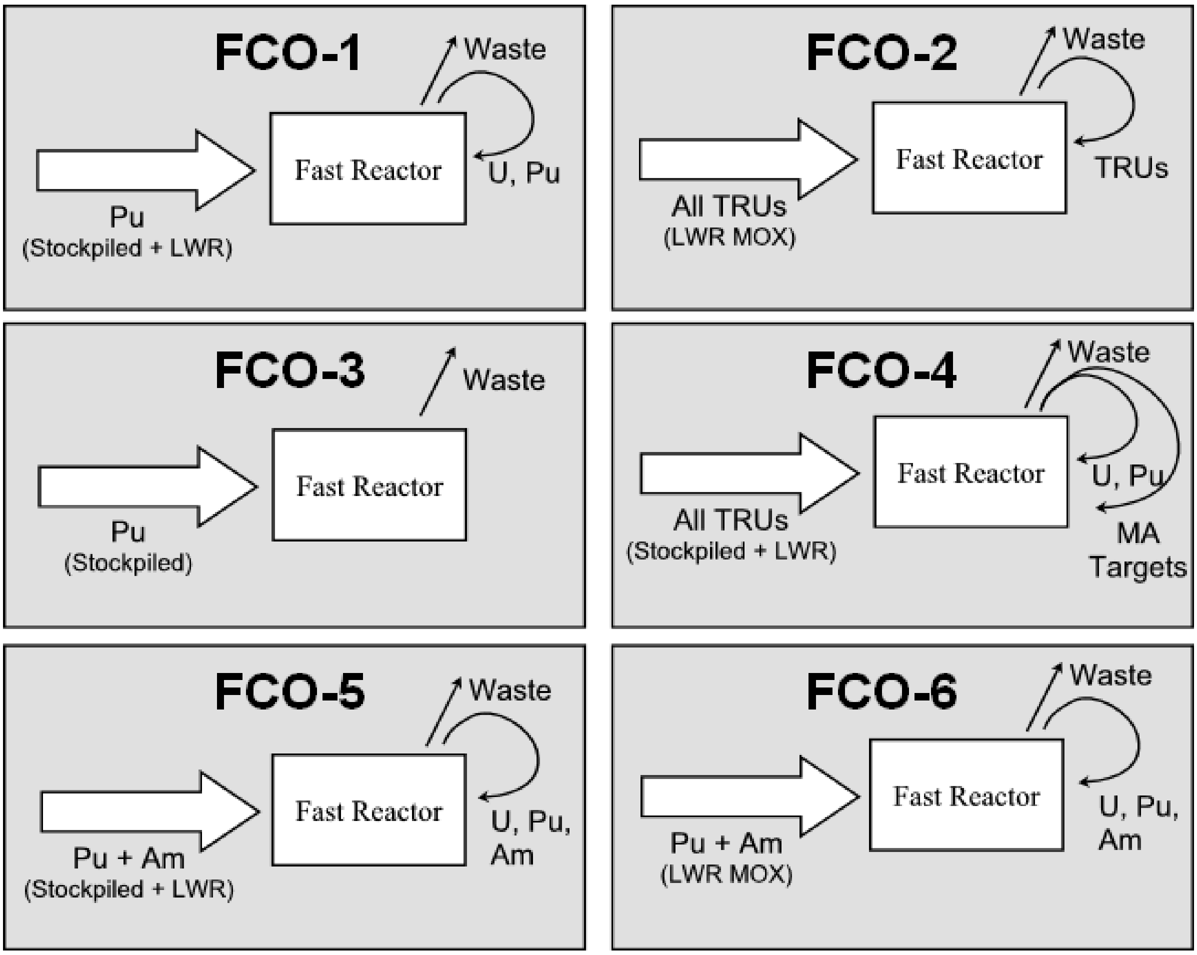

FIG. 1. Fuel cycle options showing basic material flows.

4.1. Deployment

Studies have shown that, in a high nuclear build scenario, world nuclear capacity would level off before increasing again if FRs are deployed too late. This is due to the reduction in uranium resources and the time required for breeding to build up a stockpile of fuel[17][18]. As such, consideration must be paid to whether build rates and stockpiled resources are appropriate. The scale of deployment will look at current considerations for new build as a minimum (16 GWe) and enough to begin decarbonisation of the UK as an upper limit (75 GWe).

4.2. Material stockpile

Reprocessing of spent fuel in the UK was originally intended for the weapons program. Over time, with the expected expansion of nuclear power worldwide and limited uranium resources, reprocessing was continued to provide fuel for a FR program[13]. However, the rate of nuclear expansion tailed off and the known, economically recoverable uranium resources gradually increased. This postponed the need for expensive FR programs but left the UK with the world's largest civil plutonium stockpile. Uranium fuels are still far cheaper to use than plutonium fuels and it is unlikely that the price of uranium will rise to a level where plutonium fuels would be competitive for decades[19]. However, the UK is left with 90.3 tons of civil plutonium (and 32 tons in spent fuel, giving a total of 122.3 tons as of 2011, and over 60 000 tons of depleted uranium and enrichment tails), which has no disposal route and is a proliferation concern[3].

A large FR such as the EFR, fuelled with TRUs from thermal reactors will use roughly 5 tons of plutonium per GWe of generating capacity. This means stockpiled material could roughly fuel 24 GWe of FRs as an upper limit. However, UK electricity demand peaks at over 50 GWe and, in the future, this would be higher if the UK moves away from fossil fuels for transport and heat applications. As such, if FRs are used as a sustainable base-load electricity source, there is a requirement for much more plutonium. Studies looking at variations of burnup, breeding ratio and doubling time show that, depending on the design, compound system doubling time can take between 16.5-43.5 years (this may be reduced with pyro-processing and shorter cooling times)[14]. To meet the current peak electricity demand with FRs, twice as much plutonium will be needed to seed reactors. This has a significant impact on the time to deploy a large FR program due to limited fissile stocks.

It is also unlikely that radial breeder blankets will be used due to proliferation concerns and as a result will make doubling times much longer. Therefore the scale of FRs deployment could be limited by the amount of fissile material stockpiled. This will be a more significant limiting effect on other countries, which do not have similar stockpiles. An alternative could be seeding reactors with enriched uranium, however, if FR deployment comes about due to expensive and dwindling uranium resources, this may not be feasible.

If one assumes an optimistic doubling time of 20 years (reference of heterogeneous reactor with breeding gain of 0.39) and a build rate of 1 GWe per year it would still take over 40 years to double the current plutonium inventory. A more realistic scenario, without radial blankets and breeding ratios slightly greater than one, could lead to a doubling time of up to 100 years, even with reprocessing of all new build LWR fuel. As a result, the UK would be dependent on LWRs and uranium in the interim. Therefore, deployment of FRs to meet future demand would have to begin decades before economically recoverable uranium resources begin to run low.

5. Methodology

Established codes will be used to obtain fuel cycle and reactor information, which will then contribute to the fuel cycle options analysis. The neutronics code WIMS10 with the ECCO cell lattice code will be used for FRs, whilst fuel cycle scenarios will use National Nuclear Laboratories fuel cycle analysis code ORION.

The approach to analysing these scenarios is as follows: an initial fuel cycle model will be run to its equilibrium point, which will then aid the selection of appropriate scenarios to investigate further, performing more detailed criticality designs in WIMS with more exact geometry. This will be used to check realistic doubling times, with and without radial breeders, and to obtain time dependent depletion calculations for further use in ORION. These depletion calculations will be used to more accurately model the fuel cycle, determining waste buildup and fuel utilisation for each FCO. Finally, FCO results will be analysed in terms of feasibility, repository requirements, sustainability, proliferation concern, and estimated cost. This body of work is set to begin immediately, and support with fuel cycle and neutronics modelling has already been arranged with AMEC and the National Nuclear Laboratory.

6. Summary

It is important to understand that this project is in its infancy. As a brief description of the approach and main considerations of the study, it should give an overview of the issues being examined and the criteria by which they will be assessed in further work. The potential areas that could be covered by this study are very large, so restricting the number of options to be looked at in detail will be important. Although all fuel cycle options highlighted would be interesting for comparison, they may not all be taken to the same level of detail.

ACKNOWLEDGEMENTS

Kevin Hesketh at NNL for arranging future work at Springfields, Francis Livens at The University of Manchester for support and suggestions and Joel Turner and Maureen Haverty at The University of Manchester for their constant help and guidance.

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