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CONTINGENCY OPTIONS FOR THE DRY STORAGE OF MAGNOX SPENT FUEL IN THE UK

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ABSTRACT

The UK Nuclear Decommissioning Authority (NDA) is responsible for safe and secure management of spent nuclear fuel. Magnox fuel is held at some Magnox reactor sites and at Sellafield where it is reprocessed using a number of facilities. It is intended that all Magnox fuel will be reprocessed as described in the published Magnox Operating Programme (MOP) [1]. In the event, however, that a failure occurs within the reprocessing plant, the NDA has initiated a programme of activities to explore alternative contingency options for the management of wetted Magnox spent fuel.

Magnox fuel comprises metallic uranium bar clad in a magnesium alloy, both of which corrode if exposed to oxygen or water. Consequently, contingency options are required to consider how best to manage the issues associated with the reactivity of the metals. Questions such as whether Magnox spent fuel needs to be dried, how it might be conditioned, how it might be packaged and held in temporary storage until a disposal facility becomes available, all require attention.

During storage in the presence of water, the corrosion of Magnox fuel produces hydrogen (H_2) gas, which requires careful management. When uranium reacts with hydrogen in a reducing environment, the formation of uranium hydride (UH_3) may occur, which under some circumstances can be pyrophoric, and might create hazards which may affect subsequent retrieval and/or repackaging (e.g. for disposal). Other factors that may affect the choice of a viable contingency option include criticality safety, environmental impacts, security and Safeguards and economic considerations.

Magnox fuel has been successfully dry-stored as intact fuel elements in CO_2 - and air-filled primary and secondary cells at Wylfa Power Station, UK. Storage of some fuel elements in the Wylfa secondary cells has been carried out successfully for over 25 years. Other relevant experience includes the French UNGG (Uranium Naturel Graphite Gaz) and U.S. Hanford N-Reactor spent fuels, both of which have been retrieved and dried after decades of wet storage. The dried fuels are respectively stored in sealed canisters in modular vault stores at Cadarache (CASCAD) and Hanford (Canister Storage Building). The applicability of these and other potential store designs, such as concrete and metal casks and silos, to the storage of Magnox spent fuel is discussed.

INTRODUCTION

Magnox fuel elements comprise a uranium metal bar clad in a sheath of Magnox (a magnesium (>99%) and aluminium alloy) [2], which is sealed and normally 'finned' to assist gas flow and heat transfer. The overall UK strategy that defines lifetime targets for the whole Magnox fuel cycle is the MOP (Magnox Operating Programme, currently at version 8), which covers fuel manufacture, electricity generation, fuelling and de-fuelling of reactors, and reprocessing of spent fuel [1]. According to MOP8, the existing UK Magnox spent fuel inventory (~5,500 tonnes in April 2007) will be reprocessed by 2016 [1]. It is likely for both technical and policy-related reasons that reprocessing of Magnox spent fuel will not continue in the current facilities beyond 2017. The NDA is therefore considering alternative options for Magnox spent fuel

management in the event that it is not possible to reprocess the entire UK Magnox spent fuel inventory.

One possible management option would be to dry some of the fuel that is currently in wet storage in ponds and place it into interim dry storage, pending agreement on disposal options. A review of potential dry storage options for Magnox fuel was conducted by Galson Sciences Ltd., UKAEA and the NDA, including previous UK and overseas work on drying and subsequent dry storage of formerly wet-stored metallic uranium spent fuel (Table 1).

Table 1: Summary of metallic uranium fuel types reviewed and their relationship to Magnox fuel.

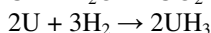
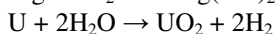
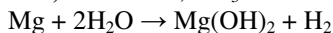
Country	Programme	Fuel type	Composition of cladding	Relationship to Magnox fuel
UK	CEGB/SSEB Sellafield/NNL	Magnox	Magnox alloy Al 80 [3]	-
USA	Westinghouse Hanford Company (with PNNL)	Hanford N-reactor	Zircaloy	Zircaloy is less reactive than Magnox.
	Idaho National Laboratory (formerly INEEL)	Plate fuel	Aluminium	Aluminium is less reactive than Magnox.
France	CEA Cadarache	UNGG	Magnesium	Slight differences in cladding and composition compared to Magnox.
Canada	AECL	CANDU	Zirconium alloy	There is no risk of criticality with CANDU fuel.

Due to the similarities between Magnox, Zircaloy and UNGG fuels, the review focused on existing spent fuel dry storage facilities at Wylfa (Magnox), CASCAD (UNGG) and Hanford (N-Reactor).

The drying and conditioning of Magnox spent fuel in preparation for storage are addressed in a companion paper.

KEY MANAGEMENT ISSUES AFFECTING THE LONG-TERM STORAGE OF MAGNOX SPENT FUEL

Both uranium metal and Magnox are chemically reactive in water, producing H₂ gas and, if stored in reducing (oxygen deficient) conditions, UH₃ which is potentially pyrophoric [4]:



Following reactor de-fuelling, both Magnox and uranium are susceptible to corrosion under wet storage conditions, either in water or moist air. Hydrogen gas is potentially flammable and causes pressurisation problems if the fuel is stored in sealed containers.

OPTIONS FOR STORAGE OF MAGNOX SPENT FUEL

At Magnox power stations in the UK, following discharge from a reactor, Magnox fuel is stored either in water-filled ponds or CO₂-filled dry storage tubes (at Wylfa) for at least ~150 days. It is assumed that wetted Magnox fuel requiring further dry storage as part of a contingency plan has exceeded this initial cooling period.

CO₂ and air are both used for dry storage of Magnox fuel in the UK, while helium, nitrogen and air are used to store metallic uranium fuel elsewhere [5]. In other countries, spent fuel either continues to be stored underwater, or is dried and then stored in air or an inert atmosphere, with some form of cooling incorporated in the design. Magnox fuel is not suitable for extended wet storage.

Vault Storage

Vaults are concrete structures containing an array of cells for storing used fuel. A wide variety of vault storage designs have been developed. Generally referred to as Modular Vault Dry Stores (MVDS), the original design was developed directly from the Magnox storage facilities at Wylfa [6]. The radiological impact of spent fuel in vault storage is minimized by bulk and labyrinth shielding from the concrete structure. For all vault store designs, criticality control is provided by the geometry of the vault well array and of any storage canisters used [10]. Heat is typically removed by convection of air or gas over the exterior of the fuel units or storage cavities. Fuel is either handled as a bare assembly within a transfer cask or fuel handling machine and placed directly into storage cells (e.g. Paks in Hungary), or placed directly into a sealed container at the reactor pond and the container is placed in a transfer flask and stored in tubes in the storage vault (e.g. Idaho and Fort St. Vrain in the USA).

Wylfa Magnox Spent Fuel Dry Store, UK Wylfa was the last Magnox power station built in the UK, in 1969, and includes three original dry buffer store cells for initial cooling of spent fuel (as opposed to water-filled cooling ponds), each with a capacity of 83 tonnes of uranium [7,8]. Irradiated Magnox fuel elements are discharged from the reactor by a fuelling machine into a chute connected to one of the steel storage tubes, which can each contain 12 elements stacked vertically [7]. The tubes are filled with 99.8% CO₂ at a pressure of 3 psi(g) to prevent oxidation of the Magnox and uranium during the initial cooling period [9]. Heat from radioactive decay is removed by radiation to the tube walls, conduction through the tubes and via a natural draught-induced atmospheric air flow across the tube bank, with no recirculation system [7]. Spent fuel stored in these cells for up to four years was in pristine condition when examined [8].

In 1979 and 1980, Cells 4 and 5 were constructed to provide an additional on-site buffer storage capacity of 700 tonnes of uranium [8]. The cells are constructed from concrete, with 2m thick walls, and are located adjacent to the original dry buffer stores [8]. Spent fuel, cooled for not less than 150 days,

is transferred from the original dry buffer store to the secondary cells using a transfer machine with a capacity of 64 fuel elements and either a CO₂ or air atmosphere. The fuel is raised into a shielded tube and measured using three gamma detectors (gamma output is proportional to heat output), to confirm that it does not exceed the 60 W safe level for the secondary dry store. When full, the machine is moved to the loading position over the new store and discharged into a skip *via* an articulating chute [9]. Fuel is stored in six rows of twenty-five skips, each consisting of a 12 x 16 array of blind tubes, with one fuel element stored in each tube. Criticality control is provided by the geometry of the storage tubes [7]. The atmosphere of the secondary dry store cells is air maintained at sub-atmospheric pressure by a filtered exhaust system, with a relative humidity below 50% to prevent condensation within the storage cells [9]. The tubes are cooled by recirculation of air passing from below over the outside of the tubes by natural convection, then through a water-based heat exchanger [9].

CEA CASCAD Dry Store, Cadarache, France At the CEA's CASCAD facility, spent fuel has been stored in canisters in a shielded vault since 1990. After reprocessing of UNGG fuel was discontinued in 1997, it was dried in the STAR treatment facility at Cadarache and stored in CASCAD. There are 319 wells in the vault, with a total capacity of 180 tonnes of uranium [10]. The tubes are passively cooled by natural convection: a boundary layer is created along the outer side of the well and heated air rises to a thermosiphon flow that extracts the heat released [11]. The internal atmosphere of each well is monitored for helium to detect leaking (helium-filled) canisters [12].

Hanford Canister Storage Building (CSB), USA At Hanford, legacy N-Reactor fuel from the K Basins was placed in Multi-Canister Overpacks (MCOs) and vacuum-dried. The CSB provides secure interim dry storage for the MCOs in a similar facility to CASCAD, located ~15km from the Columbia River on the Hanford site. A steel frame covers an operating deck of 1.5m thick reinforced concrete above a 12m deep vault, enabling passive cooling of the 220 carbon steel storage tubes by natural convection. Each storage tube holds two MCOs.

Chalk River Storage Facility, Canada AECL has been managing and storing spent nuclear fuel at its Chalk River Laboratories in Ontario for over 50 years. There are ~22 tonnes of degraded legacy aluminium-clad uranium fuels, currently stored in below-grade 'tile holes', into which water has penetrated [13]. AECL is planning to retrieve the old containers from the tile holes and transfer them into new vented stainless steel containers, which will be vacuum-dried and filled with an inert gas. The containers will be stored in tubes set into a concrete block. Each storage tube, holding one container, will be closed with a shield plug and top flange to provide a leak-tight enclosure, with continuous monitoring of the pressure and composition of the cover gas to detect leaks [14].

Cask Storage

Casks are moveable structures constructed from reinforced concrete or metal (providing structural strength and shielding), with the spent fuel placed inside a metal canister, liner or basket. Uranium oxide or mixed oxide spent fuel have been stored in casks without requirements for further shielding from a storage building. Cask storage facilities are typically purpose-built, unshielded concrete buildings, such as the Ahaus central interim storage facility, Germany [15]. However, TranStor casks are stored uncovered in the open air on concrete pads [16]. There are a wide variety of different cask designs, which have been licensed for spent fuel storage by regulatory bodies.

Spent fuel may be placed in sealed metal canisters, which are filled and transported to the storage location using a separate transport cask. The metal canister, placed inside the concrete storage cask, would be cooled by natural convection of ambient air. Alternatively, the fuel may be loaded directly into an integral metal liner in a cavity of a metal storage cask, and heat removed solely by conduction; the former designs have fewer thermal limitations [17].

CASTOR cast iron cylindrical casks are used for both transport (as an IAEA type B(U) package [17]) and long-term storage of oxide spent fuel elements, following five years cooling (for PWR and BWR fuel) in wet pond storage. 306 casks of reactor fuel are currently stored at the Ahaus facility in Germany.

The BNFL TranStor system is a dual purpose transport and storage system, comprising a welded stainless steel sealed canister, a reinforced concrete cask storage overpack and a transport overpack, which provides shielding during fuel loading and transfer operations [18]. The canister is loaded with fuel in the reactor spent fuel pond, and must be placed in the transport overpack for shipping to the storage location, then transferred to the storage overpack on arrival [18].

MOSAIK (Mobiles System für AktivIerte Kernbauteile) casks are licensed in Germany for transportation, interim storage and disposal of radioactive waste in the planned repository [19]. MOSAIK casks have been used to transport and store activated core components from PWR and BWR nuclear power plants [20]. Inner lead liners can be inserted to optimize the shielding. Over 4000 MOSAIK casks have been used at power plants and external facilities, with the oldest in storage for over 20 years. Structural parts of PWR and BWR fuel elements will be supercompacted and loaded into MOSAIK casks for disposal in a repository, while the fuel rods will be loaded into POLLUX casks for disposal [21].

Magnox spent fuel has an average burn-up of 5,000 MWd/ton, compared with 30 – 50,000 MWd/ton for LWR (Light Water Reactor) fuel, which is stored in CASTOR, Transnuclear and TranStor casks. As the requirements for shielding, heat removal and criticality control are less demanding for Magnox spent fuel, less expensive and substantial casks, such as MOSAIK cast iron casks, may be

considered. These have not previously been used to store spent fuel and would require licensing prior to use.

Silo Storage

Silo facilities are monolithic or modular reinforced concrete structures, which are not transportable, so separate transport casks are also required. The external structure provides shielding, and the spent fuel is loaded into an inner metal vessel or separate sealed metal canisters which provide containment [22]. A variety of silo storage designs have been developed for the storage of CANDU, PWR and WWER fuels; no Magnox fuel has previously been stored in silo facilities.

The NUHOMs horizontal modular concrete storage system has been used in the USA for PWR and BWR spent fuel. Fuel is loaded vertically into sealed stainless steel canisters, which have a welded and leak-tested double lid closure system. The sealed canisters are inserted horizontally into concrete storage modules in a shielded transfer cask. The system is not monitored following emplacement [23]. The NUHOMS system is licensed to store either 24 PWR or 52 BWR spent fuel assemblies with a total decay heat of less than 24kW or 19kW per canister (i.e. cooled for five years), respectively [23].

DISCUSSION

Vault storage is proven technology for the storage of Magnox fuel, with over 25 years of operational experience gained at the Wylfa secondary dry store with few technical issues. There have been no problems with the handling of dry fuel stored in air in these facilities for over 20 years. This demonstrates the inherent safety of the MVDS design, and its potential suitability for the dry storage of Magnox fuel.

At CASCAD and Hanford CSB, multiple levels of containment are provided by placing the fuel inside a sealed canister, which is stored in a sealed well. Damaged fuel can therefore be managed in the same way as intact fuel, because they are not dependent on the integrity of the fuel rod cladding [10]. Containment also reduces contamination and dose to workers during emplacement of fuel in the vault and transport for disposal or reprocessing. However, there are potential technical, logistical and financial advantages to storing bare Magnox fuel in the vault store. Placing unpassivated uranium metal in an oxygen-free environment (most canisters are back-filled with helium) risks the potential generation of pyrophoric UH_3 if limited water is also present. Storage of uranium metal in the presence of oxygen results in less reactive uranium oxide being generated. Using additional containment also results in additional waste to be managed if it does not form part of the final waste package.

At Chalk River, uranium metal fuels are stored in vented canisters in air, which is a compromise that allows H_2 gas, should it be produced, to be vented and prevents the formation of uranium hydride [13]. However, it has been demonstrated at Wylfa that adequate containment may be obtained from storage

in air without additional canisters for both intact and damaged Magnox fuel.

Compared with vault storage, cask storage provides more flexibility. Dual-purpose designs can be used for transport and storage [17,24]. Casks can either be stored at the reactor site or centrally, and the storage capacity can be increased incrementally, which is particularly useful for sites with small volumes of spent fuel [15]. Different cask types can be stored together in the same facility (e.g. highly active wastes from Sellafield reprocessing plant and spent fuel are both stored at Gorleben [15]). The capacity of the facility is also more flexible, as an unshielded building (if required) is significantly cheaper than a vault storage facility and casks can then be procured when needed. Although casks have not previously been used to store Magnox fuel, this is generally considered to be technically feasible.

Cask inserts can be designed for specific fuel types to achieve optimum packing density while avoiding criticality in enriched uranium fuels. In the CASTOR and TranStor casks, boron is incorporated into the baskets to act as a neutron poison [17]. However, storing Magnox spent fuel in casks has similar disadvantages to storing it in containers within a vault store, namely placing unpassivated uranium metal in an oxygen-free environment. Using additional containment also results in additional waste to be managed if it does not form part of the final waste package, although if the cask was licensed for disposal, this would reduce future handling of the spent fuel.

Magnox spent fuel has not previously been stored in silos; however, silos have been used to store CANDU, PWR and BWR spent fuels. The NUHOMS silo system incorporates neutron absorbing panels for criticality control, so could be considered for the storage of Magnox spent fuel [23]. The difficulty of inspecting and monitoring fuel in storage in silo facilities for signs of degradation may make silo facilities less favourable as potential Magnox spent fuel stores.

Alternative options include leaving fuel in reactor cores. Fuel is currently being stored in non-operational Magnox reactors where de-fuelling has been delayed, and this does not pose any new or unusual safety issues. Skills retention and the need to consider several de-fuelling routes are potential issues for the future. About 200 days after final shutdown, it is possible to make a safety case for the reactor core to be cooled by natural circulation of air at atmospheric pressure, meeting the requirements of the principle of passive safety.

SUMMARY

There are numerous examples of long-term interim storage facilities for spent nuclear fuel and some of these have been specifically used to store Magnox or other metallic uranium spent fuel, both dry and dried after pond storage.

The experience of the Wylfa secondary dry store cells demonstrates that Magnox spent fuel can be successfully stored in a dry air environment with suitable environmental controls and remote handling and inspection capability. Storage in air reduces the risk of UH_3 formation, and the corrosion risk is further reduced by maintaining relative humidity at ~30 %.

Cask storage may be less suitable because the casks are sealed, so the same issues arise as with the Hanford MCOs, concerning the creation of reducing conditions, UH_3 formation and the potential non-suitability of the container for disposal. It is also more difficult to monitor the fuel for possible degradation.

Silo storage has the same disadvantages as cask storage regarding the difficulty of monitoring degradation and the potential for UH_3 formation. Moreover, the waste may not be easily retrieved or transported.

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