Packaging of Spent AGR Fuel
(Preliminary stage)

Summary of Assessment Report

Issue date of Assessment Report: 30 April 2012

Introduction

The NDA provides spent fuel management services to both UK and overseas customers. By far the greatest proportion of the NDA's spent oxide fuel inventory is the Advanced Gas Reactor (AGR) fuel generated from the fleet of AGR power stations operated by EDF Energy (formerly British Energy). The NDA is committed through its contracts with EDF Energy to supply spent fuel management services for lifetime arisings of spent fuel from the AGR power stations. Current plans are to reprocess some of this fuel with the remainder to be stored at Sellafield, pending a decision on whether to dispose of it to a deep geological disposal facility (GDF), once it becomes available. The disposition of the AGR fuel is one of the key issues being addressed by the NDA's Oxide Fuel Strategy.

The NDA is undertaking an assessment of the lifecycle implications of the management of oxide spent fuel; options are being explored for managing the fuel in what it believes is the best way forward. At a high level, the technical options for the disposition of spent oxide fuel are to:

1. Reprocess the fuel in the Thermal Oxide Reprocessing Plant (THORP);
2. Long term storage of the fuel prior to disposal in a deep geological facility.

A key part of the lifecycle assessment of options is understanding the disposability of spent AGR fuel. To these ends, the NDA has sought advice from RWMD and requested that a preliminary stage disposability assessment is undertaken for spent AGR fuel through the Disposability Assessment (Letter of Compliance) process.

This Assessment Report summarises the findings of the preliminary stage disposability assessment by RWMD for packages containing spent AGR fuel.

The assessment has been carried out through the Letter of Compliance process, whereby RWMD examines the disposability of proposed waste packages by assessment against spent fuel packaging standards and specifications, and the reference spent fuel/HLW concept. This concept has been developed as part of the programme to implement geological disposal for the UK's higher activity wastes. Further information on the Letter of Compliance process is available elsewhere[1].

Objectives of the Disposability Assessment

The purpose of the disposability assessment for AGR fuel is to provide robust underpinning to the development of the NDA's Oxide Fuel Strategy. Specifically, the assessment is intended to confirm whether AGR fuel is considered suitable for geological disposal and to identify any issues that would need to be addressed to support the packaging of AGR fuel for disposal.

[1] NDA, *Guide to the Letter of Compliance Process*, NDA Document WPS/650, March 2008

Since AGR fuel is a key component of the Baseline Inventory identified in the 2008 White Paper on geological disposal[2], it is important, from RWMD's own perspective, that any risks and uncertainties associated with the disposal of AGR fuel are identified and plans implemented to address such issues as part of the developing programme of activities to support geological disposal of higher activity wastes.

Scope of the Proposals

Consideration has been given to the compatibility of packages containing spent AGR fuel with the requirements for safe long-term management, including storage, transport, emplacement underground, and disposal, as currently expressed for the Reference HLW/SF Concept[3].

A total of 8,800 tHM (tonnes of Heavy Metal) of AGR fuel is expected to arise based on current projections of AGR power station operating lifetimes. Of this quantity, over 2,300 tHM has been reprocessed to date. This leaves around 6,500 tHM of AGR fuel to be managed in the future. However, the mass of spent AGR fuel that could ultimately be disposed of in a GDF is uncertain. It depends on how, and for how long, EDF Energy operates its AGR fleet, the enrichment and burn-up of the fuels, and how much of the fuel is reprocessed through THORP. The RWMD assessment has therefore considered a range of scenarios to encompass the various options for the disposition of AGR fuel in a GDF.

The following three scenarios have been considered in this disposability assessment:

- Direct disposal of 3,000 tHM of AGR fuel – this scenario assumes that considerable further reprocessing occurs in THORP;
- Direct disposal of 6,500 tHM of AGR fuel – this scenario could occur with an earlier than currently planned cessation of reprocessing in THORP, or if EDF Energy achieves significant lifetime extensions to its AGR fleet;
- Direct disposal of 7,600 tHM of AGR fuel – this scenario provides an upper estimate of inventory for the disposal assessment, and could occur if an early cessation of reprocessing is coupled with EDF Energy achieving significant lifetime extensions to its AGR fleet.

It should be noted that the mass of fuel considered for geological disposal in the Managing Radioactive Waste Safely (MRWS) Baseline Inventory[4], and as used in the RWMD Disposal System Safety Case (DSSC)[5] is ~5,500 tHM of AGR fuel.

Following discharged from a reactor, all spent AGR fuel is stored at the station for a minimum of 180 days before being sent to Sellafield. The disposability assessment has assumed that all AGR fuel would continue to be stored at Sellafield in the future. Furthermore, it is assumed that a packaging plant would be provided at Sellafield to package the fuel into the disposal canisters for onward transfer to a GDF.

[2] BERR, *A Framework for Implementing Geological Disposal*, June 2008

[3] Nirex, *Outline Design for a Reference Repository Concept for UK High Level Waste/Spent Fuel*, Technical Note 502644, September 2005 (NDA document reference LL/6552289)

[4] NDA, Development *of the Derived Inventory for HLW and Spent Fuels Based on the 2007 UK Radioactive Waste Inventory*, NDA document reference LL/12230043, February 2010

[5] Nuclear Decommissioning Authority, *Geological Disposal: An overview of the generic Disposal System Safety Case*, NDA Report NDA/RWMD/010, 2010

Reference HLW/Spent Fuel Concept

The reference spent fuel disposal concept developed by RWMD, and included for quantified assessments within the DSSC, relies on a series of engineered barriers to control the release of radioactivity and ensure long term safety. This concept is based on the approach being adopted by the Swedish waste management organisation, SKB, for the management of spent nuclear fuel discharged from Light Water Reactors in Sweden.

The first barrier is the AGR fuel itself. AGR fuel pins consist of stacks of ceramic uranium oxide pellets sealed within stainless steel cladding. If appropriately managed, the stainless steel cladding should provide a means for safe interim storage, handling and packaging of the uranium oxide. However, over the timescales under consideration for a geological disposal facility (many thousands of years) little reliance is given to the containment function offered by the stainless steel cladding due to the potential for corrosion of this material. Nevertheless, the ceramic uranium oxide is expected to possess a very high degree of chemical stability under geological conditions and over very long timescales and it is this property that provides the first barrier.

The next barrier is the waste container. Spent fuel being consigned for geological disposal is assumed to be sealed inside robust disposal canisters that would be designed to provide containment for many thousands of years. The reference concept developed by NDA RWMD for planning purposes utilises copper for the manufacture of this canister, although other long-lasting materials are considered potentially suitable. A cast iron inner container would be used in conjunction with the copper canister to provide mechanical strength to the overall package and location of package contents.

The reference case AGR fuel disposal package comprises eight consolidated fuel bundles (approximately 1 tU fuel) in a 2.5m tall copper disposal canister. In a suitable geological environment, these packages would be expected to retain their containment for a period in excess of 100,000 years. During this time, the greater proportion of the radioactivity of the fuel would have decayed.

For the strong crystalline rock geological setting, complete AGR fuel packages are assumed to be deposited in individual vertical holes drilled into the host rock from a series of access tunnels. Each package would then be surrounded by rings of bentonite clay with a cap of crushed rock and bentonite on top. This engineered barrier would ensure that groundwater would only reach the packages very slowly by diffusion. Radionuclides would also be retained by chemical sorption onto the surface of bentonite particles following eventual failure of the package.

A suitable geological environment would provide the final barrier. This would be selected to provide very long groundwater return times to the surface.

Optimisation of Packaging

Final decisions on the design of disposal canisters and materials of construction have not been made at this stage as this will depend upon the host geological environment and detailed GDF design adopted for a site yet to be identified. As the definition of site specific designs and safety cases progresses, further information on wastes and packages will be taken into account, with a view to develop an optimised disposal concept. In support of this, the scope of the disposability assessment has included an evaluation of four variant disposal package designs for AGR fuel.

The first package examined is the 2.5m tall reference case package containing eight consolidated AGR fuel bundles.

Two further package variants containing consolidated fuel bundles have also been considered. RWMD has undertaken feasibility studies to define a standard length (4.5m tall) disposal canister for various categories of spent nuclear fuel and vitrified High Level Waste. Adopting this standard length disposal canister, it may be feasible to package either 16 AGR fuel bundles (ca. 2tU) in a 4x4 array, or up to 20 consolidated bundles (ca. 2.5t U) in a pentagonal array (1,728 to 2,160 fuel pins per package respectively). These two larger packages have been assessed as potential alternatives to the (2.5m tall) reference case package for disposal of AGR fuel.

All AGR fuel elements are dismantled shortly after receipt at Sellafield. The individual fuel pins are then consolidated into bundles in a specially designed container for storage and reprocessing at Sellafield. In recognition of the fact this disassembly of the fuel elements generates separate waste streams for future management, namely the grids/braces and graphite sleeves, the NDA has requested that consideration also be given to the disposability of packages containing undismantled AGR fuel elements. In such a case, a package would comprise the complete fuel element assembly including graphite sleeve and stainless steel braces, rather than just the stainless steel pins containing the uranium dioxide as per the previously identified packages. A single package would contain eight, sixteen or twenty fuel elements. However, this would equate to only one-third of the fuel content when compared to the packages containing consolidated fuel bundles. The disposability of variant packages containing sixteen intact AGR fuel elements has therefore also been explored.

Interim Storage of AGR Fuel

For long-term storage the AGR fuel has to be maintained in conditions that are secure, and that ensure the fuel is both retrievable and suitable for disposal in the GDF. For the spent AGR fuel remaining following completion of reprocessing operations, the strategy is to long term store the fuel in a single, modern caustic-dosed pond at Sellafield.

Caustic dosing inhibits the corrosion of stainless steel to insignificant levels compared to the projected timescales for long term storage prior to disposal. The risk of deterioration of the fuel cladding during an extended period of wet storage is deemed to be very low, provided that a caustic environment can be maintained.

An alternative to wet storage is dry storage. The dry storage of Zircaloy-clad Light Water Reactor fuels is a mature technology used by many nuclear energy companies across the world. AGR fuel is stainless steel clad and unique to the UK. The technical case for the long-term dry storage of AGR fuel has not yet been developed, although considerable work was carried out in the 1990s by Scottish Nuclear on the dry storage of undismantled AGR fuel in a vault-type store. The development work was not completed and the technology was not deployed, nevertheless, dry storage is a credible option for the long term storage of AGR fuel. In the same way as wet storage, it would be necessary to maintain suitable atmospheric and thermal conditions within a dry storage facility over extended timescales to eliminate the risk of deterioration.

If corrosion or mechanical degradation of the fuel occurs, whether in reactor, transport, dismantling or storage, this can, in severe cases, result in a breach to the cladding. Fuel with breached cladding is referred to as ‘failed’ and is considered differently from ‘intact’ fuel for a number of reasons.

Failure of AGR fuel could present a number of challenges for packaging and disposal in a GDF:

- It would be more technically difficult to safely handle and contain failed fuel due to the risk from spreading contamination;
- It may be difficult to dry failed fuel due to the potential for saturation of the fuel clad gap;
- Loss of fuel pin integrity could present a challenge to the criticality safety of packaged fuel;
- Exposure of the UO_2 may allow oxidation into the less stable U_3O_8 form, leading to accelerated degradation in a disposal environment.

It is prudent to assume that regardless of how the spent AGR fuel is stored for the long-term, a proportion of the fuel could fail during the extended period.

In addition, regardless of how AGR fuel is long-term stored, it will be necessary to develop a process to dry spent AGR fuel prior to packaging in a canister for disposal. This is because the water content of the disposal package should be kept as low as reasonably practicable to minimise corrosion processes occurring within the spent fuel canister and to minimise the potential for pressurisation due to the radiolysis of water. The drying process would need to be capable of drying both intact and failed fuel.

RWMD has yet to define an upper limit on water carryover for packages containing AGR fuel. Such a limit can only be confirmed once a disposal package (or dry storage system) becomes better defined, since this would dictate the tolerable gas pressure/corrosion allowance.

Assessment of Disposability

The disposability assessment for spent AGR fuel showed that it should be feasible to safely transport and handle any of the package variants containing AGR fuel provided the fuel can be adequately dried and packaged following wet storage, regardless of its physical condition.

Modelling has predicted that none of the four package variants containing AGR fuel[6] would result in a loss of radioactive material following an accident. This is due to the highly robust nature of the packages. In this case, transport and operational accidents involving AGR fuel packages would not have radiological consequences.

From the perspective of transport and operational safety, it was identified that there would be significant benefit from maximising the quantity of fuel consigned to each disposal package. Maximising the mass of fuel per package would reduce the total number of packages, leading to a proportionate reduction in the number of transport and handling operations and hence the duration of exposure of the public and workers to radiation. Although the dose rate for a package containing a greater inventory of fuel may be greater than that containing less fuel, the duration over which individuals are exposed to radiation during routine operations is reduced. The final waste packaging solution has yet to be defined for AGR fuel and it is therefore recommended that this issue is addressed by RWMD. It is expected that optimising the quantity of AGR fuel per disposal package would also enable the fuel to be removed from interim storage on shorter timescales, since the rate of transfer of individual packages to a GDF is currently predicted to be the rate limiting step.

A detailed evaluation of post-closure performance of packages containing spent AGR fuel was completed. Post-closure gas generation and heat output were found to be acceptable, subject to adequate drying of the fuel and control of the heat output of each package. The heat output of AGR fuel packages potentially challenges current criteria only when large quantities (i.e. 20 bundles) of the most highly irradiated fuel are placed in a single package. Nonetheless, it should be feasible to control the package content in such a way that the heat output is not a challenge, even for the highest payload packages.

To calculate post-closure risk from the groundwater pathway, in the absence of a specific site, a generic hard rock geology was assumed in the calculations. This included groundwater flow conditions that would be typical of hard rock geologies across the UK. On this basis, post-closure risk from the groundwater pathway was found to be acceptable, even for scenarios involving the disposal of the larger quantities of AGR fuel (up to 7,600 tU). However, to fully underpin this conclusion, it may be necessary to obtain further information on the performance of the fuel in a disposal environment at the point of failure of the containment, and on the longer term rate of fuel matrix dissolution.

[6] The four variants considered include packages containing 8, 16 and 20 consolidated bundles of AGR fuel pins and a further package containing 16 intact AGR fuel assemblies (i.e. undismantled elements including the graphite sleeves and stainless steel grids and braces).

RWMD will seek to obtain further information to support understanding of the long-term performance of AGR fuel in a disposal environment. This includes an understanding of the inventory of radionuclides that could be released from the fuel immediately following failure of containment – the so-called Instant Release Fraction (IRF) – as well as the longer-term rate of residual ceramic dissolution.

It is expected that the ceramic AGR fuel pellets should possess largely similar IRF and matrix dissolution rates over extended timescales to other types of ceramic uranium oxide fuels, for example, those arising from Light Water Reactor (LWR) fuel. The range of IRF and matrix dissolution rates for LWR fuel is supported by a considerable body of international research. However, there is some question over the applicability of this to AGR fuel due to slight differences in the design and operation of the AGR fuel. One such difference is the deposition of carbonaceous deposits on the cladding of AGR fuel during reactor operation, which then leads to localised heating hotspots and changes in ceramic structure; similar phenomena are not observed for LWR fuel.

In order to underpin the disposability case for AGR fuel, RWMD will initially review historical data arising from Post-Irradiation Examination (PIE) studies that have been undertaken on AGR fuel. It is hoped that this could provide key data to establish that the IRF and fuel dissolution rates are within an acceptable range.

Packaging AGR Fuel

The assessment has shown that maximising the mass of fuel consigned to each disposal package could minimise total transport and operational risk. It is expected that this would also result in considerable cost savings. The need to optimise the AGR fuel disposal package design to minimise waste volume whilst also complying with the requirements for safe handling, transport and disposal has been identified as a key issue to be addressed by RWMD.

The assessment has definitively concluded that disposal of complete AGR fuel elements, rather than bundles of consolidated fuel pins, would be an unsustainable approach. The main reasons for this include:

- Removal of the graphite sleeve greatly reduces the potential for water carryover and the technical challenges associated with fuel drying due to the porosity of the graphite;
- Consolidation achieves a three-fold increase in packing density which results in very large reductions in disposal costs, GDF operational lifetime and GDF footprint; and
- Increased transport and operational risk, simply due to the number of packages that would need to be handled.

It is therefore recommended that AGR fuel continues to be dismantled and consolidated, regardless of whether the fuel is to be reprocessed or consigned for disposal. In making this conclusion, it must be recognised that the final disposition of the ILW wastes arising from spent AGR fuel dismantling (graphite sleeves, stainless steel braces and other non-fuel components) have yet to be defined.

Recommendations for Further Work

The assessment has highlighted the following recommendations for additional studies to fully underpin the disposability of AGR fuel:

- Confirm that AGR fuel behaves in an appropriate fashion in a disposal environment, that is, the IRF and rate of ceramic uranium oxide matrix dissolution are within an acceptable range of values;
- Develop detailed proposals for long-term storage of spent AGR fuel to show that the risk of deleterious effects would be effectively managed throughout the storage period;
- Demonstrate an effective process for drying wetted AGR fuel, which would need to encompass both intact and failed fuel;
- Confirm that the upper bound mass of water carry-over with previously wetted intact or failed fuel would not adversely affect the performance of a disposal package, for example through pressurisation and premature corrosion;
- Optimise the design of the final disposal package to maximise the per-package quantity of spent AGR fuel within the constraints of heat output, criticality safety and mechanical performance; and
- Validate the design pressure limit and accident performance of the potential disposal packages.

Since it has been identified that disposal of undismantled AGR fuel elements would not be a sustainable option, a separate waste management solution must be identified for the disposal of ILW wastes arising from spent AGR fuel dismantling and consolidation. A further recommendation has been made for Sellafield Ltd to engage with RWMD to separately explore the disposability of these ILW wastes.