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International Approaches to Postclosure Criticality Safety – United States

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ABSTRACT

Many, if not all, Waste Management Organisation programs will include criticality safety. As criticality safety in the long-term, i.e. considered over post-closure timescales in dedicated disposal facilities, is a unique challenge for geological disposal there is limited opportunity for sharing of experience within an individual organization/country. Therefore, sharing of experience and knowledge between WMOs to understand any similarities and differences will be beneficial in understanding where the approaches are similar and where they are not, and the reasons for this. To achieve this benefit a project on Post-Closure Criticality Safety has been established through the Implementing Geological Disposal – Technology Platform with the overall aim to facilitate the sharing of this knowledge. This project currently has 11 participating nations, including the United States and this paper presents the current position in the United States.

Key Words: postclosure criticality, DPC disposal, IGD-TP

1. INTRODUCTION

Commercial generation of energy via nuclear power plants in the United States has generated thousands of metric tons of spent nuclear fuel (SNF), the disposal of which is the responsibility of the United States Department of Energy (DOE) according to the Nuclear Waste Policy Act of 1982. Any repository licensed to dispose of the SNF must meet requirements regarding the long-term performance of the repository. In evaluating the long-term performance of the repository, criticality is one of the events that may need to be considered. Of particular interest is the potential behavior of SNF in dual-purpose canisters (DPCs), which are currently being used to store SNF in the United States but were not designed for permanent disposal.

Rather, DPCs are designed and licensed for storage and transportation; that is, they are designed to control nuclear criticality for timescales and under conditions associated with storage and transportation, not the timescales (i.e., up to 1,000,000 years) and conditions associated with disposal. Many of the neutron absorbing materials used for criticality control in DPCs are composed of aluminum, which is expected to corrode within a few hundred years after failure of a waste package in a geologic repository, especially in an aqueous environment. Postclosure criticality then becomes a possibility for some fraction of the SNF disposed of in DPCs. If disposal of SNF in DPCs (i.e., no repackaging of SNF prior to disposal) is to be pursued in the United States, then either 1) the probability of occurrence of postclosure criticality must be lowered such that it is unlikely from a regulatory point of view, or 2) postclosure criticality must be shown to have an insignificant consequence on repository performance, or 3) both.

2. RESULTS

The DOE is studying the feasibility of several different ideas for reducing the probability of postclosure criticality occurring; some involve detailed as-loaded analysis to demonstrate DPC subcriticality over repository timescales applying inherent but uncredited criticality margins, some involve adding materials to DPCs that have already been loaded with spent fuel, and some involve re-designing the neutron absorbing materials and structures in DPCs that have yet to be loaded to provide criticality control for timescales associated with geologic disposal. The DOE is also studying the consequences of postclosure criticality on repository performance by 1) identifying the features, events, and processes (FEPs) that need to be considered in such an analysis, 2) developing the tools needed to model the relevant FEPs in a performance assessment, and 3) conducting performance assessment analyses both with and without the occurrence of a postclosure criticality and comparing the results. Each of these approaches is discussed further below.

2.1 Adding Materials to Already-Loaded DPCs

Adding materials (i.e., fillers) to DPCs that have already been loaded with spent fuel and have been welded shut has the potential to provide criticality control by means of moderator displacement [1], thereby reducing the probability of occurrence of postclosure criticality. These filler materials would be added without removing the DPC's welded lid; thus, they would be added through the original vent or drain ports, or through new ports created by drilling through the canister shell. The focus is therefore on fillers that can be emplaced as liquids and that subsequently solidify. The two major classes of materials identified for study are 1) molten metals that are introduced at higher temperatures and 2) resins or cement slurries that solidify at much lower temperatures [1].

A set of desirable properties of filler materials has been identified, in addition to the requirements that it provide moderator displacement and that it solidify after being emplaced in the DPC as a liquid. These include: provide neutron absorption if needed; minimize neutron moderation; not compact by more than 10%; promote heat transfer from the fuel during handling and after disposal; remain thermally, chemically, and radiolytically stable; remain chemically compatible with the materials inside the DPC; have limited gas generation; be homogeneous and consistent between batches; have good rheological properties; have good wetting behavior; allow for fuel recovery should the filling operation fail; be available at a reasonable cost; have low density to avoid adding excess weight; have good radiation shielding properties; be easy to emplace; and be able to be emplaced without damaging the fuel or canister [1]. These attributes may be prioritized or adjusted for specific fillers.

To date, studies of possible metal fillers have been focused on developing a multiphysics filling simulator for down-selecting filler materials. A casting/solidification simulation model was developed and laboratory experiments were performed using tin and zinc, which had been identified as promising candidate materials for unit testing; tin was chosen for further investigation for validating the casting simulation model [2]. Tin was successfully cast on a mock-up model with a geometry that was sized accurately for the full-scale canister drain pipe and that represented nine fuel pins and one grid spacer section of a fuel bundle, as well as one of the passages between assemblies' shrouds (i.e., mouse holes). Tin demonstrated compatibility with the materials in the case with no large voids detected. In addition, a computational fluid dynamics model was developed to simulate the filling process, and experimental data using various surrogate fillers were used to validate the simulation model [2].

Studies of possible cement fillers focused on aluminum phosphate cements, wollastonite phosphate cements, and calcium aluminate phosphate cements [3]. Efforts to date have focused on the optimization of the compositions of these cements as well as subsequent processing to achieve dense and well consolidated monolithic samples. To date, aluminum phosphate cements and calcium aluminate phosphate cements show the most promise for further advanced testing and scale-up; wollastonite phosphate cements remain a challenge because of their short working times [3].

2.2 Re-designing Neutron-Absorbing Materials and Structures in DPCs

Modifying DPCs that have yet to be filled with spent fuel has the potential to reduce the probability of occurrence of postclosure criticality such that it would not need to be included in the postclosure performance assessment required for a repository license application. The objective of these modifications would be to ensure the presence of neutron absorbers between or within the fuel assemblies for as long as the SNF assemblies remain in a geometry capable of criticality in the disposal environment. The materials used in these modifications would need to have long corrosion lifetimes; corrosion rates are dependent on chemistry, other materials in the waste package, temperature, radiolysis, and the geologic setting [4].

One proposed modification is the insertion of disposal control rods. In pressurized water reactor assemblies, control rods could be inserted into existing assembly guide tubes that are not occupied by spent reactor control rods or other non-fuel components such as thimble plugs. In boiling water reactor assemblies, zirconium-based fuel channels can be replaced by fuel channels fabricated from corrosion-resistant neutron absorbing materials. This idea was proposed by EPRI [5,6] and is proven by the use of control rods in reactor operations. Disposal control rods could consist of a Zircaloy tube filled with a neutron absorber, such as B_4C, or could consist of an extruded rod of borated stainless steel. The number and location of disposal control rods would be determined based on detailed reactivity calculations. Bowing of guide tubes, design features that block access, the existence of crud, thermal expansion, etc. could pose operational challenges to inserting these disposal control rods [4].

Another proposed modification consists of replacing the neutron absorbers in current DPC designs with materials that are more corrosion resistant, such as borated stainless steel or a Ni-Cr-Mo-Gd alloy. The thickness of the material would depend, in part, on its expected corrosion rate in the disposal environment. Another closely related idea is to use chevron inserts in the basket cells. The chevron inserts, which consist of two flat plates that fit against two sides of each fuel cell in a rack, would be fabricated of corrosion-resistant neutron-absorbing material. The inserts would not replace the current neutron absorber plates but would be inserted into already-loaded assembly baskets if there is sufficient clearance.

A third option consists of loading assemblies into the DPCs with the objective of reducing reactivity, referred to as "zone loading." Currently, the map for loading assemblies into a DPC is driven by thermal and surface dose rate considerations, but not reactivity considerations. Recent criticality calculations for as-loaded DPCs demonstrated that many existing DPCs would have remained subcritical under repository conditions, once they were disposed of, had they been loaded with the same SNF inventory but in a configuration that was optimized to minimize reactivity [7]. This option, unlike the other two, would not require a change to the license, would not introduce additional weight, and might be less costly. Recently discharged assemblies may be too reactive for this approach to be successful, but it could be successful for some percentage of DPCs loaded in the future [4].

2.3 Consequences of Postclosure Criticality on Repository Performance

The DOE is also studying the consequences of postclosure criticality on repository performance. Any repository licensed to dispose of SNF must meet requirements regarding long-term performance. A postclosure performance assessment is used to demonstrate that the performance of the repository meets these various requirements. The performance assessment must consider all FEPs that could affect repository performance. All FEPs are to be included in the performance assessment unless the probability of occurrence of the FEP is below a specified limit or the consequences of its occurrence, however probable, can be demonstrated not to be significant [8]. For the Yucca Mountain performance assessment, postclosure in-package criticality in the transportation, aging, and disposal canisters that were to dispose of the SNF was excluded from the performance assessment on the basis of low probability [9]. Based on recent investigations of DPC direct disposal feasibility, it is not clear that in-package criticality in DPCs could be excluded from the performance assessment for non-saline host media, on the basis of low probability [10]. Therefore, if the SNF in DPCs is to be disposed of without being repackaged or without the addition of fillers or other modifications discussed above, it may be necessary to model the consequences of postclosure criticality on repository performance to estimate what the consequences might be [4].

It is important to note that postclosure criticality cannot occur unless and until the waste package, which is assumed to consist of a DPC enclosed in a disposal overpack, has failed and a sufficient amount of water has entered. Neutron absorbers in the DPC basket would be expected to prevent criticality until they are degraded by corrosion. Criticality is then possible under these conditions.

To investigate the consequences of in-package criticality during the postclosure period, the first task was to model the effects of both a low power steady-state criticality and a high power transient criticality event in a single waste package disposed of in two different hypothetical repositories (a saturated environment and an unsaturated environment), later expanding beyond a single waste package. Two performance assessments will be conducted for each hypothetical site, one for each type of criticality event, comparing results that include criticality events to the results of a performance assessment of the same system but without the occurrence of criticality events. This will quantify the difference between performance assessment results with and without criticality for the cases examined.

To ensure that FEPs that could affect the occurrence or extent of criticality (e.g., peak power, steady-state power, duration) and/or be affected by the occurrence of criticality were identified, a study was conducted to identify such FEPs [11] so that consideration might be given to including them in models of postclosure criticality. For a steady-state criticality event, the heat generated by the postclosure criticality event was identified as being important with respect to both the occurrence and extent of criticality and with respect to the effects that the heat has on corrosion rates, mineral alteration and thermal pressurization, radionuclide adsorption and solubility, and the chemistry of water inside the waste package. In addition, the change in radionuclide inventory must be considered [12]. For a transient criticality event, factors that might cause a rapid reactivity insertion were identified as being important, as were mechanical damage to fuel, engineered barriers, and natural barriers that might result from such an event.

Developing the tools needed to model the relevant FEPs in a performance assessment incorporating the occurrence of postclosure criticality required modifying PFLOTRAN [13,14,15,16], which is an open source state-of-the-art massively parallel subsurface flow and reactive transport code used to simulate subsurface earth system processes. Modifications included the capability to specify a steady-state heat from a criticality event for a specified period of time, the capability to change the radionuclide inventory at a specified time, the capability to alter mineral types as a function of time and temperature, and the capability to incorporate a model of anisotropic temperature-dependent thermal conductivity.

To date, we have completed a performance assessment for the case of steady-state criticality in a hypothetical saturated shale repository; preliminary results indicate no difference in repository performance, as measured by dose to a member of the public, between the simulation with postclosure criticality and the simulation without postclosure criticality. The performance assessment for steady-state criticality in a hypothetical unsaturated repository has not yet run all the way to dose to a member of the public. However, results to date indicate that, in an unsaturated environment, the postclosure criticality event can sustain only very low power levels for only short periods of time, thus limiting possible thermal effects and the change in radionuclide inventory. With respect to the two transient cases, we are still developing neutronic models of a transient criticality event to estimate peak power, temperatures, total energy released, etc.

3. CONCLUSIONS

The DOE is studying the feasibility of several different ideas for reducing the probability of postclosure criticality occurring. Some involve detailed as-loaded analysis to demonstrate DPC subcriticality over repository timescales applying inherent but uncredited criticality margins, some involve adding materials to DPCs that have already been loaded with spent fuel, and some involve re-designing the neutron absorbing materials and structures in DPCs that have yet to be loaded to provide criticality control for timescales associated with geologic disposal. The DOE is also studying the consequences of postclosure criticality on repository performance by 1) identifying the FEPs that need to be considered in such an analysis, 2) developing the tools needed to model the relevant FEPs in a performance assessment, and 3) conducting performance assessment analyses both with and without the occurrence of a postclosure criticality and comparing the results. A summary and status of each of these approaches was provided above.

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This is a technical abstract that does not take into account contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). For example, under the provisions of the Standard Contract, spent nuclear fuel in multi-assembly canisters is not an acceptable waste form, absent a mutually agreed to contract amendment. To the extent discussions or recommendations in this abstract conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this abstract in no manner supersedes, overrides, or amends the Standard Contract.

This abstract reflects technical work which could support future decision making by DOE. No inferences should be drawn from this abstract regarding future actions by DOE, which are limited both by the terms of the Standard Contract and Congressional appropriations for the Department to fulfill its obligations under the Nuclear Waste Policy Act including licensing and construction of a spent nuclear fuel repository.

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