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Repositories with Retrievable Spent Nuclear Fuel: Four Options, Four Geologies

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Abstract

We do not know today whether spent nuclear fuel (SNF) is a waste or a resource. If it is a resource, there are strong incentives for storage until needed. If it is a waste, considerations such as public acceptance, intergenerational equity, and security support early disposal. To reconcile these conflicting goals, this paper examines repository designs with two goals: safe disposal of all wastes and optional future recovery of SNF. Four options are described: repositories in hard rocks, salt repositories, horizontal boreholes, and lined tunnels. Options vary from retrievable with effort to effectively an underground storage facility where SNF can be readily recovered on demand.

I. Introduction

The MIT Future of the Nuclear Fuel Cycle study (Ref) examined alternative nuclear futures in the context of a greatly expanded use of nuclear energy. A key conclusion was that we do not know today if LWR SNF is a waste or a resource.

This conclusion is based on several observations. Low cost uranium resources are greater than originally believed. Uranium from seawater may be competitive with plutonium from LWR SNF. It may be viable to start up sustainable fast reactors (breeder reactors) with low-enriched uranium—a startup option today with lower costs than startup with plutonium from LWR SNF. The fast reactor SNF would be recycled in a sustainable fuel cycle fully utilizing the energy available in natural and depleted uranium. The concentration of fissile fuel in fast reactor SNF is an order of magnitude higher than in LWR SNF—thus fast reactor SNF as a higher assay source of fissile material could be economic to recycle while LWR SNF would be uneconomic to recycle. At the same time, innovations such as collocation and integration of reprocessing and repository facilities could significantly reduce the cost of recycling fissile materials from LWR SNF (Ref).

The MIT study recommended that the design of fuel cycles should plan for SNF storage for up to a century. Safe storage could be done at the reactor, in a centralized storage facility, or in a repository designed to enable long-term recovery of SNF. The study noted that there are incentives for early disposal of SNF: (1) enhance public confidence in the repository (Ref), (2) address issues of intergenerational equity (Ref), and (3) security (Ref).

These different goals suggest that the U.S. should adopt a policy of siting, designing, and operating repositories with two goals: (1) safe disposal of waste and (2) the capability to recover the SNF if it becomes a valuable resource. Such a repository design offers other benefits. There is a significant fraction of the public with concerns about long-term disposal. A repository with designed-in retrievability provides added assurance of long-term safety. Retrievability may make a repository more attractive to local communities and states. The condition of retrieved WPs may or may not allow easy transport offsite creating large incentives to collocate and integrate any future reprocessing facility at the repository site. This would provide large local benefits to the community and state hosting the repository.

II. Requirements

There are different definitions of retrieval. At one extreme is retrieval if there are major site difficulties where economics is not a driver. In a world where mining companies operate open pit mines more than a kilometer in depth and deep mines approaching 4 kilometers in depth, all repositories are retrievable if economics is not a major consideration. At the other extreme is retrieval of specific SNF for reprocessing based on customer needs where economics is a major consideration. For the analysis herein, the retrievability must not require extraordinary engineering or high costs.

Four designs are identified with different degrees of ease in recovering the SNF. Some designs are results of major repository programs while others define new options created by recent technological developments. The requirements for long-term repository performance place the severest restrictions on design choices.

III. Traditional Hard Rock Repositories

SNF can be recovered after centuries from traditional hard rock repositories as being developed in Sweden and Finland and the proposed Canadian repository. The hard rock maintains its physical integrity along with long expected lifetimes for the WPs. The major challenge in recovering WPs is operating at the high local temperatures caused by decay heat. There is technology for mining in hot rocks (such as with ice-water slurries) that has been developed in South African mines that are as deep as 3900 meters and with rock temperatures as high as 60°C.

The design specifics offer different options. If the WP is in the wall or the floor of the disposal drifts, there is the option to maintain the drifts in an open condition and allow active air ventilation with operation of the facility as effectively a modified storage facility.

IV. Salt Repositories

Dole write with references to U.S. studies—you may be one of the few people in the country that even remember this work—time to shake people’s memories; Are there any more up-to-date German references? Do you or Kessler have the right contacts in Germany? 2-3 pages

Salt repositories present two challenges for recovery of SNF. There will be lower temperatures because of the higher thermal conductivity, but WPs can move with time because salt is plastic—the exact position of the WP may not known. Mining salt is easy and WPs can be located in salt, which is transparent to radar and allows the use of sonar. However, recovery could be complicated by the less-defined environment. Studies in the 1970s showed that shielded WPs could be recovered. Carbon steel has slow corrosion rates in salt—thus the option of using thick carbon-steel WPs to provide long-term retrieveability.

V. Horizontal Boreholes

In the proposed French repository [2] in clay, the WPs are placed in long horizontal pipes between mined drifts. There is a clearance between the WPs and the pipes that allows ventilation. It is designed for WP recovery for extended periods of time.

VI. Lined Tunnels

In many types of geologies, the disposal drifts may not remain open for long periods of time. Premature closure can be assured by lining the disposal drifts. There are two extremes in design.

The first option is a design similar to the proposed Yucca Mountain Repository (YMR) in the United States (Ref). This design uses steel braces, rock-bolts and other structures to prevent drift collapse. Bare WPs fill the center of the tunnel. Remotely-operated equipment is used to place WPs. The plan was to fill the repository over 30 years and then use active ventilation for 50 years to reduce the WP decay heat to acceptable levels before repository closure. The facility was designed to allow retrieveability if site or design problems were identified. It was not designed for retrieveablity for SNF recovery for reprocessing.

The second option is a repository with concrete lined disposal drifts with WPs in concrete shields. The concrete-lined tunnel uses modified construction techniques used for rail and road tunnels. It is a technology suitable for most geologies including weak rocks and clay formations that may deform over time. Active ventilation controls temperature and allows operation as a storage facility.

The shielded WPs allow removal of any specific WP from the repository by (1) moving packages with a heavy-duty fork-lift truck or (2) use of rail-mounted cranes going into a drift, lifting the desired WP, and moving it out of the drift over the other WPs. Such options avoid the need to handle multiple WPs if only particular WPs are desired. SNF is like uranium ore—there is high fissile assay and low fissile assay SNF. If economics determines what SNF is to be recovered, only some fraction of the SNF may be desired.

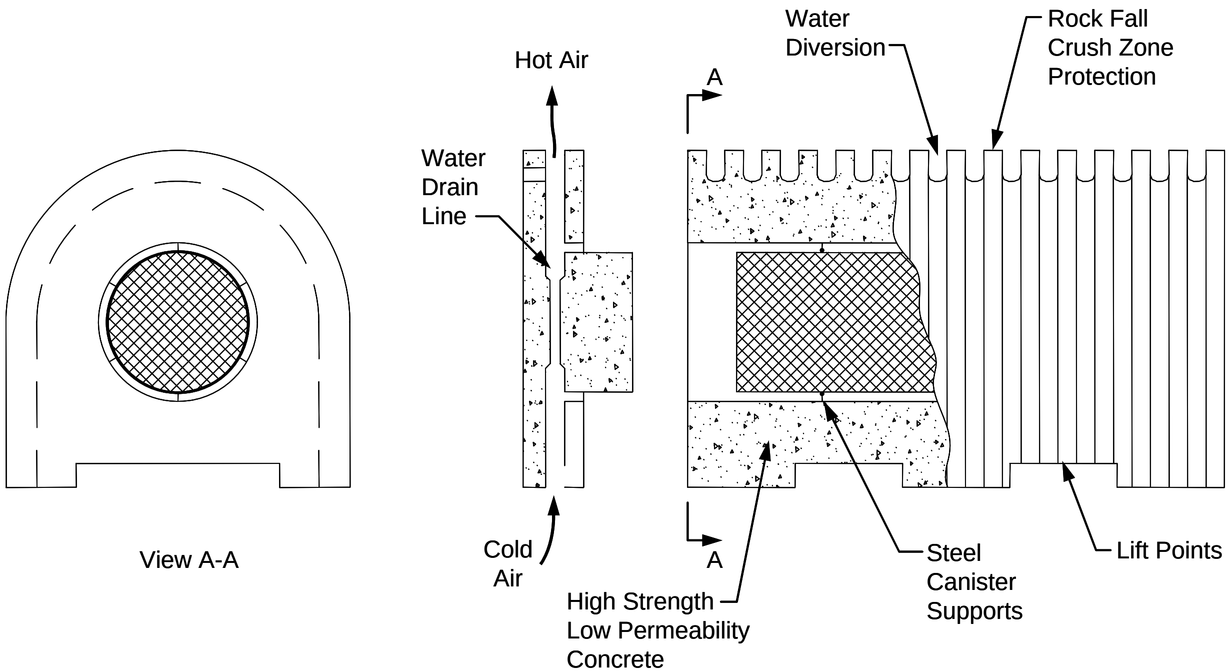

Fig. 1. Spin-Cast Concrete Package for Spent Nuclear Fuel

This is a new option has been partly developed within the last decade [3, 4]. Cements are not currently proposed for use within the disposal drifts of geological repositories. Current safety-assessment models used by the YMP assume that (1) cements accelerate the release and increase the mobility of uranium, fission products, and actinides and (2) specific selected mechanisms apply to the formation and the behavior of uranium and radionuclides in concrete-modified groundwater. These assumptions resulted in the prediction of a dose rate increase of a 100-fold for the 10,000-year peak dose to the average member of the critical off-site group. The specific chemical reactions supporting these assumptions are based on experience in processing uranium ore; data for these reactions are then extrapolated to the geochemical conditions of the YM site.

The principal concerns with the use of ordinary Portland cement (OPC) in YMP are: (1) leachates from concrete with a high pH (>10) in contact with UO_2 could increase radionuclide solubility and mobility (2) leachates from cement could dissolve the adjacent vitreous tuff and could increase the porosity, permeability, and transport properties of the adjacent formation and could result in higher water-borne transport rates of nuclides, (3) superplasticizers in the concrete matrix could form organic acids that stabilize colloids, thereby increasing radionuclide transport from the repository, and (4) The organics and calcium sulfate hydrate (gypsum) could provide a substrate for microbiological growth that would accelerate corrosion of the waste package and increase the availability of radionuclides for transport to near and far field.

The primary challenge for repository-acceptable cement is to modify the pH of the cement and address the potential impacts of soluble free calcium hydroxide (Portlandite) found in OPC and the carbonate YM groundwaters. The hexagonal crystals of Portlandite ($Ca(OH)_2$) are the most soluble, leachable phase that is embedded in the cured OPC matrix. If there were no additional buffering of the pH by a solution saturated in silicates, the hydroxyl ion, OH^-, concentrations could rise to above 1×10^{-4} mol/L (pH >10). In the presence of this high pH and groundwater carbonate anions (CO_3^{-2}), formation of soluble, mobile uranyl carbonate species, such as $UO_2(CO_3)_2^{-2}$ and $UO_2(CO_3)_3^{-4}$ can occur. However, these soluble uranium products do not occur if the groundwater-leachate or cement porewaters are saturated in silicates and aluminates and are consequently buffered. In the case of high-silica pozzolanic cement formulations, calcium hydroxide is consumed by reaction with glassy silica

In the cementitious binder, an excess SiO_2 will consume all of the free calcium hydroxide and buffer the leachates to below 10 pH.. With high-silica cements, the waste package (WP), uranium, and groundwater interactions retard the release and migration of radioactivity from the repository. With high-silica materials and other appropriate components within the cement, the concrete-modified YM groundwater can significantly delay the release and retard the mobility of uranium, fission products, and actinides by factors of 1/100 to 1/10,000. Recent experimental data is confirming the calculations and natural analoges (ref)-and thus creating the option of large-scale use of cements in repositories designed with SNF retrievability.

Industrial cement technologies such as steam curing can create cements that withstand high radiation levels without generating hydrogen and high temperatures. Spin cast fabrication techniques provide low-cost methods for high-performance cement structures. The combination of technologies is creating a new set of repository design options that may be particularly attractive for repositories with the design goal of SNF retrieveability.

VII. Conclusions

SNF retrievability has historically been a consideration in repository design as a form of safety in the event of unexpected repository failure modes are identified after start of repository operations. Many repository designs have been developed to enable SNF retrievability. Today there are additional incentives to enable SNF retrievability because we do not know if SNF is a waste or a resource. However, retrieveability for reuse of SNF imposes the added economic and technical requirements. Many of the existing designs can meet this added requirement with only small changes. New technologies, particularly new cements designed to improve repository performance, have created new classes of repository options where SNF can be recovered.

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