UPDATE TO THE LONG TERM STORAGE OF ADVANCED GAS-COOLED REACTOR (AGR) FUEL

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Abstract

The paper describes the strategy adopted by Sellafield Ltd for management of the remaining lifetime arisings of AGR fuel from EDFE reactors. AGR reprocessing operations have completed at Sellafield but fuel will continue to be received, dismantled and consolidated in line with current practice. Spent fuel will be wet stored in existing facilities for an interim period until a disposal facility becomes available, extending fuel storage time from the current 5 years (for buffer storage pending reprocessing) to 80 years. The main safety issues associated with this interim storage strategy are ensuring the long term integrity of the fuel to be stored and the structure of the storage facility. The paper summarises research on fuel corrosion resistance and the pond structure inspection reports. Storage for the interim period requires changes to the operations of facilities and examples of these changes are given.

1. INTRODUCTION

In 1998 British Nuclear Fuels plc (now Sellafield Ltd (SL)) reported its forward strategy and development work for managing the lifetime arisings of spent fuel from British Energy (now EDFE) Advanced Gas-cooled Reactors (AGR) [1]. Contracted business included a part reprocessing part storage until a deep geologic disposal facility (GDF) deal. The storage element was envisaged to span around 80 years and was based on storing whole fuel elements; compared with the 3:1 dismantled and consolidated fuel arrangement that supported reprocessing.

Some 21 years later and now that reprocessing of AGR fuel in Thorp ceased in November 2018, it is timely to report back to this conference on how the strategy has evolved, the findings from supporting development studies and what has been commissioned to support on-going AGR interim storage until a GDF becomes available (planning assumption 2075 [1]).

This paper focuses on three SL facilities which are key to the storage of AGR fuel, Fuel Handling Plant (FHP) which imports and dismantles spent AGR fuel, the AGR Storage Pond which temporarily stores dismantled AGR fuel and Thorp Receipt and Storage (TR&S) which stores dismantled AGR fuel. See section 4.5for a summary of the process.

2. STRATEGY

2.1. Previous strategy

In 1998 the proposed strategy was to "… use existing facilities and storage techniques" [2], previous work [2] had considered the alternative options for interim storage of AGR fuel following completion of reprocessing operations. Available oxide storage facilities, FHP, AGR Storage Pond and TR&S, were assessed against the criteria required for safe storage of the fuel for the required 80 years storage period. Based upon contract requirements, the projected storage only inventory and the use of existing storage equipment/layouts more than one facility was required to deliver the business. FHP and TR&S were identified as suitable facilities to accommodate the fuel based on their structural integrity, potential storage capacity and their capability to maintain the integrity of the fuel by their containerised storage regime and optimised pond chemistry.

Since 1998 the strategy has evolved, reflecting the fortunes and changes that have occurred in the UK nuclear industry. In 1998 spent fuel would have been initially stored in FHP and once full the excess would have been rolled over into TR&S. This was based upon the competing Magnox business in FHP being complete in

2006. Subsequently the operating life of the Magnox reactors was extended and now we are still reprocessing Magnox fuel while the operations in Thorp have been completed. Hence the strategy was switched to TR&S.

There were further changes in the early 2000's when British Energy underwent restructuring and was sold off to Electric de France (EDF). One of the main outcomes of this change was AGR fuel ownership going forward was transferred to the Government as new fuel was leased from the Government. This change opened up the option to dismantle the fuel to obtain a 3:1 storage compaction and realise an opportunity to store the fuel in a single facility being incorporated into the strategy. Dismantling upfront offered other strategic advantages these included;

— The facility not used became available as a contingency in the event of an acute failure;
— The scope of the final fuel conditioning plant was reduced as the fuel did not need to be dismantled for disposal[1];
— Upfront dismantling does not foreclose a future reprocessing option.

Later the strategy for managing AGR was transferred from the then British Nuclear Fuels to the Nuclear Decommissioning Authority. This initially led to a reappraisal of the strategy, but finally resulted in the preferred option being announced in 2012 [1].

2.2. Strategy going forwards

The NDA preferred option/baseline strategy [1] for storage only spent AGR fuel is to use TR&S in a "Single Pond Strategy". Once FHP has finished consolidating all of the AGR fuel and it is transferred to TR&S, Sellafield will only have fuel wet stored in TR&S. The advantages to this are:

— TR&S structure complies with the latest building standards and has been assessed against a 2085+ timeline (see section 3.4);
— There is sufficient capacity to hold the required quantity of AGR fuel (see section 4.6) and has the capability to increase capacity by adding additional ponds if needed;
— Not building a new facility avoids using resources, the energy associated in providing these resources, avoids contaminating land and avoids a major capital investment, land on the Sellafield site is at a premium and the costs required to modify the existing facility can be phased;
— The facility already has an operating licence, though a change of use application was required as well as a new safety case.

To support this approach required demonstration that long term wet storage can be safely carried out, involving work on the fuel & pond integrity as well as adapting operations to accommodate long term storage. NDA funded R&D on the dry storage of AGR fuel has been continued, to facilitate a future decision on whether to transfer to dry storage.

Originally when selecting the Single Pond strategy, it was anticipated that one of the advantages to making use of an existing facility was that the need for planning permission and a potential inquiry could be avoided. In reality there was still a requirement to submit a change of use application, as the facility was changing from a buffer store in support of reprocessing to an interim storage facility. There was also a requirement to obtain a new licence instrument from the nuclear regulator and a revised safety case.

3. DEVELOPMENT STUDY FINDINGS

3.1. Fuel integrity

Spent AGR fuel cladding performs two functions; as primary containment barrier, and for mechanical handling of individual fuel pins for rod consolidation/reprocessing purposes. The final recovery and conditioning of the fuel after 80 years storage in principle is the more restrictive of the functions. Nominally retention of half original wall thickness has been assumed for final fuel handling operations.

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[1] Disposal criteria at the time prohibited the co-disposal of graphite and fuel. Part of the fuel dismantling processes involves separating the graphite from the fuel.

Figure 1[2] outlines the bounding cladding thickness, the margin between post irradiation and post storage minimum clad thickness, and provides a very simplistic comparison with the long term wet storage of LWR fuel in 200ppm dosed sodium hydroxide demineralised pond water (nominally pH 11.4 under open pond conditions). In the absence of any failure mechanism except general corrosion, AGR wet fuel storage is expected to result in a minimum wall thickness of 312µm compared against the half wall thickness of 165µm [3]. LWR wet fuel storage is expected to result in a minimum wall thickness of 496 µm against the half wall thickness of 285 µm [3]. Both of these values are based on pessimistic values (i.e. the corrosion rate can be no faster than this, but is likely to be less), but still result in a significant safety margin of cladding thickness after planned wet storage duration. Supporting this is recent work with Post Storage Examination of AGR fuel that had been wet stored for ~25 years [4] looked at the condition of the fuel cladding and found no evidence of corrosion or thinning of the clad material after reactor service.

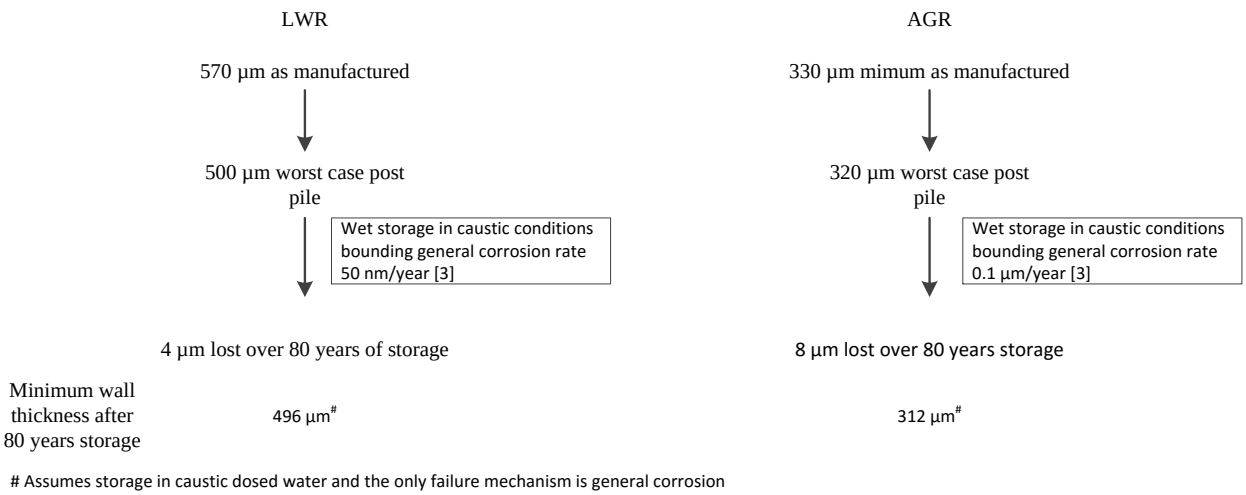

FIG. 1. Simple review of wall thickness loss during interim storage.

It has been reported [3] that the areas of stainless steel cladding and structural components of irradiated AGR fuel elements which experience in reactor temperatures between 340-520°C are susceptible to irradiation induced intergranular stress corrosion cracking. Since the original studies were completed there have been changes in the in-core operation of the AGR reactors which may have impacted the temperature profile across a 7-8 element fuel stringer and thus the locations of susceptibility on fuel cladding.

To inhibit this failure mechanism AGR fuel is stored in demineralised water dosed with sodium hydroxide to pH 11.4. Sodium hydroxide was chosen as a result of a corrosion inhibitor development programme undertaken in the early 1980s and has been used since 1986 for the interim storage of all AGR fuel at Sellafield. Operational experience to date indicates that when correct conditions have been maintained fuel cladding perforation has been totally prevented regardless of fuel susceptibility.

The technical case for the storage of AGR fuel for up to 80 years is reliant upon the continued use of corrosion inhibitors. Since the 1980's when the research into corrosion inhibitors was carried out, there have been changes to the front end of the fuel cycle, such as increasing fuel burnup, combined with a significant increase in proposed storage duration. Therefore there was a need to revisit the original corrosion development work.

Work was completed in 2012 [5] which looked at irradiated brace material (a component of an AGR element) in pH 11.4 with increasing levels of chloride. Previous work has shown brace material, when irradiated, to be more susceptible to corrosion than fuel cladding, therefore work involving irradiated brace material is taken as bounding for fuel cladding. This work found that no corrosion was detected at pH 11.4 and even when conditions were degraded (pH 9 and 2ppm Cl^-); there was no detection of the initiation of corrosion.

2This figure is included as an update of the comparison in the original paper [2], with a better understanding of general corrosion in caustic for both LWR and AGR. The original comparison used half wall thickness as this was a marker likely to withstand dismantling operations at room temperature.

Long term monitoring of the AGR Storage Pond alongside using an Activity Release Model carried out from 1997 up to 2015 gives confidence that there has been no failure of the fuel stored in this pond since it was dosed with sodium hydroxide. Figure 2 shows the agreement between modelled release rate and the actual release rate, derived from the measured activity of pond water samples. The agreement indicates that the measured activity rate matches that predicted for the known contents of the pond and no new fuel failures have occurred.

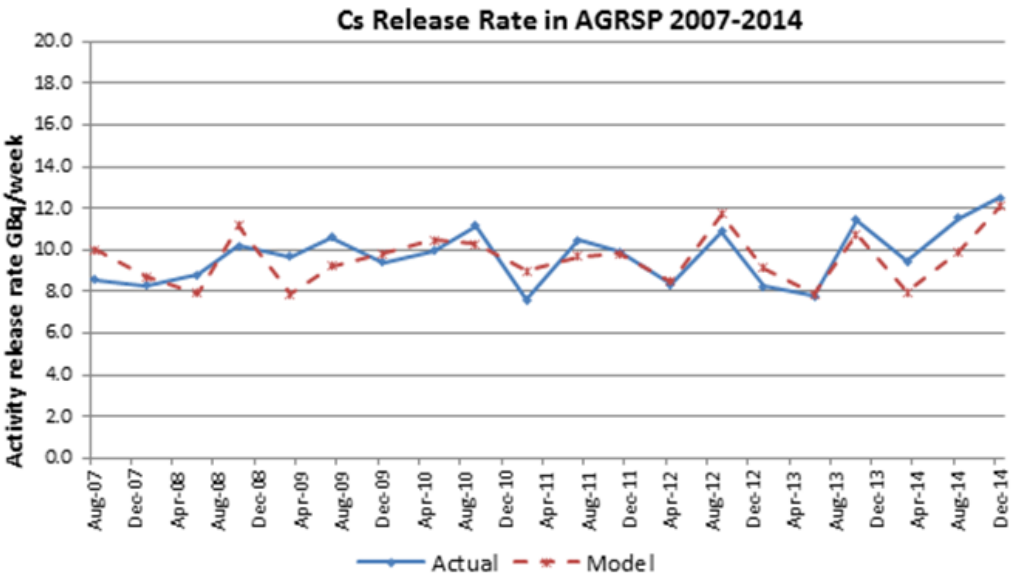

FIG. 2. Comparison between modelled release rate against measured release rate.

From 2010 until 2018, a Lead-time Container Trial was carried out which examined alternatives to caustic dosing for preventing the corrosion of AGR fuel cladding [6]. Sodium nitrate dosing was trialled from 2010 to 2012 and low dose caustic (pH 9) was trialled from 2012-2017. The trial involved separating containers of fuel from bulk pond water and controlling the chemistry of the container water, whilst taking regular water samples for analysis. The sampling allowed for tracking of corrosion products, such as nickel or chromium, as well as caesium-137 which would indicate through wall penetration of the fuel cladding. Through the course of the trial, low dose caustic proved to be an effective inhibitor up to 0.5 ppm chloride at pH 8.5.Higher levels of caustic (pH 10+) were shown to be effective at slowing down propagation of corrosion already known to be present. Figure 3 shows two example graphs from the trial where chloride was added to the container in two phases and the activity of the container liquor showed no appreciable increase in release rate.

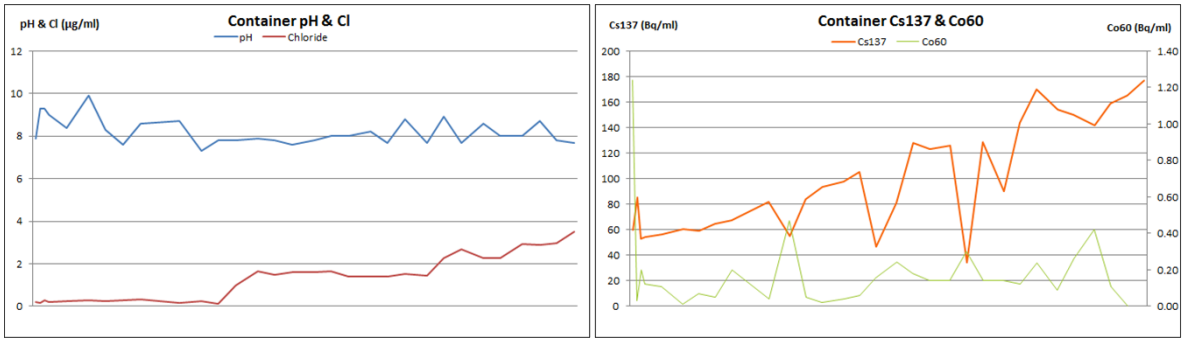

FIG. 3. Examples of container trial results with increasing chloride but no significant change in activity growth.

Fuel condition monitoring is considered necessary for long term storage. The favoured method of condition monitoring was to produce a simulant of sensitised cladding and install it into an early warning

system. However, after years of development of a material that simulates sensitised fuel cladding, there has been no success in creating an unirradiated simulant that mimics the corrosion properties of sensitised AGR cladding. The conclusion of this work was that condition monitoring could most effectively be carried out by monitoring pH and chloride levels to ensure they are within specification.

Work is ongoing to develop other methods of condition monitoring, including Eddy Currents, direct sampling of containers and Electrochemical Noise (lead by the NDA). Additionally, Post Storage Examination (PSE) of fuel is planned to take place at regular intervals to assess the impact of interim storage on fuel cladding. The PSE will involve taking a can of the oldest stored intact fuel on site into an active lab, conducting non-destructive macroscopy and taking sections of selected pins for destructive microscopy. Previous PSE completed in 2014 showed the cladding of fuel to be fully intact, with no signs of degradation. The results of the 2014 PSE will be used to compare against future PSE to investigate changes, if any, to fuel cladding over long term storage. Figure 4 shows some of the images that resulted from that investigation at different magnifications. They show that there has been no intergranular attack of the stainless steel cladding, despite examination of the composition of these sections proving that they are susceptible to attack.

FIG. 4. Images from Post Storage Examination of long stored intact fuel showing no signs of degradation during storage.

Future PSE are planned which involve the examination of long stored fuel which is known to have suffered from intergranular attack. This task has multiple objectives to assess:

- Mechanical integrity of fuel that has been stored for 20+ years after being affected by IGA;
- Requirements for drying long stored failed fuel;
- Effects on surface of cladding and the thickness of long term storage after a brief period in high chloride environment;
- Degree of IGA which occurred when the cladding failed in 1986 and if the sites of IGA have worsened during storage.

3.2. Pond integrity

The structural integrity of TR&S is key to the long term storage of fuel. TR&S was built to: 1 in 10,000 year severe wind case, 0.25g horizontal acceleration and to retain boiling water. It also benefited from SL's learning from experience in constructing nuclear complexes and the internal building techniques, QA and standards (particularly for concrete structures) which it had developed over many years. These standards led to TR&S collecting three awards including a special award from the Institution of Structural Engineers (1990) in recognition of "construction to the highest modern quality and safety standards".

Everything but the pond structure in TR&S, such as lifting equipment, services, roofing etc. can be refurbished, upgraded or replaced. This is not possible with the structure of the pond itself and reinforced concrete is prone to multiple deterioration mechanisms. As such it is the pond structure where studies on its longevity and techniques for repair have been directed

Structural surveys to determine the status of Sellafield ponds, looking for signs which may cause concern for long term integrity, have been carried out and found all of the ponds to be in good condition. Required tests outlined in the previous report [2] have been carried out, where a test core of small diameter and short length was extracted from the pond wall. A report was issued which determined that "there are currently no limiting issues on the [TR&S] structure. With ongoing monitoring and maintenance a lifetime until 2086 is achievable".

Into the future, there are annual checks of TR&S building condition which includes the pond structure, and 5 yearly Non-Destructive-Testing of the pond structure.

Should any breaches of the pond wall occur, a study into the available repair techniques conducted in 2010 outlines the available options for repairing the pond, including techniques such as overbanding, resin injection and crystal growth surface treatment.

4. POND OPERATIONS

4.1. Current process

The current process for receiving and storing AGR fuel has been communicated previously and is largely unchanged, see [2] for details. A brief summary of the process can be seen below.

- Fuel received from reactor in elements of 36 pins with stainless steel braces and graphite sleeves;
- Stored at Fuel Handling Plant, and then dismantled to remove braces and sleeves, leaving only pins to be stored in slotted cans which hold 108 pins and resulting in a four-fold increase in storage capacity;
- Fuel is subsequently stored at one of three ponds, depending on its cooling time, Fuel Handling Plant, AGR Storage Pond or TR&S.

Now that the strategy has moved to interim storage, fuel transfers to TR&S will be the last conducted until fuel is exported for storage in the GDF

4.2. Move to interim storage

In comparison with previous operations the longer term requirements are to enable the reactor defueling programme to meet its accelerated schedule, once reactors move to decommissioning, and maintain fuel in a good condition for 80 years; such that when the GDF is ready the fuel can be handled and in condition for long term storage. This involves ensuring:

- There is throughput capacity in Fuel Handling Plant to receive fuel from the reactors;
- There is space in TR&S to store the fuel;
- The pond chemistry specification is correct and is maintained;
- There are plans in place to investigate the condition of the fuel cladding in readiness for conditioning for GDF.

In order to ensure there is space in Fuel Handling Plant to receive fuel from the reactors for each skip of fuel received, a space in the pond needs to be created[3]. This is done by exporting skips of dismantled fuel and dismantling skips of fuel. If spaces are not created as they are being filled, then over time spare positions in Fuel Handling Plant will be taken up and restrict the facilities ability to manoeuvre containers before becoming unable to accept any further fuel. The throughput of the dismantler is key to this, it is expected that once the reactors begin defueling the demand on the dismantler will near its operating capability.

There is sufficient capacity in TR&S now, using existing storage techniques (i.e. skips with 20 canisters holding 108 pins each), if the reactors produce the expected amount of spent fuel. However, the Receipt and Storage facility was designed to accommodate mainly LWR fuel (80%) with a small buffer (20%) to accommodate AGR fuel transferred from the AGR Storage Pond just prior to reprocessing. The physical operation of the pond includes interlocks associated with LWR fuel rack storage and transfers. For this reason, when the TR&S facility was selected as the primary option for interim storage of AGR fuel, a storage container that would utilise the existing operational footprint and maximise the storage capacity was considered. This is known as the 63-can rack which occupies the same footprint as an LWR storage rack. The rack has a 7x3 array of channels which can each accommodate 3 canisters (108-pin). This is approximately equivalent capacity to a stack of 3 containers (containing 20 canisters each) but the rack footprint is 25% smaller than the container footprint and therefore several more racks than containers can fit across the width of the pond giving a

[3]This applies for maintaining the current storage set-up in FHP, if contingency options in FHP are implemented then the buffer storage space will be increased considerably.

significant increase in capacity when considered over the length of the pond (as well as a small gain due to the potential for 3 extra canisters per rack compared with a container stack).

These new high density storage containers will ensure the facility has sufficient capacity for the predicted lifetime AGR arisings and flexibility to accommodate reasonable changes (up to 5 years extension of receipts).

A further feature of the 63-can rack is the capability to isolate the rack from the bulk pond water in the event that fuel cladding failure occurs. Fuel failure is not expected since the pond chemistry and temperature will be carefully controlled and monitored to ensure maximum protection of the fuel cladding against corrosion, however the capability to isolate any leaking fuel that does arise is a precaution being built into the rack at the design stage.

The pond chemistry of TR&S has been demineralised water dosed with caustic to a pH of 9 for the last 3 years. Whilst there is confidence in the ability of pH 9 to prevent initiation of corrosion, there is a greater safety margin by moving to pH 11.4 as well as a wealth of experience operating in these conditions across site. Therefore, the Technical Specification for AGR storage will be updated to reflect this. Regular samples and trending will be carried out to ensure the pond chemistry is under control, and the caustic used to dose the pond is of the right quality, with minimal impurities.

Another aspect of the pond that needs to be controlled is the temperature. Spent fuel generates heat which needs to be managed. In Fuel Handling Plant and AGR Storage Pond the heat load is managed with cooling towers. Work is ongoing to upgrade the current cooling system to meet the predicted increased demand on cooling capacity to ensure TR&S is capable of storing lifetime arisings of AGR fuel. There is an investigation being carried out into the use of passive cooling, which will provide additional protection against accident scenarios affecting cooling capacity.

Until the additional cooling capacity is installed, the heat load of the pond will be monitored using models and daily measurements of temperature.

Conditioning and drying of wet stored fuel is not required until 2075, however when opportunities arise to investigate information relevant for conditioning it will be taken, e.g. Post Storage Examination of long stored failed fuel will involve drying the fuel which is expected to have had water seeping into the pin itself. By recording how long/how many drying cycles it takes to dry the fuel to the drying rig's capability, information on how long it might take to dry fuel and to what extent the fuel can be dried can be obtained. The requirement for further study has been noted for future work and awareness of gaps in knowledge will be maintained.

5. SUMMARY

The strategy planned by SL for managing the spent AGR fuel arisings has been out-lined. Since reprocessing has ceased Thorp Receipt and Storage is being transitioned to an interim storage facility with fuel storage planned to continue until 2086. To enable this transition the buildings have been assessed and found to be capable of storing fuel over this lifetime with maintenance. Studies into the integrity of fuel and its resistance to corrosion have been completed which give confidence that spent AGR fuel is capable of being stored for up to 80 years and can still be mechanically handled at the end of this period to prepare it for long term storage.

Acknowledgement

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