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Abstract - *This paper provides an overview of a feature, event, and process (FEP) screening argument developed for the issue of pyrophoricity as it pertains to the post-closure interment of Department of Energy (DOE) spent nuclear fuel (DSNF) at the Yucca Mountain Repository.*

I. INTRODUCTION

A FEP database has been compiled that contains all the FEPs identified for the Yucca Mountain Repository. The FEPs contained in it are classified as either primary or secondary, with each secondary FEP being associated with one or more primary FEPs. An analysis is required for each primary FEP that addresses all the issues raised by it and its associated secondary FEPs. Primary FEPs can then be screened from further consideration on the basis of either probability (less than one chance in 10,000 of occurring during the first 10,000 years) or consequence (no significant impact on repository performance).[1] If a primary FEP is screened, then so are its associated secondary FEPs.

This paper provides the results of an analysis of the primary FEP "Pyrophoricity" (Yucca Mountain FEP database # 2.1.02.08.00)[2] and its associated secondary FEPs. For our purposes, pyrophoricity will be defined as the self-sustaining oxidation of SNF. The issue of a pyrophoric event (PE) occurring needs to be addressed because a PE has the potential for increasing the release rate of radionuclides, which could impact repository performance. This analysis will examine such issues as: the conditions required for a PE to occur, which types of SNF are a concern, the impact on adjacent waste packages, and the impact a PE would have on repository performance.

There is not sufficient data available at this time to definitely exclude PEs based on their low probability of occurrence. Therefore, this analysis will assume that PEs are possible and look at the impact they would have on repository performance if they were to occur.

II. ASSUMPTIONS

The following assumptions were used in this analysis. Although some of these assumptions appear to be contradictory, they were made to create a worst-case scenario. This worst-case scenario will then act as a bounding analysis to determine the maximum impact pyrophoricity can have on repository performance.

- Because the SNF canisters will be purged of oxygen, no PE can occur until after both the waste package and SNF canister have breached.
- There is sufficient oxygen available to support a PE.
- An ignition source is possible.
- The main impact a PE would have on the involved waste form would be a nearly instantaneous release of its soluble radionuclide inventory to the environment. The insoluble radionuclides will have a much longer migration time.
- The main impact of a PE on the adjacent waste packages would be to cause the waste package to breach, and the waste form inside to undergo a nearly instantaneous release of its soluble radionuclide inventory.
- A PE's impact on fuel cladding and non-oxidized waste form will change its dissolution rate.
- A PE will not propagate beyond the two adjacent waste packages.
- The N-reactor waste packages will be evenly distributed throughout the repository.

III. POTENTIAL PYROPHORIC IMPACTS

A PE can impact repository performance in a number of ways. The most obvious effect would be an increase in the release rate of radionuclides from the affected waste package to the environment. The following are other effects of concern.

- The impact a PE would have on other nearby waste packages.

- The potential degradation of the cladding and/or waste form of the DSNF contained within the involved waste package but not directly involved in the pyrophoric oxidation.

- The impact that a large, quick release of thermal energy would have on the surrounding geohydrologic system (e.g., could a PE result in an increase or decrease in local percolation rates?).

With the exception of the impact on the surrounding geohydrologic system, this analysis will address these issues either by direct analysis or by the use of bounding arguments. For example, the issue of a PE's impact on non-oxidized fuel cladding and waste form within the involved waste package will be bounded by assuming that intact fuel cladding does not impact DSNF dissolution rates. This is a conservative assumption, but is in-step with the TSPA-VA,[3] which took no credit for DSNF cladding.

The issue of the impact a PE would have on the involved waste package is addressed by the assumptions that a PE can only occur after its waste package has breached (no further credit is given for waste package integrity following its breach). The impact a PE would have on nearby waste packages is addressed by conservatively assuming they would fail.

Regarding the issue of the impact on the surrounding geohydrologic system, it can be postulated that changes in local percolation rates could result from changes in the surrounding rock strata caused by a PE's thermal energy. However, it was assumed that a waste package must be breached prior to undergoing a PE. Also, the TSPA-VA models the complete dissolution of the waste form within a breached waste package to occur within one time step following its breach. Therefore, changes in local percolation rates would not significantly impact the TSPA model.

Because the N-reactor fuel (zirconium-clad uranium-metal fuel) has the greatest potential for being pyrophoric, for simplicity, this analysis was limited to N-reactor SNF. Other reasons for making this simplification include the following. The N-reactor fuel represents the overwhelming majority of the DSNF (2100 MTHM of the total 2721 MTHM).[4] The N-reactor DSNF waste packages will contain the largest concentrations of DSNF (up to about 20 MTHM each). Most of the other DSNF will be packaged in relatively low concentrations (averaging approximately 0.15 MTHM per waste package) in co-disposal waste packages, which contain one canister of DSNF along with four or five canisters of high level waste (HLW). And, most of the other DSNFs are not pyrophoric in nature.

IIIA. Screening Argument (Consequence-Based)

The following argument covers a spectrum of PE scenarios and evaluates their consequences on repository performance. It uses conservative assumptions regarding the impact on adjacent waste packages. It addresses pyrophoricity in terms of both the total radionuclides that could be released due to a PE and the effect a PE could have on the peak offsite dose. A sensitivity analysis is included to evaluate the effects of clustering.

IIIB. Potential impact on the total amount of radionuclide released

Over the period of one million years following repository closure, some percentage of the 12,000 total waste packages will fail. Using the conservative assumptions that every N-reactor waste package breach will result in a PE and each PE will fail the two adjacent waste packages, adjacent waste packages equal to twice the number of failed N-reactor waste packages could potentially fail due to PEs. In reality, some portions of these adjacent waste packages may have failed prior to its corresponding PE and another portion would have failed independently sometime later in the million-year period. Therefore, by assuming the various types of waste packages (WPs) are evenly distributed throughout the repository, the increase in the total number of waste-package failures during the million-year period due to PEs can be calculated as follows:

(# non-failed WPs/total WPs)(# PE-induced failures/event)(PE rate per # WPs failed) (total # WPs failed)

Table 1 looks at a range of potential repository performances (measured in terms of the fraction of waste packages that fail during the one-million-year period). It provides the potential increase in the number of waste-package failures resulting from PEs for a range of possible repository performances. Because an even distribution of waste-package types was assumed, this should correspond to the increase in the total amount of radionuclides released over the one-million-year period. It should be noted that the TSPA-VA analysis indicated that approximately 100% of the waste packages will be failed at 1,000,000 years and the Enhanced Design Alternative-II (EDA-II)[5] estimated that approximately 89% of the waste packages will have failed at 1,000,000 years.

Thus, assuming that over the million-year period, some additional waste packages could fail due to PEs, Table 1 provides the range of possible impacts. It is interesting to note that the better the repository performs (i.e., the lower the percentage of failed waste packages at 1,000,000 years), the greater the impact PEs could have in term of percent increase in radionuclide release. However, the total repository release would also be significantly lower as repository performance increases. It should be noted that these values were achieved by conservatively assuming that all breached N-reactor waste packages resulted in a PE of sufficient intensity to damage the two adjacent waste packages.

Assuming PEs are possible, the proceeding analysis provides an estimated range of the maximum overall increase in the amount of radionuclides that could be released during the million-year period, over that which would occur if PEs are not possible. However, it does not address the potential impact PEs could have on peak-offsite-dose rates. Nor does it address the possible impacts that could arise from the clustering of PEs in a short time frame.

IIIC. Impact of PE on peak offsite dose

The impact a single PE would have on peak offsite dose can be bounded by probabilistically assessing the potential worst-case release from a failed waste package, in terms of the potential percent increase in radionuclide release. The following presents an assessment based on the worst-case release from a failed waste package, in terms of the potential percent increase in radionuclide release, if the waste package failure results in a PE. It is independent of any particular repository model.

The initial peak dose following waste package failure is due primarily to the release of the highly soluble isotopes I-129 and Tc-99. The corresponding long-term dose is associated with the much slower release rate of Np-237. A pyrophoric event involving a single N-reactor waste package with the simultaneous failure of the two adjacent commercial SNF waste packages could be estimated to result in a peak offsite dose that is equivalent to approximately three times the value of a single waste package failure. In actuality, even though the N-reactor waste packages contain more SNF, they contain significantly smaller amounts of Tc-99, I-129, and Np-237.

Table 1. Potential increase in radionuclide release.

% Waste Packages Failed at 1,000,000 years	Total # of Waste Packages Failed	# of N-reactor Waste Packages Failed	# of Additional Waste Packages Failed Because of PEs	% Increase in Radionuclide Inventory Released Due to PEs
60	7200	60	48	0.7%
70	8400	70	42	0.5%
80	9600	80	32	0.3%
90	10,800	90	18	0.2%
100	12,000	100	0	0.0%

In terms of the percent increase in radionuclide release, the worst case a PE involving a single N-reactor waste package can have (assuming the two adjacent waste packages also fail) would be if it involved the repository's first waste-package failure. In this case the initial release would be approximately three waste package equivalents (WPEs) of radionuclides rather than one waste package equivalent. However, the probability that an N-reactor waste package is the first waste package to fail is equal to approximately 100 divided by 12,000, or about 0.01.

Therefore, on average, the worst-case increase in radionuclide release attributable to a single PE can be calculated as the probability that it does not involve an N-reactor waste package times 1 WPE plus the probability it does involve an N-reactor waste package times three WPEs.

$$(0.99)(1\ \text{WPE}) + (0.01)(3\ \text{WPEs}) = 1.02\ \text{WPEs}.$$

This represents a 2% increase in peak offsite dose above that which would result if PEs are not possible. To put this into perspective, the TSPA-VA estimates a peak offsite dose of approximately 300 mrem at around the 300,000-year period. If PEs are possible, then the peak offsite dose could increase to 306 mrem.

IIID. Clustering sensitivity model

Clustering can be defined as multiple waste packages failing in a short time period. They can be postulated as being either induced by some initiating event that is not associated with pyrophoricity or DSNF (non-pyrophorically-induced cluster) or induced by an initiating PE that results in subsequent PEs (pyrophorically-induced cluster). Clustering events can be potentially important in that they could result in a higher peak offsite dose. Although no credible mechanisms have been identified that would result in a clustering of PEs, we will address the impact on peak offsite dose that would result, should a clustering event occur.

Regarding non-pyrophorically-induced clusters, an argument can be made similar to that in the preceding section. It does not matter how many waste packages are involved in some random event that results in clustering, each waste package involved has approximately 0.01 probability of being an N-reactor waste package, which might then result in a PE. Therefore, the maximum impact PEs could have on the peak dose associated with a non-pyrophorically-induced clustering event would be a 2% increase in the dose resulting from that clustered event. This conservatively assumes that the waste packages adjacent to the PE waste package were not failed during the clustering event. It also assumes that none of the involved waste packages (or their adjacent waste packages) had failed at some previous time and all the involved N-reactor waste package failures result in a PE.

Climatic changes have been postulated as a mechanism for inducing simultaneous PEs. However, because of the rapid dissolution of the waste form following waste package failure (less than 1000 years), climatic changes have been dismissed as a cause for PE-induced clustering. The PE-induced clustering event can be dismissed based on the expected separation that will exist between N-reactor waste packages. Also, there is probably insufficient oxygen available in a drift to support multiple PEs occurring simultaneously.

IV. CONCLUSIONS

From the proceeding consequence-based analysis, it can be seen that a pyrophoric event would have only a minimal impact on repository performance. In terms of the potential increase in total radionuclides released over the repository's lifetime, the impact of PEs would probably not exceed a 1% increase in the total amount of radionuclides released. In terms of the peak offsite dose that could result from a single PE, it was demonstrated that regardless of the model used a PE would, at most, have a 2% increase in peak offsite dose above the dose that would be obtained if PEs were not possible. To put this into perspective, the TSPA-VA estimates a peak offsite dose of approximately 300 mrem at around the 300,000-year period. If PEs are possible, then the peak offsite dose could increase to 306 mrem. As for clustered events, unrealistic scenarios involving incredible mechanisms would be required to generate more than a 2% increase in peak offsite dose.

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