The Feasibility of Using the KBS-3 Technology for Disposal of US Department of Energy's Used Nuclear Fuel – 14438

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ABSTRACT

The Office of Environmental Management of the U.S. Department of Energy (DOE EM) seeks information on technologies for long-term storage and disposition of used nuclear fuel (UNF) from the defence program and from a variety of other sources, mainly from prototype and research reactors in the United States. In support of this objective DOE EM organized an unclassified information exchange with SKB International of Sweden to look into the feasibility of using the KBS-3 technology for disposal of DOE EM's which is of a wide range of enrichments, geometries and materials.

From a first assessment based on engineering judgment it is concluded that the KBS-3 technology could be applied for disposal of DOE EM managed fuel provided that the geologic conditions are suitable (reducing conditions, low rate of water movement). The main advantage of the KBS-3 copper canister is that it will remain intact for very long periods, well beyond the time frame during which the UNF poses a risk to humans and the environment. If, nevertheless, a canister is breached the issues of concern are the same as for the breach of a canister of any type or material, i.e. fuel corrosion, long-term criticality risks and radionuclide release.

INTRODUCTION

In addition to UNF from U.S. commercial nuclear power plants the U.S. DOE is responsible for the management and disposal of UNF from the defence program and from a variety of other sources, mainly different types of prototype and research reactors. In total about 250 different types of UNF are included with a total weight of about 2,400 tonnes heavy metal (tHM). This fuel is handled by DOE EM.

The DOE EM strategy had been to re-package and encapsulate the UNF in standardized canisters. After encapsulation the canisters would have been transported to Yucca Mountain for disposal. But with the suspension of the Yucca Mountain project DOE EM decided to look at other possibilities for storing and encapsulating its UNF for final disposal.

In January 2013, The Secretary of Energy issued a *Strategy for the Management and Disposal of Used Nuclear Fuel and High-level Radioactive Waste*, and endorsed the key principles of the 2012 Blue Ribbon Commission on America's Nuclear Future (BRC) report. During preparation of its report the BRC evaluated the Swedish approach to siting a geological repository. It provides flexibility and sustains the public trust and confidence needed to see controversial facilities through to completion. The BRC suggested that the US consider a similar approach as it develops its own disposal strategy. The KBS-3 technology, for deep geological disposal of UNF, which was developed by SKB through a research, development, and demonstration program, could provide DOE with innovative ideas for encapsulating and disposing of UNF and avoid "reinventing the wheel". DOE was also interested in learning about the Swedish consent-based approach to siting a geologic repository, about SKB's operation as an independent agency managing the siting activities, and about the management of a dedicated nuclear waste fund.

The KBS-3 technology developed by SKB in close co-operation with Posiva in Finland is today the basis for building systems for disposal of UNF in Sweden and in Finland. Licence applications were submitted in 2011 and 2012 respectively for the construction and operation of encapsulation and deep disposal facilities.

THE DOE EM USED NUCLEAR FUEL

The information below on DOE EM UNF is a brief summary of data provided to SKB International during the information exchange.

The largest amount of fuel is low-enriched uranium metal fuel from the Hanford N-reactor (2,100 tHM). About 100 tHM is standard power reactor fuel and about 100 tHM is fuel and fuel debris from the TMI-2 reactor. A substantial quantity of fuel (about 160 tHM) is medium and high-enriched[1] fuel of different types from test and research reactors.

The fuels have different geometries - rods, tubes, cylinders, plates, assemblies and cans of scrap. The length of intact fuel ranges between 0.8 and 14.7 feet (24 – 420 cm). The longest fuel assemblies are 13.8 feet (420 cm), which can be compared with the Swedish standard fuel assemblies that are up to 14.4 feet (440 cm) long. The width and diameter of the material varies between 0.1 and 25.5 inches (0.3 – 65 cm).

The largest quantity of the fuel, about 2,100 tHM, is uranium metal fuel with zirconium cladding. The second largest quantity, about 180 tHM, is uranium oxide, mostly with zirconium cladding. The rest of the fuel has a large variety of uranium, plutonium and thorium compounds including metals, alloys, oxides, silicides and carbides. Most of the fuel has zirconium or zircaloy cladding, but also different types of stainless steel and aluminium cladding are used.

The end of life enrichment varies between depleted uranium at 0.2 w/o U-235 and highly enriched uranium (HEU) at 98.4 w/o U-235. The largest amount of fuel, about 2,100 tHM, has enrichments of 0.5 to 1.7 w/o U-235.

Burn-ups range from about 2,400 to 43,000 MWd/tHM. In 2010 the total activity in all DOE EM fuel was estimated to 1.9×10^{8} Ci (7×10^{18} Bq), and dominated by Cs/Ba-137 and Sr/Y-90, each corresponding to $3\text{-}4 \times 10^{7}$ Ci ($1\text{-}1{,}5 \times 10^{18}$ Bq). For comparison, a typical Swedish disposal canister with 2 tHM of fuel will contain about 5×10^{15} Bq Cs-137.

The reported total thermal output of all the DOE EM fuel in 2010 is about 1,000 kW. Again for comparison, one Swedish disposal canister will accept a maximum of 1.7 kW.

CURRENT STORAGE AND PLANS FOR DISPOSAL

DOE EM's UNF is stored mainly at four locations in the US: Hanford, Fort St.Vrain, Idaho National Laboratory (INL) and Savannah River. Most of the fuel is stored dry in casks or vaults, while some is stored in a water pool (L basin at Savannah River).

The N-reactor fuel at Hanford is stored in approximately 400 Multicanister Overpacks (MCO). This fuel is considered to already be in its final package. The MCOs are not intended to be re-opened before disposal. Some of the fuel in the MCOs is damaged.

[1] The fuel is classified as HEU if the enrichment is higher than 20 w/o U-235, as MEU if between 5 and 20 w/o and LEU if below 5 w/o.

The Hanford MCO is made from stainless steel. A drawing is shown in Figure 1. It has a length of 166.4 inch (423 cm) and a diameter of 25.3 inch (64.3 cm) and contains several baskets with fuel stacked on top of each other. For the Hanford N-reactor fuel one MCO contains about 5 tHM.

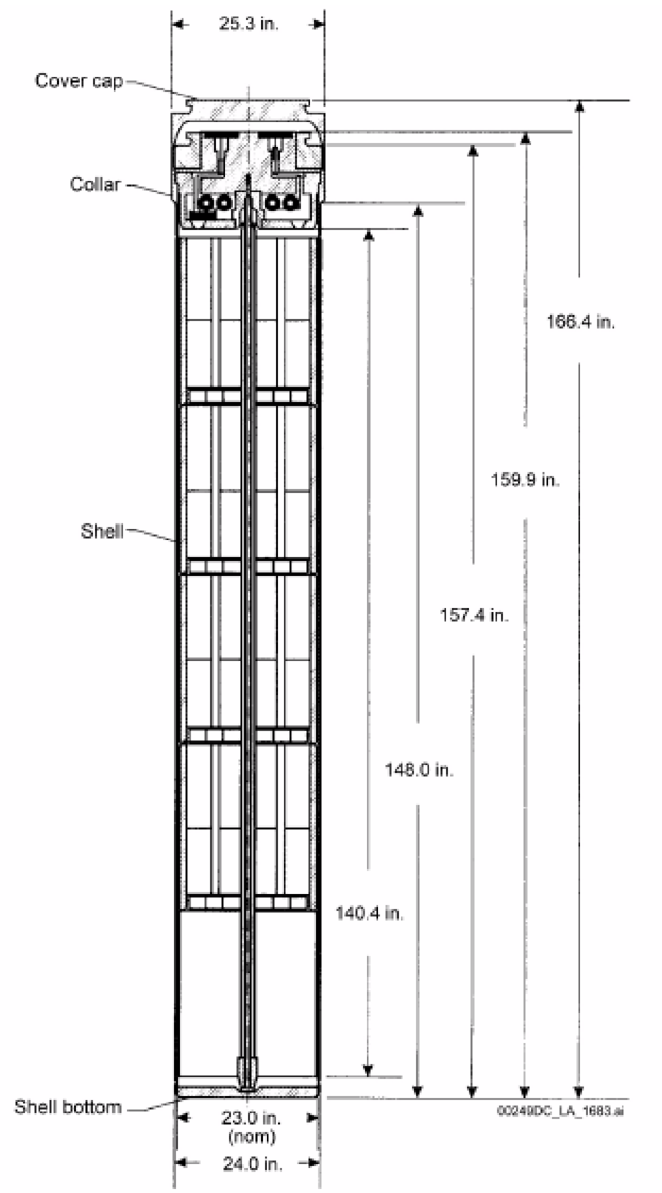

Fig. 1. Hanford Multicanister Overpack (MCO).

In addition, a small portion of Hanford´s fuel is stored in dry casks. Three different types of casks are used. They are stored in the Hanford 200 Interim Storage Area. These casks are foreseen to be re-opened before disposal. This is the case also for the Fort St. Vrain fuel stored in the Independent Spent Fuel Storage Installation, for the fuel in Idaho stored in several dry storage facilities and for the fuel stored in pools at Savannah River Site.

The DOE EM strategy has been to repackage and encapsulate the UNF in standardized canisters at the site where they are presently stored. After encapsulation the canisters would be transported to Yucca Mountain for disposal. The standardized canisters were developed to fit in the Yucca Mountain disposal package. They were planned to be 18 or 24 inches (46 or 61 cm) wide and 10 or 15 feet long (3 or 4.5 m), and have different internal structures depending on the type of fuel. The structure was designed to ensure sub-criticality during handling. This was achieved by distance between the fuel assemblies, by filling of empty space in the canister to reduce the moderator volume and by using neutron absorbers. One disposal package would take up to five standardized DOE EM UNF canisters.

THE KBS-3 TECHNOLOGY

The Swedish program for disposal of UNF is designed to manage the UNF from a fleet of twelve light water reactors. The work on the back-end started already in 1976. A strategy was developed to build a sea-based transport system, a central repository for low- and intermediate-level waste (LILW), a central interim storage facility for UNF, and initiate a research, development and demonstration (RD&D) program on disposal of high-level waste (HLW) from reprocessing and UNF. The reprocessing option was abandoned in the early 1980s as a result of economic and political considerations.

In 1976 the responsibility for the backend program was placed with the owners of nuclear power reactors. They formed SKB to assume this task. By 1988 the transport system, the waste repository (SFR) and the UNF interim store (Clab) were all constructed and in operation, and the development program for UNF disposal was well under way. The total cost to develop, build and operate the necessary facilities for UNF disposal in Sweden is estimated at approximately SEK 72 billion (US$ 10 billion) for the 100+ years program [1]. The program is financed by the utilities through the Swedish Nuclear Waste Fund (NWF), which currently has a capital of about US$ 8 billion.

Following studies of several concepts, the KBS-3 report in 1983 [2] described the direct disposal of UNF in the Swedish bedrock. The concept was further developed from the mid-1980s through a research, development and demonstration program that included the construction of the Äspö Hard Rock Laboratory (Äspö HRL), the Canister Laboratory and the Bentonite Laboratory, all situated in the Oskarshamn municipality.

The KBS-3 technology is based on a multi-barrier philosophy with a copper canister, a bentonite clay buffer surrounding the copper canister, and crystalline bedrock at a depth of about 500 meters forming a natural barrier around the buffer and the canister. The primary safety function is the long-term total containment provided by the copper canister. If the containment is breached, the buffer and the bedrock prevent or retard the dispersion of radioactive substances to the biosphere.

The repository is located in stable bedrock of no economic interest to future generations. The barriers, constructed of naturally occurring materials with long-term stability in the repository

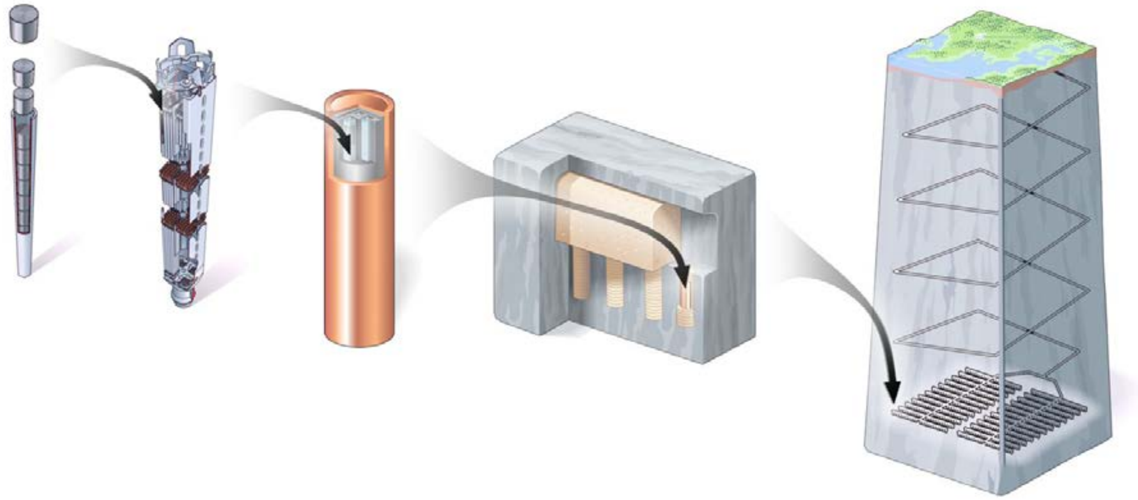

Fig. 2. The KBS-3 concept.

environment, shall work passively, i.e. without human intervention and without input of energy or materials or need for monitoring after closure.

Several canister designs were evaluated including canisters made of steel, ceramic material, titanium and copper. Also for the internal load-bearing structure several options were evaluated including filling with lead and hot isostatic pressing (HIP) of copper powder, both high-temperature processes. Ultimately a copper canister with a cast iron insert was selected to encapsulate entire fuel assemblies in a cold process. The canister diameter is just over one metre and the length is nearly five meters. The total weight of a canister, including spent fuel, is 27 tons for PWR fuel and 25 tons for BWR fuel.

In the years 1977-1985 comprehensive “Type Investigations” of the Swedish bedrock were carried out in eight different locations. These early investigations met with protests from the local population at several of the locations, in some cases leading to the investigations being stopped. 1992 was the starting point for the actual siting of a final repository for UNF. Based on desk studies conducted by SKB in close cooperation with the concerned municipalities, feasibility studies in eight interested municipalities were initiated, each of which included a comprehensive communication programme with the local inhabitants.

In 2001 SKB selected the Östhammar and Oskarshamn municipalities for full-scale site investigations. Based on the two site investigations and about 80 % support from the inhabitants in both communities for hosting a repository, SKB decided in June 2009 that a site next to the Forsmark nuclear power plant in Östhammar municipality would be the basis for SKB’s license application to construct the deep geological repository. The site for the Encapsulation Facility was selected already in 2006. Subject to obtaining the necessary licence this facility will be built as an extension to the Clab interim storage facility in Oskarshamn.

In March 2011 SKB submitted licence applications to build the Repository and the Encapsulation Facility [3]. It is planned that construction of the facilities can start in 2019 and that operation can start in 2029.

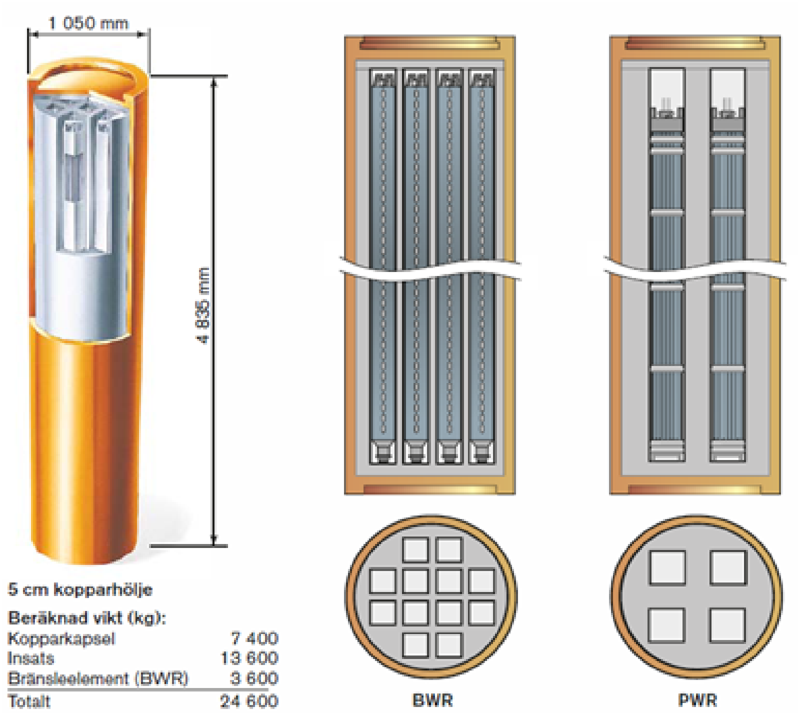

Fig. 3. The copper canister with inserts designed for BWR and PWR fuel (weight numbers in the figure are for the copper canister shell, insert, fuel assembly and total weight of loaded canister).

The Government and its authorities are now reviewing the licence applications for compliance with Swedish laws and regulations. Before the Government can grant the licences, it will consult with the Östhammar and Oskarshamn municipalities, where the facilities will be built. The municipalities have the right to veto the projects.

The Swedish Government requested that a review of the long-term safety assessment in SKB's licence application be reviewed by the OECD Nuclear Energy Agency (NEA). In its report in 2012 NEA concluded: "From an international perspective, SKB's post-closure radiological safety analysis report, SR-Site, is sufficient and credible for the licensing decision at hand. SKB's spent fuel disposal programme is a mature programme - at the same time innovative and implementing best practice - capable in principle to fulfil the industrial and safety-related requirements that will be relevant for the next licensing steps."

A DOE EM DISPOSAL SYSTEM BASED ON KBS-3

To take full advantage of the KBS-3 technology already developed by SKB a copper canister of the same diameter (about 1 meter) and wall thickness (50 mm) as in Sweden should, if possible, be used for DOE EM's UNF. The first consideration is therefore about the geometrical aspects of the UNF in relation to this canister.

The Swedish KBS-3 canister has an insert, which was purpose-designed for the two main types of fuel that are used in the Swedish nuclear power plants. The insert is a cast iron monolith with channels for the UNF. Since the DOE EM UNF will have a great variety of geometrical configurations this approach was reviewed. A steel cylinder was suggested and preliminary calculations were performed to determine an adequate thickness of the cylinder and lids. In this case criticality control will be obtained by the addition of neutron poisons and filling material to reduce the moderator volume. Further calculations will be needed to ensure the mechanical strength of the steel cylinder and to more precisely estimate the corrosion of the cylinder before and after water ingress. Also, further calculations of the sub-criticality of the proposed configuration are needed.

It is not possible to assess at this stage if disposal of the DOE EM UNF in a KBS-3 canister would be acceptable using Swedish safety standards. It can, however, be concluded that the main effect of using a KBS-3-canister for the DOE EM UNF as compared to using a steel canister is that the copper canisters will most probably remain intact for millions of years (for Swedish host rock conditions similar to those at Forsmark). If there would be a breach of the integrity of the canister it would be the effect of external events that would breach the integrity also of a steel canister. Once a breach has taken place and water enters into the canister the processes for criticality and for release will be the same for both types of canisters.

The main differences between a KBS-3-canister with DOE EM UNF and one with Swedish UNF are the risk of criticality and the dissolution mechanism for the UNF if a canister is breached. Further studies will be needed to clarify the impact of this difference on the long-term safety. The discussion is based on disposal of a KBS-3 canister with DOE EM UNF in bedrock with similar characteristics as the pre-Cambrian igneous basement bedrock at the Swedish repository site at Forsmark. The conclusions are therefore not universally applicable, especially not for other geological media.

Using the proposed canister, a total of about 1,850 canisters would be needed for disposal of the 2,400 tons of DOE EM UNF, see table 1. A fuel assembly that fits in a 10 feet long DOE standard canister has been assumed to occupy a full KBS-3-canister. In reality some of the fuel could probably be packaged in longer canisters and thus better utilize the space. The total number of canisters could then be reduced from 1847 to about 1600.

The total estimated disposal cost for disposal of the DOE EM UNF using the KBS-3 technology is US$ 5.0 billion based on the Swedish project environment and cost level [1]. This includes RD&D costs, siting costs, facility investments, operational costs and a 15 % contingency. It would probably be higher in a US project environment and using the US cost level. The canister cost would be about 5 % of the total cost.

SAFETY ASPECTS

The long term safety of the KBS-3 disposal system is based on the total containment over long time scales provided by the copper canister and the retardation of any release in the buffer and bedrock should a canister be damaged.

For the conditions prevailing at Forsmark and their expected development over time the safety assessment shows that the most probable result is that the copper canister will stay intact for millions of years. Only two mechanisms have been identified that could lead to a breach of the canister, rock shear due to a future earthquake and enhanced corrosion following buffer erosion caused by ground water of low ionic strength. Both these mechanisms have a low probability.

Table 1. Calculation of the number of KBS-3-size canisters needed to accommodate all the DOE EM UNF.

Criticality group	Fuel type	Enr. (w/o)	Mass (tHM)	Number of KBS-3 canisters	Mass per canister (tHM)

1	U-metal	1.15	2110	460	4.6
2	MOX (FFTF)	29.3	12	34	0.4
3	UZr-UMo (Fermi)	25.7	5	17	0.3
4	HEU oxide (Shippingport)	93	10	175	0.05
5	U-Th oxide (Shippingport LWBR)	100	50	72	0.7
6	U-Th carbide (Fort St Vrain)	100	26	302	0.09
7	UZrHx (TRIGA)	70	2	55	0.04
8	UAlx (Advanced Test Reactor)	93	17	614	0.03
9	LEU oxide (TMI)	2.96	173	118	1.5
Total				1847	

Under similar conditions in the U.S. the copper canisters with DOE EM fuel could be expected to behave in the same way. All safety functions connected to containment and canister integrity will be the same as for copper canisters with Swedish LWR fuel. The safety functions for retardation after breach of containment will, however, be different. An analysis of the associated features, events and processes (FEPs) was performed. The most important differences are connected to the fast corrosion of some of the DOE EM fuel and the subsequent radionuclide transport after water has penetrated, and the risk of criticality in the disposed canister after canister penetration. Both these issues will need further studies. It should be noted, however, that these issues will be even more important for a canister with a shorter life.

CONCLUSIONS

A first assessment shows that the KBS-3 technology could be applied for disposal of DOE EM fuel provided that the geologic conditions are suitable (reducing conditions, low rate of water movement). It appears that a copper canister of the same dimensions as in the Swedish and Finnish programs could be used but the load-bearing insert would need to be modified to accommodate the different fuel geometries of the DOE EM fuel.

The main advantage of the KBS-3 copper canister is that it will remain intact for very long periods, well beyond the time frame during which the UNF poses a risk to humans and the environment. If, nevertheless, a canister is breached the issues of concern are the same as for a breached canister of any type or material, i.e. fuel corrosion, long-term criticality and radionuclide release.

The consequences of early encapsulation in a copper canister for storage were not studied. If this option is of interest there is a possibility to encapsulate the fuel in thin steel canisters that could later be inserted in a KBS-3 copper/steel canister.

These conclusions are based on engineering judgment and need as such to be scrutinized in an in-depth safety assessment to show that regulatory requirements can be met.

DOE EM's conclusions based on the information exchange are as follows: Understanding KBS-3 technology and its advantages and disadvantages helps DOE with narrowing down the options for managing its SNF. Working in collaboration with Sweden and utilizing technical experts of both countries helps DOE avoid reinventing the wheel for many aspects of UNF management. DOE benefitted from the Swedish experience, not just the technical aspects, but also the process for siting facilities and working with host communities. One of the key areas of emphasis is communication. SKB dedicated about 10 % of its personnel to information exchange and dialogue with the local public. The use of local citizens, such as a hairdresser and a taxi driver, hired to communicate with the local communities, is creative. On the other scale, elected officials have an important role in ensuring the rights of the citizens and the possibility of a veto. This approach should be considered as the US develops its communication plan. Another approach that has proven successful for Sweden and that DOE should pursue is establishing a new organization dedicated solely to implementing the UNF program and empowered with authority and resources to succeed and provide this organization with access to the funds nuclear utility ratepayers are providing for the purpose of nuclear waste management, as also recommended by the BRC Commission.

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