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Consequences of Nuclear Criticality in Dual Purpose Canisters After Disposal

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INTRODUCTION

This is a technical paper 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) [1]. For example, under the provisions of the Standard Contract, spent nuclear fuel (SNF) 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 paper conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this paper in no manner supersedes, overrides, or amends the Standard Contract. This paper reflects technical work which could support future decision making by the U.S Department of Energy (DOE). No inferences should be drawn from this paper regarding future actions by DOE, which are limited both by the terms of the Standard Contract and a lack of Congressional appropriations for the Department to fulfill its obligations under the Nuclear Waste Policy Act [2] including licensing and construction of a SNF repository.

Commercial generation of energy via nuclear power plants in the United States (U.S.) has generated thousands of metric tons of SNF, the disposal of which is the responsibility of the DOE [2]. 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, one of the events that may need to be considered is the possibility of SNF achieving a critical configuration inside the waste package. Of particular interest is the potential behavior of SNF in dual-purpose canisters (DPCs). DPCs are designed to meet relevant NRC requirements for storage and transport of SNF. While DPCs are designed, licensed, and loaded to preclude the possibility of a criticality event during SNF storage and transport, they were not designed or loaded to preclude the possibility of a criticality event during the regulated postclosure period following disposal, which can be up to 1,000,000 years.

One of the requirements for assessing the long-term performance of a repository is that all features, events, or processes (FEPs) be included in a Performance Assessment (PA) unless the probability of occurrence of the FEP is below a specified limit or the consequences of its occurrence, however probable, can be demonstrated to not be significant [3]. Based on studies investigating the probability of occurrence of in-package criticality in DPCs during a postclosure performance period, it is not clear that in-package criticality in DPCs could be excluded from a PA on the basis of probability for non-salt geologies [4].

The SNF currently in DPCs could be repackaged into canisters that are designed to remain subcritical during the regulated postclosure period following disposal. However, it is estimated that not repackaging the SNF currently in DPCs prior to disposal (i.e., disposing of SNF in DPCs) would save approximately $20B [5], increasing the attractiveness of this option. If SNF is to be disposed of in DPCs in a non-salt geology, and if the probability of occurrence of criticality during the postclosure period cannot be reduced by other means (e.g., fillers [6]), the consequences of criticality during a 1,000,000-year postclosure period would have to be analyzed as part of a PA. If the analysis shows that the consequences of criticality during the postclosure period are not significant in terms of repository performance, then criticality could be excluded from PAcalculations based on low consequence. Otherwise, the occurrence and consequences of criticality would have to be included in PA calculations.

This paper describes research currently being conducted for the DOE that is focused on developing the modeling tools and techniques that may eventually be required to either exclude criticality from a PA or include criticality in a PA for a proposed repository.

RESULTS

The approach to analyzing the consequences of a critical event in a DPC during the postclosure period includes a discussion of the relevant postclosure PA requirements and guidelines, the physics and effects of criticality, and the strategy for criticality consequence analysis. These are discussed below.

Relevant Requirements and Guidelines

Both the NRC and the U.S. Environmental Protection Agency (EPA) have promulgated requirements for disposal of SNF and high-level waste. After developing these requirements, both the NRC and the EPA promulgated requirements for disposal of SNF and high-level waste in Yucca Mountain, i.e., 10 CFR Part 63 [7] and 40 CFR Part 197 [8] respectively. These latter requirements apply only to Yucca Mountain and, thus, would not apply to a proposed repository that was not at Yucca Mountain. However, it is likely that both the NRC and the EPA will revise their SNF and high-level waste disposal requirements to be risk-informed and performance-based [9]. Therefore, for the

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purposes of this study, it is assumed that the requirements at 10 CFR 63 [7] and 40 CFR 197 [8] would apply to any proposed repository.

There are three postclosure performance requirements: the individual-protection standard (10 CFR 63.311 and 40 CFR 197.20), the human-intrusion standard (10 CFR 63.321 and 40 CFR 197.25), and the ground water protection standard (10 CFR 63.331 and 40 CFR 197.30). The individual-protection standard limits the annual committed effective dose equivalent to a reasonably maximally exposed individual to 15 mrem for the first 10,000 years after closure and to 100 mrem for the period between 10,000 years and up to 1,000,000 years. The human-intrusion standard has the same dose limits as the individual-protection standard but with the stipulation that a stylized human intrusion event occurs. The ground water protection standard limits the activity of certain radionuclides in a representative volume of water.

Both the NRC and the EPA place limits on the FEPs that must be considered when conducting a postclosure PA of a repository. Specifically, events and processes that are estimated to have less than one chance in 100,000,000 per year of occurring are not to be included in the postclosure PA. In addition, the effects of events and processes or sequences of events and processes with a higher chance of occurring need not be included in the PA if their effect on repository performance (however probable) can be demonstrated to be insignificant [3]. FEPs that cannot be excluded from the PA based on probability or based on consequence must, in general, be included in the PA.

Calculations used to demonstrate that a particular FEP can be excluded from a postclosure PA on the basis of consequence often employ conservative assumptions and bounding estimates. If the consequences of a particular event or process are insignificant to repository performance under worst-case conditions, then the particular event or process does not need to be considered in PA calculations. In the approach described below, two configurations of DPC internals will be considered: (1) total loss of neutron absorber with the internal basket structure still intact and (2) loss of the internal basket structure (including the neutron absorber). Only in-package criticality is considered; critical events outside the waste package, which consists of a DPC inside a disposal overpack, are not considered in this paper.

The FEPs screening process outlined in 10 CFR 63.114 [7] specifies that FEPs must be evaluated over a time period of 10,000 years after repository closure. For the purposes of the studies described in this paper, and consistent with the DOE's methodology for performing criticality analyses during the postclosure period [10], two critical events are considered: a steady-state criticality and a transient criticality. The steady-state criticality event is assumed to begin 9,000 years after closure and to continue for another 10,000 years, and the single, short-duration transient criticality event occurs 9,000 years after closure. However, for the purposes of developing a fuller understanding of the consequences of criticality in a DPC, follow-on studies may examine those consequences at an initiation time that is beyond 10,000 years.

According to the DOE [10], the steady-state criticality event would produce energy at a relatively low but constant rate while a transient criticality event has the potential of generating a much higher power level than a steady-state event. Accordingly, the principal consequences of the steady-state criticality event are the incremental increase in the radionuclide inventory available for transport to the accessible environment and the additional heat generated by the on-going critical event. These consequences are also applicable to a transient criticality event. An additional consequence of transient criticality is damage to the engineered barrier system that could increase the rate at which radionuclides are available for transport to the accessible environment. Both types of critical events are assumed to occur once a waste package fails and water enters the waste package. The transient criticality event occurs as a result of a rapid reactivity insertion due to sudden movement, such as the occurrence of a seismic event, rock fall, or sudden loss of the DPC basket structure.

Physics and Effects of Criticality

Criticality in a disposed of DPC is not possible unless water is present; therefore, the disposal overpack and the DPC must first be breached so that water can enter the DPC before critical conditions can be achieved. Once water has entered the DPC, the reactivity of the SNF in a DPC is controlled by multiple factors, including fissile mass in the fuel rods; the presence of neutron absorbers in the fuel, in the water, or integral to the basket; the presence of moderator; moderator volume and temperature; basket geometry; and fuel temperature [9]. The criticality analyses described below will consider some of these factors.

Figure 1 shows the coupling between the various processes that are of concern in the context of critical conditions inside a waste package disposed of in a repository. Each process in Figure 1 is modeled by its own set of appropriate mathematical equations; these models and equations will be explained in more detail in the report describing the results of this study. The processes in the shaded ovals are included in the approach described below; the other processes that are not shaded may be included as a part of follow-on studies.

The critical event will create radionuclides; the changes to fuel composition due to criticality can be described as falling into the following categories [9]:

- Radionuclides important to dose estimates in the nominal PA (e.g., ^{99}Tc)

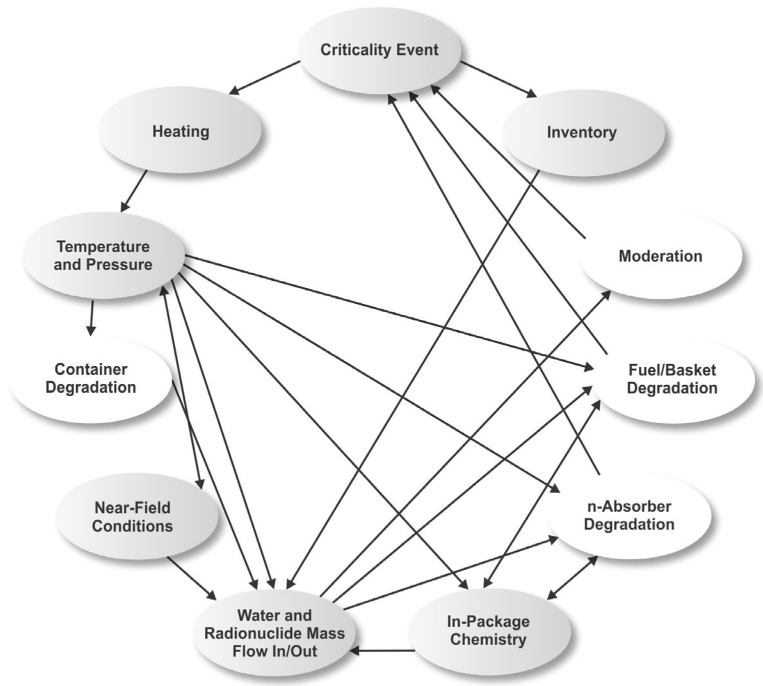

Figure 1. Coupled processes

- Additional radionuclides with moderate half-lives that may impact dose estimates based on release time and transport duration
- Radionuclides that increase decay heat (e.g., ^{137}Cs)
- Radionuclides that could impact waste package chemistry
- Radionuclides included in the burnup credit methodology (i.e., the 29 principal isotopes)
- Radionuclides that could impact system reactivity not included in the burnup credit methodology due to their relatively short half-lives (e.g., ^{135}Xe) or solubility (e.g., ^{135}Cs)

The heat generated by the critical event will increase the temperature of the waste package and everything in it, as well as the host rock and any backfill material surrounding the waste package. The pressure inside a breached waste package would not build up unless the breach(es) in the waste package become plugged or a rapid positive reactivity change causes a steam flash that overwhelms a small breach.

A transient critical event with a sufficiently large energy spike could deform or rupture the fuel rod cladding, the fuel basket or fuel assemblies, or the DPC canister and its overpack. If the waste package is surrounded by backfill material, this material may be compressed by a pressure pulse, such as from a steam explosion, resulting from a transient critical event in a DPC, and DPCs directly adjacent to a critical DPC might also be damaged by the pressure pulse from the critical DPC.

Radiolysis due to ionizing radiation could lead to the formation of carbon dioxide, carbon monoxide, hydrogen, oxygen, methane, and various nitrogen oxide forms. Oxidizing radicals and molecules may include OH^+, O_2^-, H_2O_2, and O_2. Radiolysis could also lead to the formation of reductants (e.g., H^+, H_2). Production of NO, NO_2 and HNO_3, which is a corrosive chemical, is possible due to radiolysis. Radiolysis can impact the chemistry within the waste package, thereby affecting the rate of release of radionuclides important to PA. The change in chemistry due to radiolysis and the increase in temperature can also affect the rates of SNF and steel degradation, as well as radionuclide and neutron absorber solubilities. This could affect the degradation rates of engineered barriers as well as radionuclide release rates.

As noted above, the heat generated by the critical event will increase the temperature of any backfill material surround the waste package. If the backfill consists of clay-based materials, there is a concern that the clay will dehydrate and no longer act as a barrier to water flow into the waste package or to radionuclide transport away from the package.

Strategy for Criticality Consequence Analysis

The initial approach for analyzing the consequences of postclosure criticality on repository performance is described below. The first step is to identify a DPC loaded with SNF to include in the model. A DPC containing 37-pressurized water reactor (PWR) assemblies was selected, namely the TSC-37. This particular DPC, along with many others, has been analyzed to determine its potential for forming critical configurations during repository timeframes [11]. It was determined that, assuming there is a total loss of basket neutron absorber components and the DPC is flooded with groundwater, the SNF in this DPC will have a k_{eff} of about 1.05 approximately 9,000 years from now [9]. The information available for the PWR SNF in this DPC includes the radionuclide inventory and decay heat as a function of time; and the burnup, initial enrichment, initial mass of U, and discharge date for each of the 37 assemblies.

Four different conceptual models will be developed and implemented to address possible combinations of saturated repository versus unsaturated repository and steady-state versus transient criticality. The saturated repository is assumed to be in a saturated shale formation and the unsaturated repository is assumed to be in an alluvial formation. Both are assumed to be backfilled, the saturated repository with a high thermal conductivity material and the unsaturated repository with crushed alluvium. In each model, the DPC is placed in a disposal overpack and disposed of horizontally directly on the drift floor. The outer disposal overpack and inner DPC are assumed to fail such that water could enter the waste package and criticality commence 9,000 years after disposal. The steady state critical event is assumed to last for 10,000 years while the transient event is assumed to occur only once and disrupt the configuration such that it could no longer achieve a critical configuration. Further details of these four conceptual models are provided in the cited reference [9].

Using the characteristics of SNF in the waste package, the waste package, the different types of criticality, and the geologic settings, models will be run to calculate outputs of interest, as shown in Figure 1. Outputs include neutron flux, power of the criticality, changes in radionuclide inventory, changes in the chemistry inside the waste package, the effects of radiolysis, among others. The multiple models that will be run have varying time and spatial scales. These will be coupled to the extent possible, with some couplings being stronger than others.

Once the effects of the processes shown in Figure 1 have been quantified to the extent possible, the performance of each of the four hypothetical repositories will be analyzed, in accordance with applicable performance requirements. These calculations will be performed with the occurrence of criticality and in the absence of criticality to establish the differential in repository performance due to the occurrence of a critical event.

REFERENCES

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