17 ANNEX 5 - SCENARIO MODELLING

17.1 Introduction
A study of the potential role of various P&T strategies within a projected UK nuclear programme is presented in this section. Current operational reactors and their associated fuel cycles are used as a starting point for the study, and assumptions about the future growth of nuclear power within the UK are used. A range of scenarios are examined ranging from a once-through fuel cycle in which spent fuel is stored prior to direct geological disposal, to double strata multiple recycling schemes utilising fast reactors and accelerator-driven systems. The alternate scenarios are compared on the basis of masses and radiotoxicities of waste materials, to illustrate the role that P&T could potentially play in a future UK nuclear programme.

17.2 Assumptions and calculational methods

17.2.1 Future UK nuclear electricity projections
The future requirement for electricity generation within the UK forms the basis of the scenario studies. Nuclear electricity projections have therefore been formulated by examining and extrapolating current trends. DTI energy paper 68\(^{26}\) presents Government projections for future UK energy demands and energy related emissions of carbon dioxide. Projections are based on three GDP growth rate scenarios (low, central and high) and two energy price scenarios (low and high), providing six possible scenarios. As nuclear energy contributes to the UK base load generating capacity, the total nuclear capacity is not dependent on the GDP growth or energy price assumptions, and therefore follows the same profile in each of the 6 DTI scenarios. The decline in nuclear generating capacity over the period 2000 to 2020 due to retirement of existing stations is shown in Figure 1.

On the basis of current economic assumptions, Energy Paper 68 forecasts that no new nuclear plants will be built in the UK before 2020. By 2010, nuclear generation will still form a relatively high proportion of total UK electricity generation of around 17 to 18%. This will fall to 7% of the total by 2020.

During the projection period covered by EP68, electricity demand is projected to rise steadily throughout the projection period, requiring substantial additions to generating capacity. Electricity supplied by all types of plant operated by all generating companies in the UK totalled around 350 TWh in 1999\(^{27}\). For the low energy price escalation scenario, electricity supplied to the grid is assumed to grow by around 1.25% per annum between 2000 and 2010. For the high energy price escalation scenario, supplied electricity is assumed to grow by around 0.8% per annum over the same period.

Long term estimates of the role of nuclear energy within the UK are more speculative. EP68 predicts that the total annual electricity demand in 2020 will be 408 TWh in the low energy

\(^{26}\) Energy Projections for the UK - DTI Energy Paper 68
price escalation scenario, and 387 TWh in the high price escalation scenario. This is equivalent to a rise of around 0.45% per annum for the low price escalation scenario, and 0.42% per annum for the high escalation scenario. For the purpose of the scenario studies, the lower demand growth rate of 0.42% is assumed. Generating capacity is assumed to rise at the same rate as electricity demand.

17.2.2 Overview of Scenarios

The study presents a range of scenarios in which various recycling strategies are examined. An initial scenario 0 is included for completeness in which no further nuclear build is undertaken within the UK. Waste arisings in this case cannot be directly compared with subsequent scenarios, as the total nuclear electrical energy is clearly substantially lower. However, the case is included as an illustration of the current default position within the UK. Five further scenarios are examined based upon the projected rising demand for nuclear energy as previously defined. Scenario 1 is a base case in which no reprocessing or recycling is undertaken, and spent fuel is committed to a geological disposal route. Subsequent scenarios examine the recycling of plutonium in thermal and fast reactors, and the partitioning and recycling of minor actinides. Two variants of Scenario 3 are included in order to directly explore recycling versus disposal of minor actinides in an otherwise identical scheme. The Scenarios are briefly defined as follows:

**No new UK nuclear build**

0. Continuation of existing station operation leading to eventual nuclear phase-out following closure of Sizewell B in 2035

**New build to meet reference electricity demand growth scenario**

1. PWR UO₂ once-through cycle followed by direct disposal of spent fuel
2. Single plutonium recycle in PWR MOX followed by disposal of spent MOX
3. PWR UO₂ cycle followed by plutonium and minor actinide recycle (3a) or plutonium-only recycle (3b) in gas cooled fast reactors
4. PWR UO₂/ single Pu recycle in PWR MOX, followed by plutonium and minor actinide recycle in gas cooled fast reactors
5. PWR UO₂ cycle followed by plutonium recycle in gas cooled fast reactors and minor actinide recycle in a dedicated accelerator driven sub-critical reactor.

The main parameters defining the Scenarios are tabulated in Table 1, and the associated fuel cycle schemes are illustrated in Figures 2 to 7.

17.2.3 Calculational Methods

Models of the scenarios defined above have been established using OSIRIS²⁸, a fuel cycle scenario analysis code developed by NNC with support from BNFL. The models include individual representations of each of the reactor systems present in the scenarios, together

---

²⁸ Millington, DN. OSIRIS : An Object Oriented Software Tool For Modelling The Logistics, Economics And Environmental Impact Of The Nuclear Fuel Cycle
with front and back-end process plants, stores and buffers. The models predict future inventories of actinides and key fission products arising, as a function of time, for each of the scenarios. The long term potential radiotoxicities due to ingestion of the waste streams are also determined, using published ingestion dose factors\(^{29}\).

Within any given scenario, each individual reactor is represented discretely and is assumed to have a finite operational lifetime, after which it must be replaced by equivalent generating capacity. The introduction dates of new reactors, as shown in Table 1, are subject to two key constraints. Firstly, a reactor can only be introduced if it is needed to meet the steadily rising electrical capacity demand, or to replace a retired reactor. Secondly, sufficient nuclear materials must be available to fabricate the initial core of a new reactor; this is particularly important for fast reactors which require a large plutonium inventory within the core. The introduction dates thus determined are therefore sensitive to many other assumptions within the study, and should therefore be regarded as indicative.

### 17.3 Scenario 0

This is the reference UK scenario, which reflects current UK nuclear generating policy. Existing Magnox and AGR stations are operated until their currently published retirement dates, and are then closed down. In accordance with current government energy policy, no new nuclear stations are ordered, and therefore the UK nuclear programme ends in 2035 with the closure of Sizewell B.

The spent fuel from all UK reactors (with the exception of Sizewell B), is reprocessed. This process involves dissolving the spent fuel and separating the uranium and plutonium content from the residual waste fission and actinide products. The plutonium is stored as PuO\(_2\) powder in small 10kg tins. The high level waste streams are conditioned and vitrified, and are stored at Sellafield, pending the development of a final disposal route. As there is currently no contract between British Energy and BNFL for reprocessing the spent fuel from Sizewell B, this fuel is assumed to be stored indefinitely for eventual consignment to a direct disposal route. Total spent fuel arisings from this station will be around 1240 tU over the 40 year design lifetime of the station.

The reduction in the annual nuclear generating capacity up to 2035, as stations are successively retired, is shown in Figure 8. The plutonium arising from the reprocessing of spent AGR and Magnox fuel is shown in Figure 9, broken down by isotope. \(^{241}\)Am is present in this store due to the decay of \(^{241}\)Pu with a half-life of 14.4 years. In scenario 0, this plutonium has no further industrial usage in the UK and remains in interim above-ground storage pending final geological disposal. The mass of plutonium in this form reaches around 155 tonnes. Figure 10 shows the accumulation of spent fuel arising from Sizewell B, which reaches around 1200 tonnes following its closure in 2035. This spent fuel will contain around 12 tonnes of plutonium, which will of course be unusable unless the fuel were to be reprocessed.

Comparisons between the waste streams arising in the different scenarios has been made on the basis of potential radiotoxicity. This is a measure of the total potential human dose in

\(^{29}\)ICRP Publication 48
The Metabolism of Plutonium and Related Elements, 1986
Sieverts of a mass of material, on the basis of a weighted sum of the nuclide inventory and their associated ingestion factors. Potential radiotoxicity makes no assumptions about the physical or chemical form of the waste nor the possible release mechanisms of the nuclides to the environment. It therefore serves as a convenient theoretical means of comparing different waste streams.

Figure 11 shows the potential radiotoxicity in man-sieverts of the principal waste streams in Scenario 0. Even though nuclear energy production ends in 2035 in this scenario, these are evaluated at 2150 for comparison with the later scenarios. Around 80% of the radiotoxicity present in 2150 is due to separated plutonium from gas reactor reprocessing. High level waste from early reprocessing operations, and spent fuel from Sizewell B each account for 10% of the total radiotoxicity burden.

17.4 Scenario 1

As in scenario 0, Scenario 1 adopts the same default UK back-end strategy for spent fuel, and existing stations are retired according to currently published retirement dates. However, a new build programme is initiated in 2020, to bring the nuclear fraction of the UK generating capacity back to 25%. Total generating capacity is assumed to rise at 0.42% per annum, and the nuclear fraction remains as 25% of this. The new reactors are generic 1 GWe advanced PWRs (APWR) with a fuel burnup of 51GWd/tHM. The APWRs are phased in over a 10 year programme from 2020, to bring the initial number of new reactors in the UK to 14 by 2030. New stations are subsequently added as necessary to match the annual 0.42% target capacity rise, and also to replace stations which have reached the end of their design lifetime of 60 years.

Figure 12 shows the generating capacity as a function of time up to year 2150. The yellow region shows the contribution to total nuclear generating capacity from existing UK reactors, which falls off as these reach the end of their operational lifetimes. The red region shows the new capacity introduced through the construction of APWRs. The spent fuel for the Magnox and AGR stations in reprocessed and separated into uranium, plutonium and high level waste (HLW). A loss factor of 1% is assumed, which implies that 1% of uranium and plutonium enters the high level waste stream. Spent fuel arising from the APWRs is stored without reprocessing.

The plutonium arising from the reprocessing of spent AGR and Magnox fuel in the UK is shown in Figure 13, broken down by isotope. 241Am is present in this store due to the decay of 241Pu with a half-life of 14.4 years. In scenario 1, this plutonium has no further industrial usage in the UK and remains in interim above-ground storage pending final geological disposal.

Figure 14 shows the accumulation of spent PWR fuel. Around 1200 tonnes of spent fuel from Sizewell B have arisen by 2035. The rate of production increases dramatically from this time onwards, as the replacement APWRs begin to discharge spent fuel. As the APWRs are assumed to have an operational lifetime of 60 years, the initial 14 stations are retired between 2080 and 2090, and the final core discharges of these stations accounts for the slight discontinuity in the gradient of the curve at this time. By 2150, 45,000 tonnes of spent PWR fuel have arisen in the UK, containing 470 tonnes of plutonium.
Figure 15 shows the potential radiotoxicity in man-Sv of the principal waste streams in Scenario 1. This shows a snapshot of the waste existing outside of reactors and fuel cycle facilities in 2150 and indicates how the radiotoxicity of this waste changes over long time scales. The bulk of the radiotoxicity in 2150 is due to spent PWR fuel, with around 8% due to the separated plutonium from gas reactor reprocessing. High level waste radiotoxicity from early reprocessing operations provides a negligible contribution.

17.5 Scenario 2
Plutonium oxide can be mixed with uranium oxide to form MOX fuel for use in conventional thermal reactors. This strategy reduces the amount of separated plutonium in store, by burning some of the plutonium and leaving the remainder in the form of the 'spent fuel standard', which is desirable for proliferation resistance. Reprocessing of spent UO\textsubscript{2} fuel solely to produce plutonium for thermal MOX recycling is not economically viable, but given that reprocessing is already underway, then the extra cost of fabricating MOX fuel could be justified, when offset against fresh uranium conversion and enrichment costs. Although MOX usage can reduce the inventory of separated PuO\textsubscript{2}, there is a penalty due to the increased creation of higher actinides.

No UK reactors are currently licensed to use MOX. Sizewell B is capable of using MOX fuel, as are the AGRs, but the latter would require modifications to the fuel route. A Pu MOX recycle scenario is therefore proposed in which it is assumed that current reprocessing operations will be extended to any new reactors constructed in the UK, and these reactors will be licensed to utilise MOX fuel.

Scenario 2 features an identical new reactor installation and replacement programme to Scenario 1. However, unlike Scenario 1, spent UO\textsubscript{2} arising from Sizewell B and advanced PWRs is reprocessed. This is separated into uranium, plutonium and HLW. A loss factor of 1% is assumed, which implies that 1% of uranium and plutonium enters the high level waste stream. The separated plutonium is then used to fabricate MOX which is introduced into the advanced PWRs.

The advanced PWRs are initially loaded with 30% MOX and 70% UO\textsubscript{2} in order to recycle the stocks of legacy plutonium as quickly as possible. Due to the characteristics of a conventional PWR-type core, the maximum achievable MOX loading is 30%. The 30% MOX fraction is maintained until 2039 when most of the legacy stocks have been recycled; it is reduced to 8.5% in order to balance the plutonium production in the UOX regions of the APWRs. The required enrichment of the MOX is 9% Pu and this rises steadily to 12% as the scenario progress due to the worsening quality of the separated plutonium. The viability of this level of plutonium enrichment in specific advanced PWR designs would require confirmation using detailed core calculations.

The contents of the separated plutonium stockpile is shown in Figure 16. Stocks are stabilised until around 2080 when first generation of APWRs are replaced. From this time onwards the worsening quality of the available plutonium requires the enrichment of the MOX to rise, and hence the total stocks of separated plutonium to steadily reduce.

Figure 17 shows the inventory of spent MOX as a function of time. By 2150 3,800 tonnes of spent MOX have been discharged from reactors for direct disposal; this compares with 45,000 tonnes of spent UO\textsubscript{2} in Scenario 1. The spent MOX contains 360 tonnes of plutonium. The
reduced mass of spent fuel for direct disposal in Scenario 2 is offset by the increased mass of HLW. In Scenario 1, 540 tonnes of HLW arise from legacy reprocessing operations, whilst 1100 tonnes arise in Scenario 2 due to the continued reprocessing of UO₂.

Figure 18 shows the potential radiotoxicity of the principal waste streams and separated material stocks in Scenario 2. This shows a snapshot of the wastes and materials existing outside of reactors and fuel cycle facilities in 2150 and indicates how the radiotoxicity of this waste and working material changes over long time scales. In 2150, spent PWR MOX accounts for 80% of the total radiotoxicity of the products, with the remaining 20% due to high level waste.

The separated plutonium stock is included here for completeness. As this material is destined for eventual recycle rather than disposal if the same recycling strategy were continued beyond 2150, it will not be consigned to geological disposal. This is examined further in the comparison of the scenarios in Section 17.9.

17.6 Scenarios 3a and 3b
Scenario 3 illustrates the role of a hypothetical gas-cooled fast reactor (GCFR) programme in the UK fuel cycle. The GCFR concept considered is a carbon dioxide cooled system based upon existing AGR technology. It is assumed to have a thermal power of 3600 MWth and an electrical power of 1458 MWe. It is fuelled with UO₂/PUO₂ MOX and operates on a 6 batch cycle with a cycle length of 428 EFPD. Each plant is assumed to have an operational lifetime of 40 years.

Two variants of this scenario, 3a and 3b are presented, in which plutonium and minor actinide, and plutonium-only recycling are performed respectively. Scenario 3a examines the introduction of a minor actinide partitioning and transmutation strategy using the GCFR. The nuclides chosen for partitioning are the minor actinides americium, neptunium and curium. It is assumed that these nuclides are chemically separated from the spent fuel during reprocessing into two additional streams. Neptunium is separated individually. Americium and curium are separated together into a second stream.

Neptunium is introduced homogenously into the MOX fuel. Americium and curium are kept separate from the fuel to avoid reintroducing them into the fuel cycle. Instead they are fabricated into inert matrix targets which are introduced heterogeneously into the core. The targets are irradiated within the core for 10 years, after which they are removed from the core for disposal, and are replaced on a two batch cycle. Reprocessing of spent targets and further partitioning of the products is a possible option, but this is considered to be technically and economically difficult and is outside the scope of this study.

Scenario 3b is based upon an identical GCFR installation programme to Scenario 3a, but does not included minor actinide partitioning and recycle. In this variant, the minor actinides continue to be directed to the HLW stream for the duration of the scenario, as in Scenarios 0, 30

Murgatroyd J. T., Hulme G. Thermal Hydraulics Analysis of a Plutonium Burning Gas-Cooled Fast Reactor
1 and 2. This variant is included as a sensitivity to assess the performance of GCFR as a transmutation device.

As in Scenarios 1 and 2, existing stations are retired according to currently published retirement dates. A new build programme is initiated in 2020, to bring the nuclear fraction of the UK generating capacity back to 25%. Total generating capacity is assumed to rise at 0.42% per annum, and the nuclear fraction remains as 25% of this. The new reactors are a combination of APWRs and GCFR, which are phased in over a 10 year programme from 2020, to bring the initial number of new reactors in the UK to 14 by 2030, consisting of 9 APWRs and 5 GCFRs.

The generating capacity profile as a function of time for Scenarios 3a and 3b are shown in Figure 19. The yellow region shows the contribution to total nuclear generating capacity from existing UK reactors, which falls off as these reach the end of their operational lifetimes. The red region shows the new capacity introduced through the construction of APWRs, and the blue region shows the new capacity provided by GCFRs. The ratio of GCFRs to APWRs is determined by the requirement to stabilise separated plutonium stocks. It is necessary to build GCFRs at the same time as APWRs during the initial new nuclear build phase of these scenarios, as, apart from the small annual growth in generating capacity target, there is no further opportunity to introduce GCFRs until the first generation of APWRs retire between 2080 and 2090. An additional GCFR is introduced in 2125 to maintain the necessary ratio of reactors for plutonium stabilisation.

Spent fuel from the existing UK AGR and Magnox stations is reprocessed according to current practices, and as such, no partitioning of the high level waste stream from these reactors is performed. The current practise of waste conditioning and vitrification is continued unchanged. However, spent fuel arising from the new generation of APWRs is partitioned according to the scheme outlined above. Spent fuel arising from GCFRs is also reprocessed and partitioned according to the same scheme.

The plutonium content of the MOX fuel fabricated for the GCFR depends on the quality of that which is available in separated form, and this is determined on a batch by batch basis for each reload of each GCFR.

In Scenario 3a, minor actinide targets are introduced into the GCFR cores as necessary to minimize stocks of separated americium and curium. This was achieved by loading 50% of the available target locations between years 2030 and 2060. Target loading is suspended between 2060 and 2070 whilst the first generation of GCFRs is replaced. When loaded with targets the new stations will require both batches of targets to be fabricated, hence the necessity for the temporary suspension of target throughput. After 2060 targets are introduced at the slightly higher level of 60% maximum capacity to continue to stabilise stocks. Neptunium is introduced into the GCFR MOX by an appropriate fraction in order to stabilise stocks. In Scenario 3a, this fraction is steadily ramped up to 0.7% by 2100.

Figure 20 shows the separated plutonium stocks for Scenario 3a, broken down by isotope. Following the initial installation of GCFR capacity, plutonium stocks are stabilised at around 40 tonnes. This is necessary in order to fabricate the initial cores of the replacement GCFRs from 2060 to 2070 and again from 2100 to 2100, as is apparent from the figure. Figure 21 shows the accumulation of spent GCFR MA targets as Scenari 3a progresses, broken down
by nuclide. By 2510, 35 tonnes of spent targets have arisen for disposal. In variant 3b, target recycling is not performed.

The separated plutonium stocks in Scenario 3b follow an almost identical profile to those of Scenario 3a, and is therefore not explicitly illustrated. The plutonium enrichment of GCFR batch reloads needed to meet reactivity targets over successive cycles differs slightly due to the presence or absence of neptunium within the MOX. However, this is a relatively minor effect which does not greatly affect the evolution of the mass or composition of the separated Pu stock, and does not require GCFR introduction dates to be modified between variants 3a and 3b.

Figure 22 shows the potential radiotoxicity of the principal waste streams in Scenario 3a. This shows a snapshot of the wastes and materials existing outside of reactors and fuel cycle facilities in 2150 and indicates how the radiotoxicity of these materials changes over long time scales. In 2150, 75% of the total radiotoxicity burden is due to spent minor actinide targets, with a further 10% due to separated minor actinides awaiting fabrication into targets or MOX. 10% is due to separated plutonium and the remaining 5% due to high level waste. The separated plutonium and minor actinide stocks are again included here for completeness, but will not leave the fuel cycle if the same recycling strategy is continued beyond 2150 and will therefore not be consigned to geological disposal. Of the two waste streams, namely HLW and spent targets, 13% of the radiotoxicity is due to the HLW, with the remaining 87% due to the targets.

The corresponding curves for Scenario 3b are shown in Figure 23, in which HLW is the only waste stream of significance. The sum of the target and HLW radiotoxicities in Scenario 3a can be compared directly with the HLW in 3b to explicitly assess the radiotoxicity benefit of MA partitioning and GCFR-based transmutation. The reduction factor is greatest at timescales of the order of 1000 years, when the combined target and HLW radiotoxicities in Scenario 3a is around one-third that of the HLW from Scenario 3b. This is illustrated further in Figure 34 and Figure 35.

17.7 Scenario 4
Scenario 4 is a combination of Scenarios 2 and 3a. It features minor actinide partitioning beginning in 2020 and transmutation of plutonium and minor actinides in GCFRs as in Scenario 3a. However, an initial stage of plutonium recycle in PWR MOX is also performed as in Scenario 2. The spent PWR MOX is reprocessed and partitioned and the recovered plutonium is used to fabricate GCFR MOX. This contrasts with Scenario 2 in which spent PWR MOX is consigned to direct disposal.

The generating capacity profile as a function of time is shown for scenario 4 in Figure 24. The yellow region shows the contribution to total nuclear generating capacity from existing UK reactors, which falls off as these reach the end of their operational lifetimes. The red region shows the new capacity introduced through the construction of APWRs, and the blue region shows the new capacity provided by GCFRs. As legacy stocks of gas reactor plutonium are initially cycled though APWR MOX, the construction of GCFRs is later than in Scenarios 3a and 3b, and fewer stations are needed to stabilise plutonium stocks. The first GCFR is introduced in 2053, followed by 3 additional new stations over the following 30 years.
The separated plutonium stocks in Scenario 4 are broken down by originating reactor type in Figure 25 and by nuclide in Figure 26. Higher stocks are maintained than in Scenarios 2 and 3 due to the stocks of spent MOX arising from both reactor types.

Full uses of the available target locations within the GCFR cores is made during scenario 4 from 2050 onwards. Despite this, as scenario 4 features less GCFRs than Scenario 3, there is less capacity for target irradiation. Figure 27 shows the accumulation of spent GCFR MA targets as Scenario 4 progresses, broken down by nuclide. By 2150, 36 tonnes of spent targets have arisen for disposal. This is similar to that achieved in Scenario 3, as although there are fewer GCFRs installed, the available target locations are fully utilised.

Figure 28 shows the potential radiotoxicity of the principal waste streams and material stocks in Scenario 4. In 2150, spent GCFR MA targets account for around 30% of the total radiotoxicity of the products and a further 45% is due to the separated plutonium and minor actinide stocks present at 2150. High level waste contributes around 5% of the total radiotoxicity. Of the material to be consigned to geological disposal, the HLW contributes around 25% of the total radiotoxicity, with the remaining 75% due to the spent targets.

### 17.8 Scenario 5

Scenario 5 includes a sub-critical accelerator driven system (ADS) which operates as a dedicated minor actinide transmutation device. ADS reactors include a particle accelerator which injects protons onto a spallation target to produce source neutrons for driving a sub-critical core. The freedom to design and operate a reactor core at a neutron multiplication factor of less than 1 enables dedicated minor actinide burning cores with degraded safety characteristics to be developed.

The ADS device included in this scenario is a 200 MWth carbon-dioxide cooled concept\(^{31}\). The system includes an accelerator which delivers a 1 GeV proton beam and requires 10 MWe for operation. The overall thermal power of the ADS is fixed at 200 MWth. The system has a overall efficiency of 45% and hence delivers a net electrical power of 80 MWe. The core is uranium-free and uses a particulate fuel, in which a minor actinide/plutonium fuel kernel is surrounded by two TiN layers of differing density. The fuel particles are constrained by steel mesh boxes and located in central channels within hexagonal graphite subassemblies.

The ADS scenario developed here assumes that APWRs are operated on a UO\(_2\) based once through cycle, together with plutonium multiple recycle in GCFRs. Americium, curium and neptunium partitioning is performed during reprocessing of fuel from both reactor types. A single ADS is introduced in 2070 and is fuelled with the separated minor actinides, supplemented with plutonium. Introduction of the ADS is delayed until 2070, as an initial separated Am/Cm stock of around 13 tonnes is necessary to fuel the initial ADS core and sustain the fuel loop, which includes a 5 year cooling period following discharge from the reactor. The fuel from the ADS is reprocessed and is in turn partitioned and recycled. In this scenario, no minor actinides enter the high level waste stream. This is in contrast to scenarios 3a and 4, in which the irradiated targets consigned to geological disposal still contain substantial masses of minor actinides.

---

\(^{31}\) CEA/SERCO design - No open literature reference currently available
The generating capacity profile for Scenario 5 is shown in Figure 29. The ADS requires a core inventory of around 4.5 tonnes of plutonium, which is diverted away from the GCFR programme, and therefore the 5th GCFR to be constructed is delayed from 2029 (as in Scenarios 3a and 3b) to 2050. As the ADS contributes a modest net electrical capacity of 80 MW to the UK total, it does not alter the broad balance of APWRs and GCFRs to supply the bulk of the nuclear output. Figure 30 shows the plutonium stockpile in Scenario 5, which follows the same broad trends as Scenario 3a.

Figure 31 shows the radiotoxicities of material stocks and waste streams present in 2150 and their evolution over long timescales. 10% of the total radiotoxicity in 2150 is due to the HLW, with the remainder due to separated plutonium and minor actinides awaiting recycling. The HLW consigned to disposal has significantly lower radiotoxicities than in scenarios 3a or 4, as in this scenario, no minor actinides leave the fuel cycle other than those entering the HLW stream due to reprocessing losses.

### 17.9 Comparison of Scenarios

Figure 32 compares the masses of high level waste which have arisen by 2150 for each of the Scenarios. In each of the scenarios in which reprocessing is continued, there is little difference in the masses of HLW generated, although the composition of this waste is clearly sensitive to the mix of reactors and recycling strategy in each case. Figure 33 compares the masses of fuel and/or target elements consigned to geological disposal for each scenario. The curves, shown on a logarithmic scale, illustrate the general trend of reprocessing and recycling as a means of reducing the mass of spent fuel arising, and hence the potential size of a geological repository.

The long term potential radiotoxicities of all waste materials which have left the fuel cycle as waste by 2150 are compared for each of the scenarios in Figure 34. These include high level waste, spent fuel and spent MA targets. In Scenarios 0 and 1, the separated plutonium which has no further industrial use and is essentially a waste is included. Contributions from irradiated uranium recovered during reprocessing, and depleted uranium arising as tails from the enrichment process are also included in these totals. Figure 35 shows similar curves but excluded the contributions from the uranium. For timescales in excess of one million years, the uranium is shown to be the main contributor to the potential radiotoxicity, due to the ingrowth of radon gas from the decay of the uranium.

Further comparisons of radiotoxicity contributions in each of the scenarios are shown in a series of bar charts (Figures 36-47). The radiotoxicities of all wastes and materials in buffer stores at 2150 are shown in Figure 36. These are shown separately as separated materials awaiting recycling, and waste materials which have left the fuel cycle for geological disposal in Figure 37 and Figure 38 respectively. Figure 39 shows the contributions from irradiated uranium recovered during reprocessing, and depleted uranium arising as enrichment tails. Successive figures show the same quantities at further intervals of 100 and 10,000 years.

The present scenarios studies, which focus on plutonium and MA recycling, do not explicitly investigate and compare uranium utilisations, or consider uranium recycling options. Uranium recovered from spent UO\textsubscript{2} typically contains around 0.5% U\textsubscript{235}, and this can be reused in the manufacture of fresh UO\textsubscript{2} to offset the need for uranium ore mining. However, this recycling is not performed in any of the scenarios presented here. A small fraction of the depleted uranium, which arises as tails from uranium enrichment, is used as the carrier for...
PWR or FR MOX where appropriate in the scenarios presented. However this generally continues to accumulate due to the continued need for thermal reactor fuel, and is currently stored as UF₆. Strategies for the disposal of depleted uranium are actively being studied and include conversion to oxide for disposal as LLW. As the radiotoxicity burden of depleted uranium is low relative to the other materials covered in this study, this is not explored in detail.

Radiotoxicities in Scenario 0 are obviously much lower than the other scenarios, due to the early abandonment of nuclear power in the UK. In Scenario 1, most of the radiotoxicity is clearly due to spent APWR fuel. In Scenario 2, the total radiotoxicity is reduced, as there is less spent fuel than in Scenario 1, but the contributions from HLW and separated plutonium are clearly greater, as reprocessing continues in this scenario, rather than ending when current gas cooled reactors are retired as in Scenario 1. The composition of the HLW differs in Scenario 2, as there are greater masses of the americium isotopes produced in MOX during irradiation than in equivalent UO₂ due to neutron capture by the plutonium isotopes. This is shown in Figure 48 which shows the long-live isotopic composition of the HLW. HLW in Scenario 1 is due entirely to legacy reprocessing operations, and the radiotoxicity will have decayed for over 100 years by the comparison point of 2150.

Scenario 3a reduces total radiotoxicity in the waste streams by over a half compared to Scenario 1. This is due to the increased utilisation of separated plutonium in GCFRs and also to the partitioning from the HLW stream of neptunium, americium and curium and subsequent transmutation in the GCFRs. However, the reduction can partly be attributed to the use of GCFRs essentially as alternate, albeit power-producing, plutonium stores, and there is a much greater radiotoxicity burden within the fuel cycle due to separated materials awaiting recycling. HLW radiotoxicity is reduced by a factor of 6 from Scenario 2 to Scenario 3a, but this is clearly offset by the arising of spent minor actinide targets in Scenario 3a. Scenario 3a does not show any immediate benefit in 2150 over Scenario 3b, in which plutonium-only recycle is performed in GCFRs, but the benefit of minor actinide recycling in the GCFRs, as opposed to plutonium-only recycle, becomes more apparent on timescales of around 1000 years.

Total radiotoxicity of waste materials in Scenario 4 is similar to that of Scenario 3. However the radiotoxicity of separated material awaiting recycling is around 4 times greater in Scenario 4 than in Scenarios 3a and 3b due to the necessity of maintaining larger stocks of separated plutonium outside reactors for the fabrication of both APWR and GCFR MOX. The radiotoxicity of separated minor actinide stocks is 5 times greater in Scenario 4 then Scenario 3a. This is due to the lower number of GCFRs available for target irradiation, and also to the increased americium production in APWR MOX.

In Scenario 5, the radiotoxicity of the waste material, which in this case is exclusively due to HLW, is less than 10% that of the other MA recycling scenarios. This is due to the multiple recycle of all minor actinides performed by the ADS, as opposed to the single recycle of americium and curium within the GCFR targets. However, the operation of an ADS requires that a large inventory of MAs are present within the recycle loop compared to a once-through strategy; this is apparent from Figure 37.

Figure 48 shows the inventories of major long-lived minor actinides and fission products in the high level waste stream for each of the scenarios. Figure 49 show the same inventories having undergone 10,000 years decay. Isotopes of uranium and plutonium, which are present
in the high level waste streams due to reprocessing losses are omitted from these figures for clarity. Clearly high level waste inventories are substantially lower in Scenario 1 due to early suspension of reprocessing. Scenario 2 includes substantially greater inventories of $^{241}$Am, $^{243}$Am and $^{237}$Np than the two P&T scenarios 3 and 4. However there is very little difference in the inventories of the principal long-lived fission products $^{93}$Zr, $^{129}$I, $^{135}$Cs, $^{99}$Tc and $^{107}$Pd between scenarios 2, 3 and 4.

17.10 Discussion

The comparative scenario studies show that a P&T strategy introduced in the UK in the context of a future nuclear build programme has the potential to reduce the masses and radiotoxcities of materials which require ultimate consignment to a geological disposal route. Minor actinide recycle will be possible within the UK if a reactor system with a fast neutron flux is included within a future mix of reactors. This can be provided by a large fast reactor or by a dedicated transmutation device such as an ADS. Fast reactors are able to utilise the plutonium generated by the operation of thermal reactors. They also have the flexibility to switch to a plutonium breeding cycle, although this is outside the scope of the current study. In contrast, a dedicated minor actinide burning ADS cannot be used in isolation to reduce plutonium stockpiles, but can achieve greater MA transmutation rates than a standard power fast reactor. A double strata approach, such as that illustrated in Scenario 5, has the potential to achieve optimum reduction of waste radiotoxcities.

There is some potential for improving the minor actinide burning performance of a GCFR-type system beyond that of the design assumed in this study. The scenarios examined here assume that neptunium is mixed homogenously with the MOX and as such undergoes multiple recycling. The americium and curium are restricted to dedicated target assemblies which are irradiated prior to disposal. This avoids the handling difficulties associated with introducing the highly active isotopes of these elements into the fuel, but greatly restricts the throughput of these materials which can be achieved. Full homogeneous multiple recycle of all minor actinides within a GCFR could deliver improved transmutation performance, and detailed design studies of such a system would be required to confirm this.

A consequence of plutonium and minor actinide recycling strategies is the need to maintain stocks of these materials within the fuel loop in order to achieve continued transmutation. The scenarios presented here take a snapshot of materials and wastes at 2150, with the implicit assumption that nuclear generation and the selected recycling strategy are continued indefinitely (with the clear exception of Scenario 0). If nuclear power were to be continued within the UK for several decades or indeed centuries and then phased out, a very different managed P&T strategy would be required to reduce the final waste arisings of reactors. This is beyond the scope of the current study, but is important to establish the practical limits achievable by P&T.
### 17.11 Table 1 – Summary of Scenario Assumptions

<table>
<thead>
<tr>
<th>Scenario</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3a</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnox/AGR spent fuel reprocessed and separated into Pu, U and HLW</td>
<td></td>
<td></td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Advanced PWRs programme initiated in 2020</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Reprocessing of Sizewell B and APWR UO₂ fuel</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Single MOX Pu recycle in advanced PWRs</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Reprocessing of APWR MOX</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>Partitioning of Np, Am and Cm from 2020</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>GCFR introduction dates (excludes replacement plants after 40 year lifetime)</td>
<td></td>
<td>2021, 2023, 2025, 2027, 2029, 2125</td>
<td>2021, 2023, 2025, 2027, 2029, 2125</td>
<td>2053, 2068, 2083, 2086</td>
<td>2021, 2023, 2025, 2027, 2050</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADS introduction date (excludes replacement plant after 40 year lifetime)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2070</td>
</tr>
</tbody>
</table>

(1) "The APWR cores are loaded with 30% MOX and 70% UOX prior to 2038, and 8.5% MOX / 91.5% UOX subsequently"
Figures

Figure 1 - Reduction of nuclear capacity up to 2020 due to retirement of existing stations
Figure 2 – Scenarios 0 and 1 flow-path model - LWR once-through followed by direct disposal
Figure 3 - Scenario 2 flow-path model – LWR single MOX recycle

- **AGR**
  - Cooling (5 year)
  - Reprocessing
  - Uranium
  - MOX Fabrication

- **Magnox**
  - Cooling (6 month)
  - Reprocessing
  - Plutonium

- **Natural Uranium**
  - Conversion, Enrichment & Fabrication
  - Depleted Uranium
  - MOX

- **PWR**
  - MOX
  - Spent MOX

- **UOX**
  - High Level Waste
Figure 4 - Scenario 3a flow-path model – Pu/Np multirecycle in GCFR and Am/Cm single recycle in once through targets
Figure 5 - Scenario 3b flow-path model – Pu multirecycle in GCFR, minor actindes consigned to HLW
Figure 6 - Scenario 4 flow-path model – Single Pu recycle in LWR MOX followed by Pu/Np multirecycle in GCFR and Am/Cm single recycle in once through targets.
Figure 7 - Scenario 5 flow-path model – Pu multirecycle in GCFR and Am/Cm/Np multirecycle in dedicated accelerator-driven transmutation system
Figure 8 - UK Nuclear Generating Capacity (Scenario 0)

Figure 9 – UK Separated plutonium stockpile (Scenario 0)
Figure 10 – Advanced PWR Spent UOX fuel inventory (Scenario 0)

![Graph showing Advanced PWR Spent UOX fuel inventory](image1)

Figure 11 – Potential Radiotoxicities of major waste streams (Scenario 0)

![Graph showing Potential Radiotoxicities of major waste streams](image2)
Figure 12 - UK Nuclear Generating Capacity broken down by reactor type (Scenarios 1 and 2)

![Chart showing UK Nuclear Generating Capacity broken down by reactor type.](chart1.png)

Figure 13 – UK Separated plutonium stockpile (Scenario 1)

![Chart showing UK Separated plutonium stockpile.](chart2.png)
Figure 14 – Advanced PWR Spent UOX fuel inventory (Scenario 1)

Figure 15 – Potential Radiotoxicities of major waste streams (Scenario 1)
Figure 16 - UK Separated plutonium stockpile (Scenario 2)

Figure 17 - Advanced PWR Spent MOX fuel inventory (Scenario 2)
Figure 18 - Potential Radiotoxicities of major waste streams (Scenario 2)

![Graph showing potential radiotoxicities of major waste streams.](image)

Figure 19 - UK Nuclear Generating Capacity broken down by reactor type (Scenarios 3a and 3b)

![Graph showing UK nuclear generating capacity by reactor type.](image)
Figure 20 - UK Separated plutonium stockpile (Scenario 3a)

![Graph showing the UK Separated plutonium stockpile over time.](image)

Figure 21 – Composition of Spent GCFR Minor Actinide Targets (Scenario 3a)

![Graph showing the composition of Spent GCFR Minor Actinide Targets.](image)
Figure 22 - Potential Radiotoxicities of major waste streams (Scenario 3a)

Figure 23 - Potential Radiotoxicities of major waste streams (Scenario 3b)
Figure 24 - UK Nuclear Generating Capacity broken down by reactor type (Scenario 4)

Figure 25 – Total Separated Plutonium Stocks (By Originating Reactor Type) (Scenario 4)
Figure 26 - Total Separated Plutonium Stocks (By Isotope) (Scenario 4)

Figure 27 – Composition of Spent GCFR Minor Actinide Targets (Scenario 4)
Figure 28 - Potential Radiotoxicities of major waste streams (Scenario 4)

Figure 29 - UK Nuclear Generating Capacity broken down by reactor type (Scenario 5)
Figure 30 - Total Separated Plutonium Stocks (By Isotope) (Scenario 5)

Figure 31 - Potential Radiotoxicities of major waste streams (Scenario 5)
Figure 32 – Comparison of High Level Waste arisings by mass

Figure 33 – Comparison of masses of spent fuel and/or targets for geological disposal
Figure 34 – Comparison of total potential radiotoxities of all materials consigned to long-term waste disposal (including recovered and depleted uranium)

Figure 35 – Comparison of total potential radiotoxities of all materials consigned to long-term waste disposal (excluding recovered and depleted uranium)
Figure 36 – Comparison of potential radiotoxicities of material and waste stream totals in 2150

![Graph showing potential radiotoxicities of material and waste stream totals in 2150]

Figure 37 – Comparison of potential radiotoxicities of separated materials awaiting recycling in 2150

![Graph showing potential radiotoxicities of separated materials awaiting recycling in 2150]
Figure 38 – Comparison of potential radiotoxicities of waste streams in 2150

![Graph](image)

Figure 39 – Comparison of potential radiotoxicities of recovered and depleted uranium in 2150

![Graph](image)
Figure 40 – Comparison of potential radiotoxicities of material and waste stream totals in 2150 ± 100 years

![Comparison of potential radiotoxicities of material and waste stream totals](image)

Figure 41 – Comparison of potential radiotoxicities of separated materials awaiting recycling in 2150 ± 100 years

![Comparison of potential radiotoxicities of separated materials awaiting recycling](image)
Figure 42 – Comparison of potential radiotoxicities of waste streams in 2150 + 100 years

Figure 43 – Comparison of potential radiotoxicities of recovered and depleted uranium in 2150 + 100 years
Figure 44 – Comparison of potential radiotoxicities of material and waste stream totals in 2150 + 10,000 years

Figure 45 – Comparison of potential radiotoxicities of separated materials awaiting recycling in 2150 + 10,000 years
Figure 46 – Comparison of potential radiotoxicities of waste streams in 2150 + 10,000 years

Figure 47 – Comparison of potential radiotoxicities of recovered and depleted uranium in 2150 + 10,000 years
Figure 48 – Comparison of long-lived nuclide inventories in high level waste stream in 2150 (excluding U and Pu isotopes)

Figure 49 – Comparison of long-lived nuclide inventories in high level waste stream in 2150 + 10,000 years (excluding U and Pu isotopes)