Assessing the Consequences of an In-Package Criticality Event at a High-Level Nuclear Waste Repository

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Introduction

The Nuclear Regulatory Commission (NRC) has the responsibility for reviewing any license application that may be submitted for the proposed high-level nuclear waste repository at Yucca Mountain, Nevada. Part of this review will be an assessment of the effects of potential disruptive events on repository performance. One low probability event that may occur within the repository is nuclear criticality of the spent nuclear fuel within the waste package. Nuclear criticality within a waste package, if it occurs, can increase the inventory of radionuclides in the waste package, raise the temperature of the waste package, or damage the engineered barriers of the repository. These changes in the fuel and engineered barriers could affect the the ability of the repository to isolate waste from the environment. Evaluating the importance of criticality in the performance of the repository requires an understanding of both the probability and consequences of a criticality event.

The potential of criticality occurring outside the waste package in locations where fissile material could accumulate also needs to be evaluated. However, this paper only focuses on the occurrence of a criticality event within a waste package.

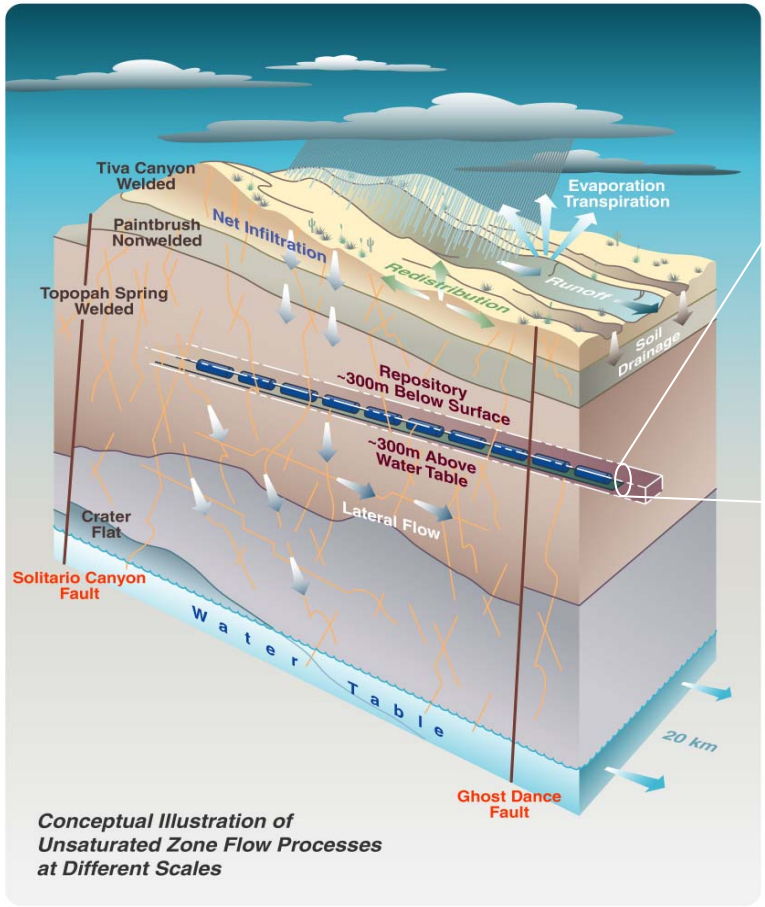


Figure 1. **Illustration of the Yucca Mountain repository system.**

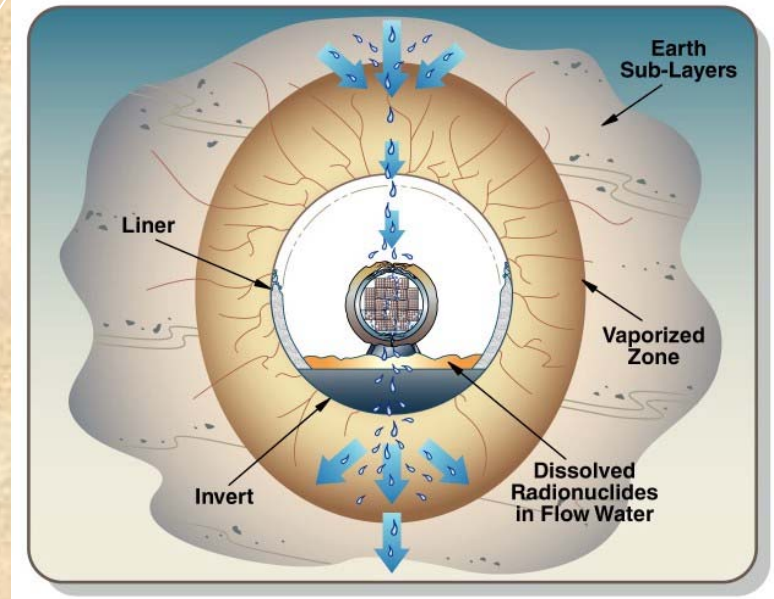


Figure 2. **Schematic of engineered barriers including the waste package containing spent fuel or other high-level waste sitting on a pedestal on top of an invert. Current DOE designs include a drip shield above the waste package (not shown in figure) to restrict water from contacting a waste package.**

Total-system Performance Assessment Code, Version 4.1

The Total-system Performance Assessment code, Version 4.1 (TPA 4.1)[1] was used to conservatively model the consequences of a criticality event within a waste package and its effect on the overall performance of the repository system. TPA 4.1 is a probabilistic performance assessment code that was jointly developed by the NRC and Center for Nuclear Waste Regulatory Analyses (CNWRA) to simulate various natural and repository-induced events and processes that may affect the long-term performance of the proposed repository.

NRC intends to use TPA 4.1 to obtain insights into the performance of the repository system and assist in their review of any license application submitted by the Department of Energy. The code can be used to probe assumptions made by the Department of Energy, investigate the significance of alternative models, and identify the most important barriers in the repository system to risk-inform the review.

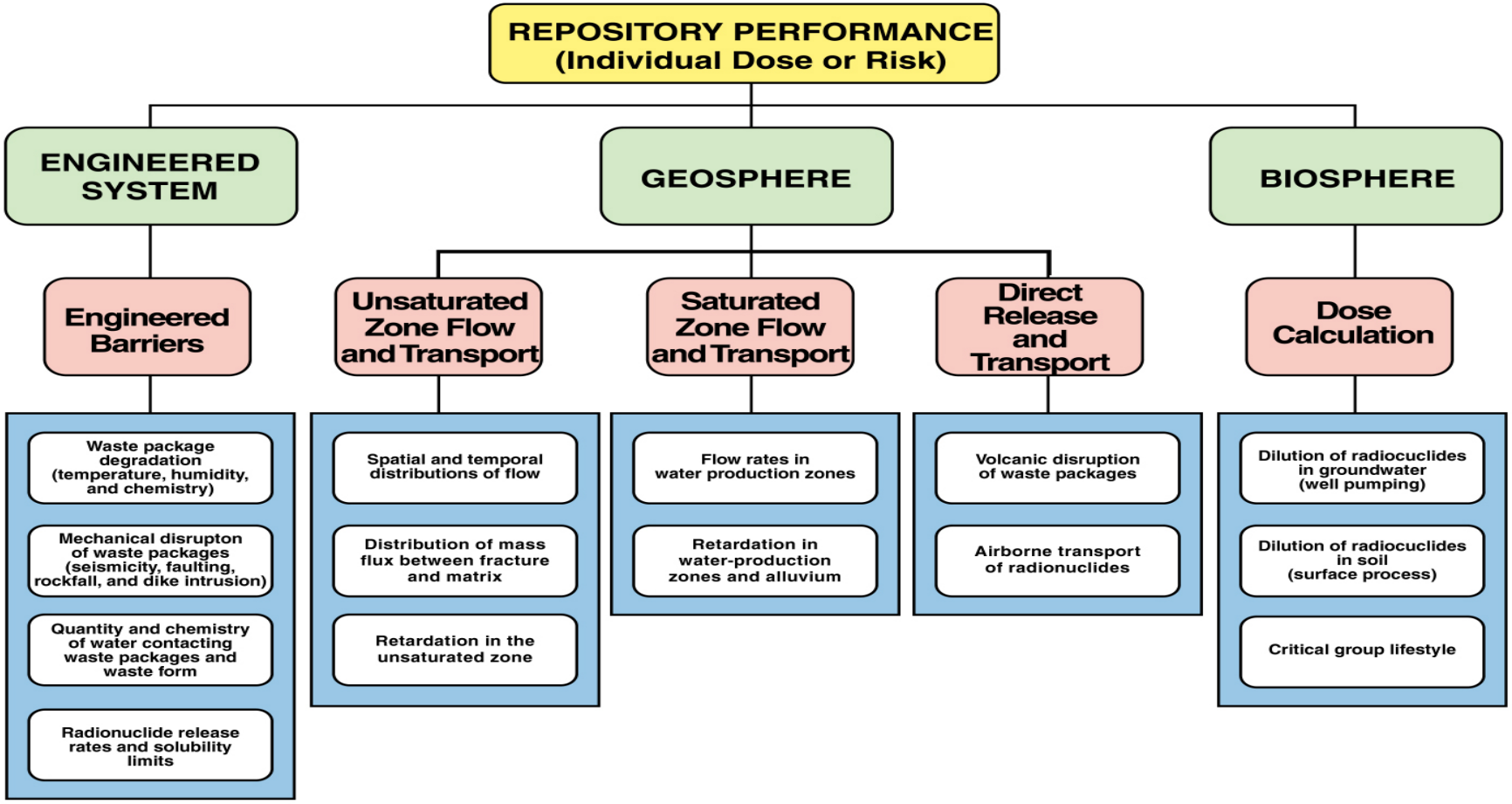
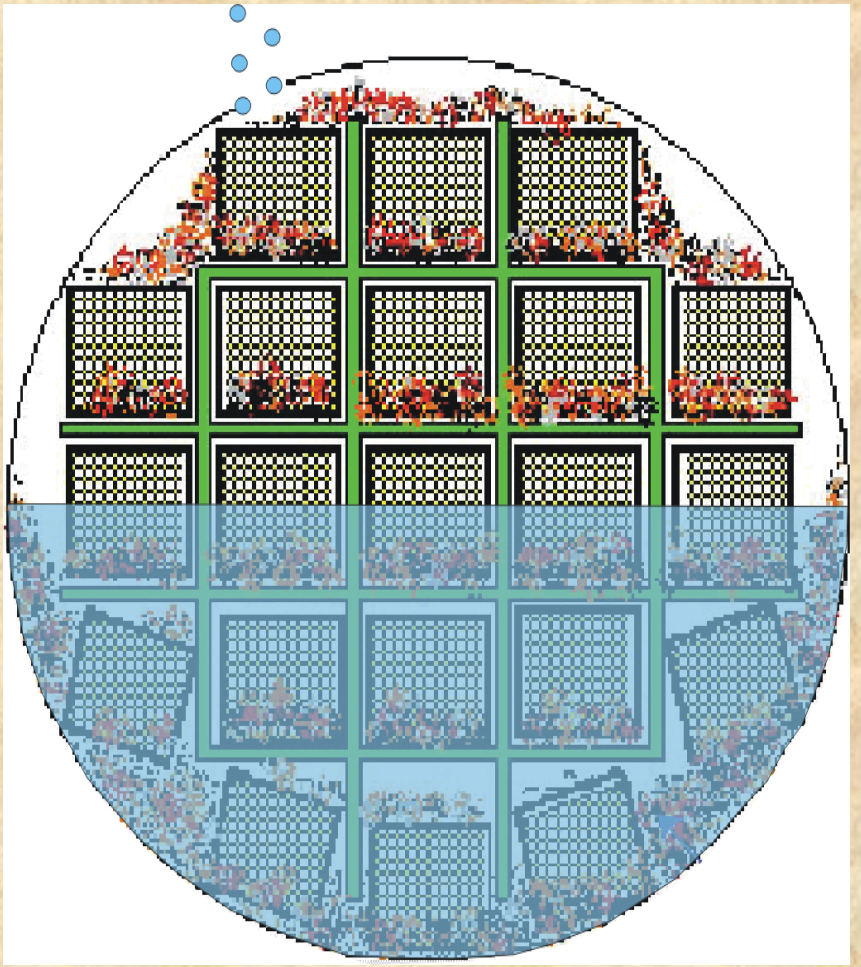


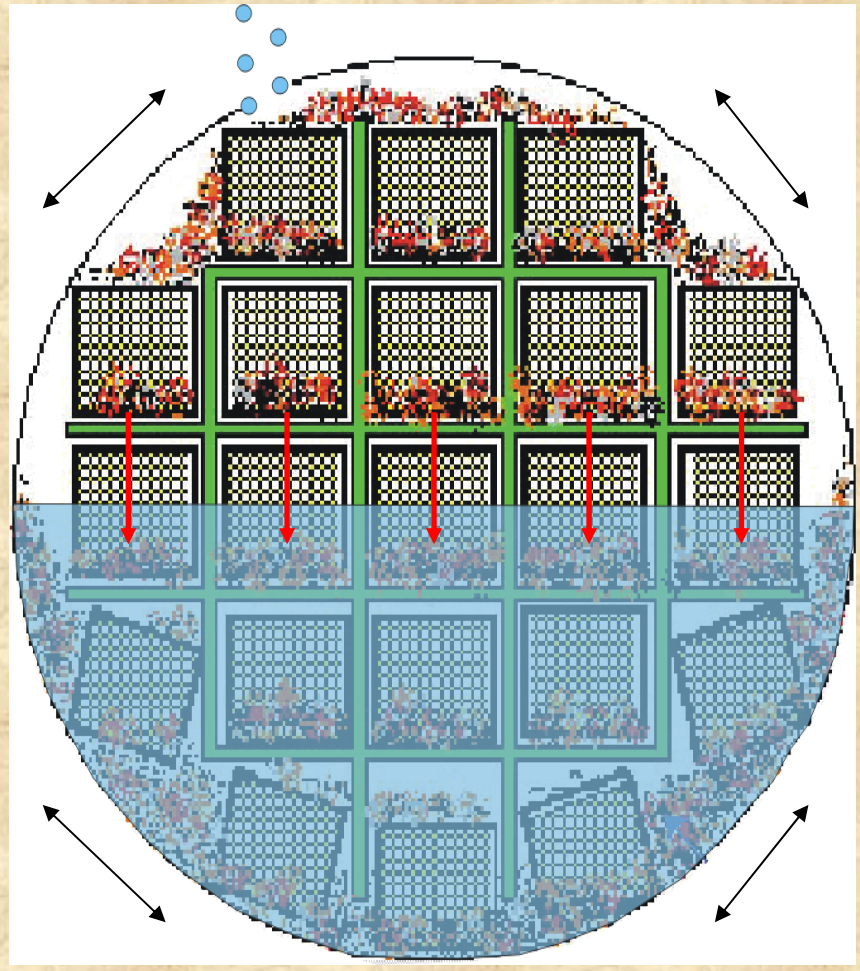
Figure 3. **The repository system is discretized into subsystems. The features, events, and processes in each of these subsystems and interactions among various components of the subsystems are modeled in the TPA 4.1. This paper evaluates the risk significance of criticality to determine whether criticality models should be developed for the TPA 4.1 for estimating overall performance.**

Figure 4. **Internal view of a waste package corroding and filling with water.**



Following waste package breach, water can fill the waste package as long as the bottom of the waste package is intact. As the water collects in the waste package, the internal structures of the waste package will corrode, releasing the neutron poison into solution. Neutron poison loss will begin when the water reaches a level where it can flow out of the waste package. If the waste package bottom remains intact while a sufficient fraction of the poison is removed, some of the spent nuclear fuel could go critical.

Figure 5. **Motion induced by seismic events could initiate a transient criticality event.**



Seismic events could cause a rapid insertion of reactivity by shaking the waste package so that several fuel assemblies, held above the water level by degraded internal structures of the waste package, would drop into the water. This rapid insertion of reactivity could result in a transient criticality with a rapid increase in temperatures and pressures in the waste package. Transient criticality could potentially cause mechanical damage to the fuel, waste package, and surrounding engineered barriers.

Objective

The objective of this study is to estimate the consequences of criticality events occurring inside waste packages in a high-level nuclear waste repository.

The two consequences of a steady-state criticality that were evaluated are the increase in the radionuclide inventory and the additional heat generated by the event.

The consequence of a transient criticality was limited to the assessment of the mechanical damage to the fuel, waste package, and other engineered barriers.

Steady-State Criticality

An important factor in the determination of the consequences of a steady-state criticality is the power level that the waste package is able to maintain. The power level that can be maintained by a steady-state criticality over long periods of time is dependent on the rate at which water enters the waste package. As the power level goes up, the temperature will increase causing more water to be evaporated. This loss of water will cause the water level to fall, reducing the moderation and reactivity of the system. Therefore, the maximum steady-state power level cannot exceed the power corresponding to an evaporation rate equal to the rate at which water enters the waste package plus the power required to make up for heat lost to the surrounding rock.

In this paper, the potential effects of criticality were bounded by a conservative analysis. It was assumed that at year 5,000 all failed waste packages go critical and remain critical for 10,000 years. The analysis evaluated whether the generation of additional radionuclides and the increased temperature from the criticality event significantly affected the repository performance.

To calculate the power level that could be maintained for a long-term steady-state criticality event, the heat loss from a waste package to the surrounding environment must be calculated. Assuming that there is no backfill in the repository, the heat loss from a waste package is given by[1]:

$$Q_{wp}=(G_{rad}+G_{conv}+G_{cond})(T_{wp}-T_{rock})$$

where Q_{wp} is the thermal output of the waste package (kW), G_{rad}, G_{conv}, and G_{cond} are the effective thermal conductance for radiative, convective, and conductive heat transfer (kW/°C), T_{wp} is the temperature of the waste package (° C) and T_{rock} is the temperature of the rock (°C).

The power level in the waste package must be sufficient to make up for heat losses to the environment and maintain an evaporation rate of water equal to the rate at which the water enters the waste package.

The power level for a steady state criticality is therefore limited to[2]:

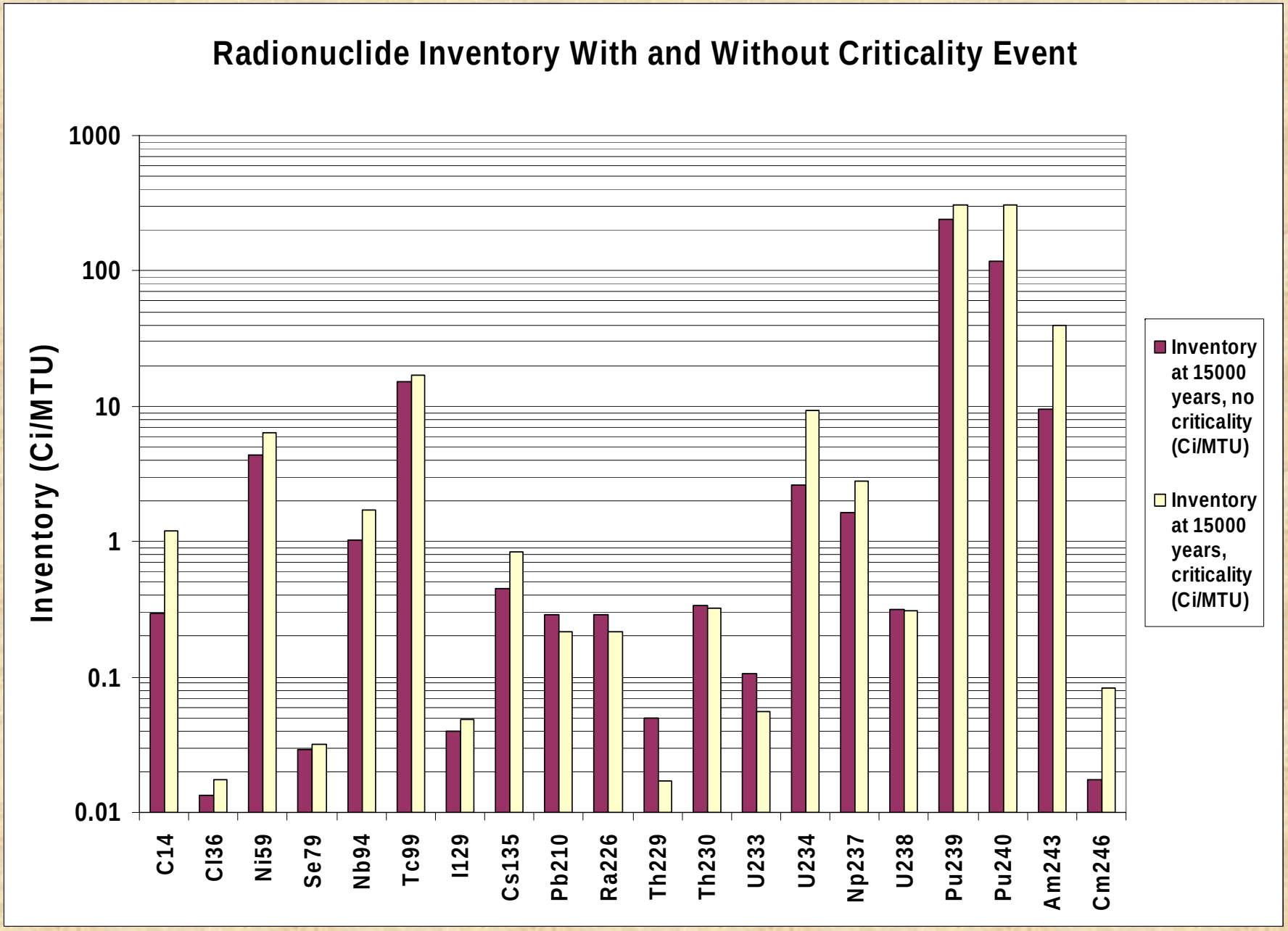
$$P_{wp} = Q_{wp} + \dot{m}\,(h_2 - h_1)$$

where P_{wp} is the power level (kW), $\dot{m}$ is the water mass flow rate (kg/sec) into the waste package, h_2 is the enthalpy of the water before evaporation (kJ/kg), and h_1 is the enthalpy of the water after evaporation (kJ/kg).

Use of a reasonably high water flow rate[3] into the waste package of 0.1 m^3/yr results in the calculation of a power level of 4.8 kW. This power level is used to calculate the increase in radionuclide inventory due to the criticality event.

The ORIGEN 2.1 computer code[4] was utilized to calculate the increase in radionuclide inventory due to a 10,000-year steady-state criticality event with a power level of 4.8 kW. This results in an additional burnup of about 17,500 MWd/MTU, which is about 40 percent of the burnup of an average PWR fuel assembly. The changes in the inventory of the key radionuclides are charted in figure 6.

Figure 6. **Effect of a long-term steady-state criticality on radionuclide inventory.**



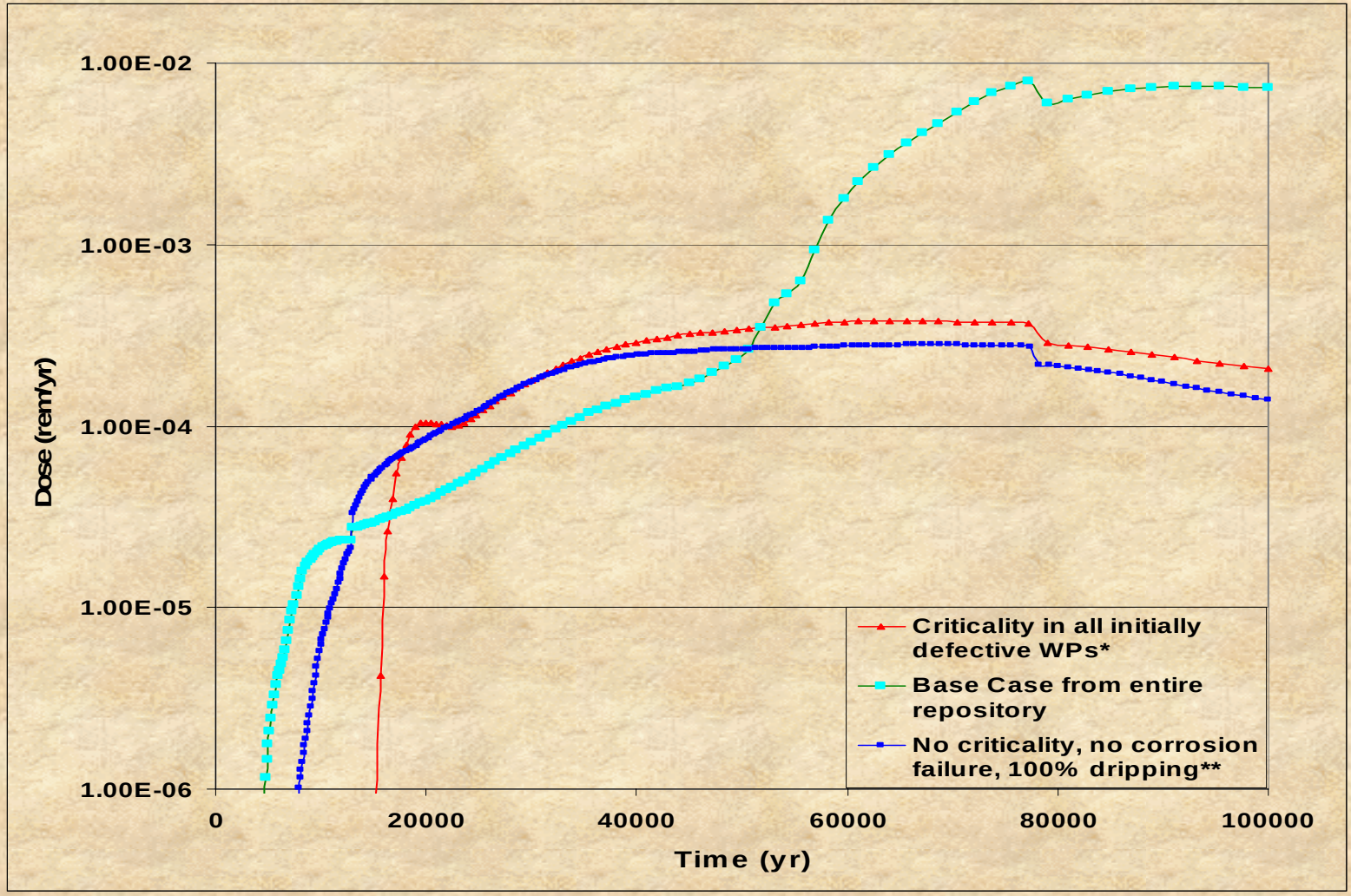
The calculated inventory was input into the TPA 4.1. Other modifications to the reference input data set included:

- **Increasing the temperature in the waste package by 25 °C to simulate the temperature increase due to criticality event**
- **Forcing dripping into all breached waste packages because water is necessary to achieve criticality; in reality water may not drip into some breached waste package**
- **Stopping water flow out of the waste package during the criticality event to simulate evaporation of all water from the added heat**
- **Turning off all other waste package failure modes to calculate the effects of only those waste packages that are assumed to go critical**

For additional comparison, an additional case was run with the TPA 4.1 that represented the base case with dripping on all waste packages that were failed at year 5000 and no additional waste package failure beyond this time. This case allows separation of the direct effects of the criticality event and the modeling assumptions that were made to represent the event and is identified as "No criticality, no corrosion failure, 100 percent dripping."

Results: Steady-State Criticality

Figure 7. **Effect of steady-state criticality on repository performance**



*Dose dominated by Tc-99, I-129, and Np-237

** 100% of the waste packages are dripped upon so water can enter the waste package

Transient Criticality

A transient criticality event would not generate a significant quantity of additional radionuclides due to the short duration of the event. However, the high pressures and temperatures generated by the event could cause significant mechanical damage to repository components. Different assumptions about the rate of insertion of reactivity and processes that would end the transient criticality event could result in significant variations in the consequences of the event.

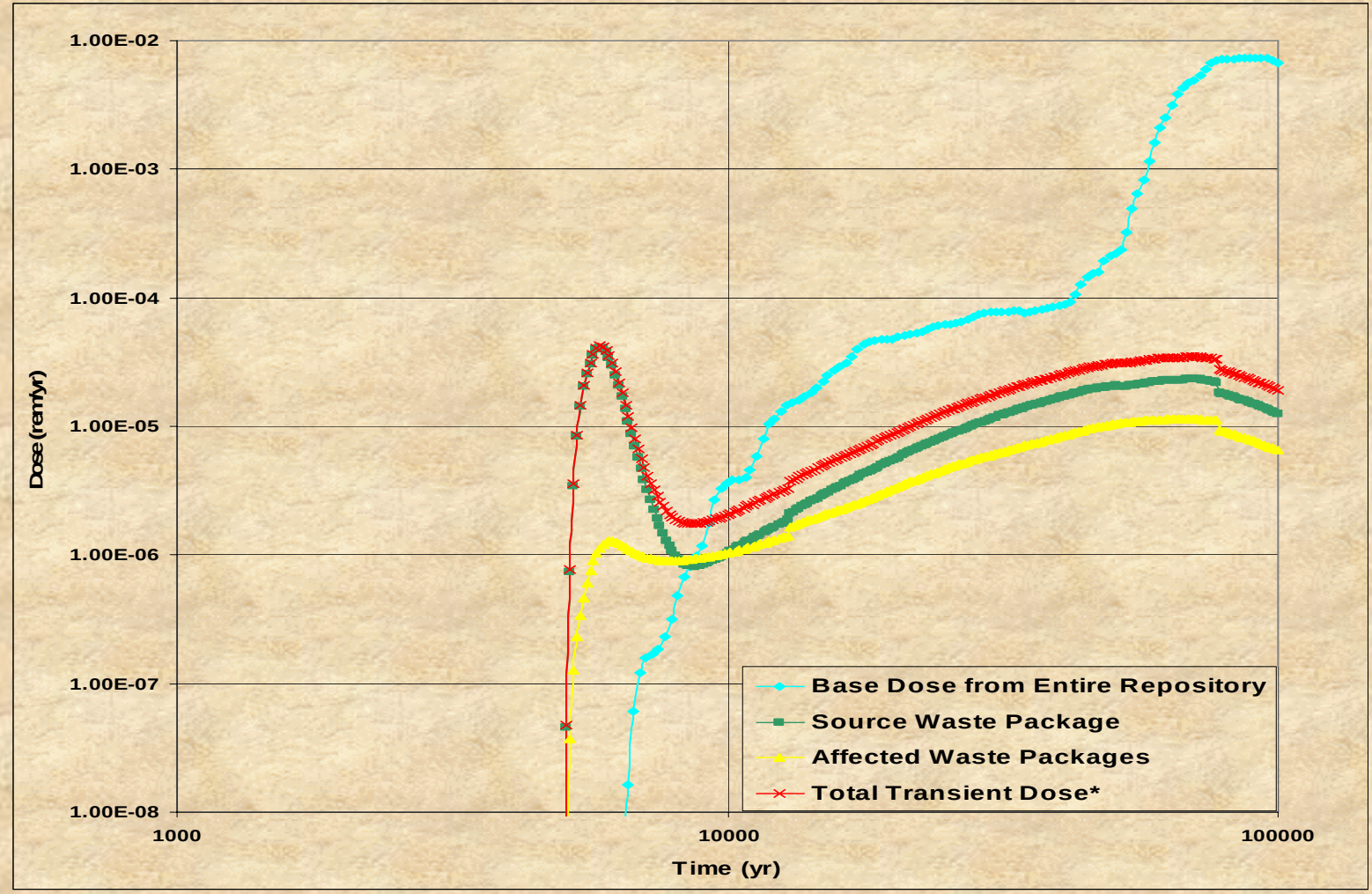
To reduce speculation, a bound on the damage resulting from the transient criticality was identified so that the consequences of this bounding event could be determined. If this bounding dose could be determined to be relatively minor, more detailed calculations of the consequences of the event would not be necessary. It was again assumed that the criticality event occurred at year 5,000.

The mechanical effects of the transient criticality were assumed to cause the following damage to the repository components:

- **All fuel within the source waste package (the waste package in which the transient criticality occurs) was assumed to be degraded very quickly into small particles available for removal through advective release**
- **One waste package on each side of the source waste package was assumed to be breached (referred to as affected waste packages)**
- **The drip shield above the source waste package and the affected waste packages were assumed to fail and not provide any further protection**
- **The invert below the source waste package and the affected waste packages was assumed to be degraded such that radionuclides were not retarded within it**

Results: Transient Criticality

Figure 8. **Effect of transient criticality on repository performance.**



***Peak dose dominated by Tc-99 and I-129**

Discussion of Results

Based on the results of this simplified analysis, both the steady-state and transient criticality cases show a moderate increase in dose following a criticality event. However, these results do not incorporate the probability of a criticality event occurring in the repository. Due to factors such as the long projected lifetime of the waste package, variations in initial enrichment and burnup of the fuel, the limited fraction of waste packages that will be dripped upon, and the potential for failures to occur on the bottom of the waste package, the probability of criticality within a waste package is considered within the 10,000 year regulatory period of interest.

The proposed NRC (10 CFR Part 63) and EPA (40 CFR Part 197) regulations for the repository both specify a limit on the probability-weighted dose. It is necessary to weigh the dose from a criticality event by an appropriate probability of occurrence for either the steady-state or transient criticality in order to appropriately compare the results to either the base case results or the proposed regulatory requirements. However, we did not estimate the probability of such an event.

Summary and Conclusions

The results of this analysis indicate that the occurrence of an in-package criticality event would moderately increase the dose to the critical group from a high-level nuclear waste repository at Yucca Mountain, Nevada.

A conservative calculation of the consequences of a steady-state criticality indicates that with conservative consumption, the conditional dose rate to the critical group can be three times the dose rate from the basecase scenario. Some of this increase is due to the modeling assumption that all failed waste packages are located where water drips from the drift ceiling.

A conservatively simplified calculation of the consequences of a transient criticality show a large peak dose shortly after the event is assumed to occur that is ten times the dose from the peak dose within 10,000 years in the basecase scenario. The peak dissipates quickly however.

The results presented do not incorporate the probability of the event and represent relatively conservative assumptions regarding the consequences of a criticality event. Factoring in the probability of the criticality event into the results or reducing the level of conservatism in the calculations would likely reduce the magnitude of these effects compared to the results for the most likely scenario.

Additionally, assessments of postclosure performance contain large uncertainties and the TPA 4.1 is frequently updated to reflect new information collected about the site, so results obtained in this analysis may change as models within the code are updated and improved upon.

References

1. Mohanty, S. and T. J. McCartin. Total-system Performance Assessment Version 3.2 Code: Module Descriptions and User's Guide. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses. 1998.
2. Sonntag, R. and G. Van Wylen. Introduction to Thermodynamics: Classical and Statistical. New York, NY: John Wiley & Sons. 1991.
3. Civilian Radioactive Waste Management System M&O. Total System Performance Assessment for the Site Recommendation. 2000. TDR–WIS–PA–000001. Rev. 00. ICN 01. Las Vegas, NV: TRW Environmental Safety Systems, Inc.
4. Oak Ridge National Laboratory. ORIGEN 2.1–Isotope Generation and Depletion Code. CCC-371. Oak Ridge, TN: Oak Ridge National Laboratory. 1991.

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