Factors Affecting Radiation Dose from a Hypothetical Extrusive Volcanic Event at Yucca Mountain, Nevada

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ABSTRACT

This paper describes the factors that could affect doses to the reasonably maximally exposed individual (RMEI) as a result of a hypothetical extrusive igneous event at Yucca Mountain. Based on available information, there is no evidence that most of the spent fuel in waste packages intersected by a volcanic conduit would be reduced to fine-grained material and subsequently erupted as volcanic ash.

INTRODUCTION

One of the factors affecting the performance of the Department of Energy's (DOE's) proposed high-level radioactive waste repository at Yucca Mountain is a potential volcanic eruption that could intersect the repository, since the site of the proposed repository is in a field of ancient volcanoes.

Eighty thousand years ago a small-volume basaltic volcano, Lathrop Wells, erupted 20 km south of the proposed repository (Fig. 1). This is one of the infrequent basaltic volcanoes that erupted near Yucca Mountain during the past 10 million years. In spite of uncertainties and differing views about igneous processes in the region, there is general agreement that either extrusive or intrusive igneous activity may occur. The extrusive scenario (a surface eruption) could cause the larger risk, greatest during the first thousand years after repository closure, when the inventory of relatively short-lived radionuclides is largest. The nature of igneous activity that could occur would likely be similar in composition, structure, and style to the Lathrop Wells volcano.

A number of waste packages could be destroyed in the extrusive scenario, and some of the spent fuel contents could be reduced to small particles dispersed by the eruption plume. This deposited particulate matter can be remobilized by surface water or wind to the vicinity of the Reasonably Maximally Exposed Individual (RMEI), resulting in a radiation dose. Radionuclides can persist in the environment, causing exposure hundreds to thousands of years after the event. However, erosion and mixing with uncontaminated soil will decrease the concentration of radionuclides and the resulting exposure.

In wind (eolian) transport, deposited ash is resuspended and carried downwind, although the shape and footprint of the resuspended ash depends on particle size and density and on meteorological conditions. Water (fluvial) transport depends on water volume and speed and on the predominant direction of water flow. Both eolian and fluvial dispersion can carry suspended particles past the RMEI. The further material is carried, the more dilute the plume.

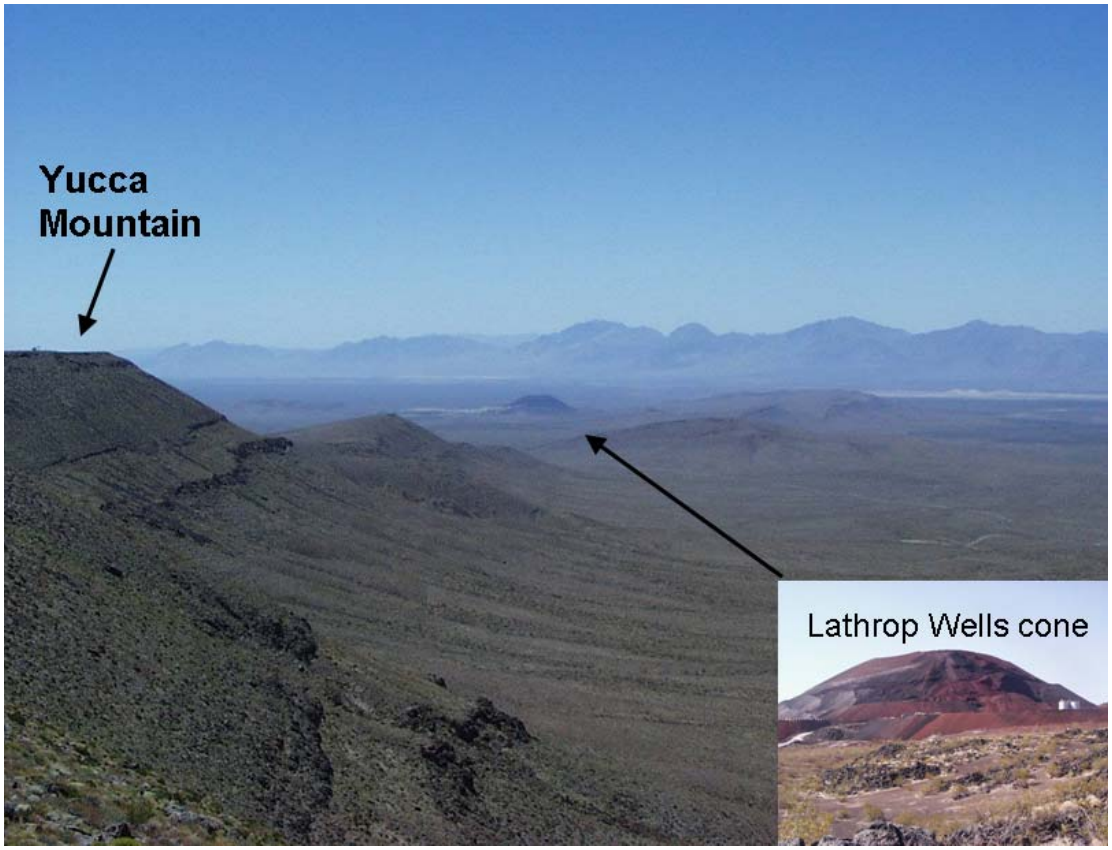

Fig. 1. The Lathrop Wells volcanic cone as seen looking south from Yucca Mountain.

Radioactively contaminated ash could deliver an external dose from groundshine, an external dose from cloudshine, an ingestion dose, and an inhalation dose. Groundshine would be significant only at the time of the eruption. Cloudshine is rarely significant.[1]

An ingestion dose to the RMEI would depend on uptake of radionuclides by food crops. Smaller particles and dissolved material are more likely to be taken up than larger particles. Lee et al. [2] observed that a ten-fold increase in rainfall would be needed to provide enough water for locally grown crops. The groundwater used for irrigation [3] would not be affected by surface remobilization of contaminated ash. Any ingestion dose would probably be limited to meat and milk. Some fallout could be absorbed by pasture-type vegetation but there is not enough locally grown alfalfa to maintain either beef or dairy cattle[1]. Therefore, any ingestion dose would be a negligible contributor to a radiation dose to the RMEI.

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[1] As was observed in the 2004 ACNW&M tour of the Amargosa Valley, the one commercial farm, a dairy farm, imports most of its alfalfa.

An inhalation dose would be the only significant dose to the RMEI and would likely be a small fraction of the dose standard. This 50-year committed effective dose equivalent (CEDE) depends on metabolism and particle size. Dose conversion factors (DCFs) for each radionuclide [4-6] reflect the energy absorbed by various organs and the type of radiation; these are specific to the exposure pathway and the absorbing organ, and take into account radioactive decay and physiological elimination.

The number of waste packages possibly damaged or destroyed by extrusive volcanism depends on the diameter of a volcanic conduit intersecting a repository drift. The DOE has estimated a median of ten waste packages that would be disrupted in an eruption scenario. The NRC currently assumes that volcanic conduits would have an average diameter of ~50 m. If the center of a conduit and the axis of a drift coincided, then ~5 waste packages could be entrained and their contents potentially transported to the surface. The latest estimate of the average conduit diameter at the Lathrop Wells volcano is about 8-9 m.[7] If the lavas and fallout deposits at Lathrop Wells have a similar xenolith content, the added volume of xenoliths would imply a maximum average conduit diameter of about 21 m, which would limit the number of waste packages that could become entrained. The latter estimates represent the most current and plausible conduit diameter.

Assumptions about volcanic conduit diameter significantly affect dose estimates for volcanic intersection of a geologic repository. Final results of the Probabilistic Volcanic Hazard Assessment-Update (PVHA-U) expert elicitation will not be available until 2008, but are expected to provide the best available estimate of conduit diameter at repository depth.

POTENTIAL FATE OF HIGH-LEVEL WASTE IN A VOLCANIC CONDUIT

Available information provides practical insights about the plausible fate of high-level radioactive waste (HLW) if it should become entrained within a volcanic conduit and transported to the surface. The following points need to be considered in a realistic assessment of volcanic processes.

Most of the waste planned for disposal at Yucca Mountain consists of spent nuclear fuel rods from PWR and BWR reactors. The physical form of the waste is ceramic pellets of $UO_{2,}$ about a centimeter in diameter, with a melting point of >2800°C. This is much higher than the magma temperatures of 1000-1200°C.

A volcanic conduit is not born full size. Its diameter increases as the eruption proceeds. This means that only one nuclear waste package could be initially entrained in the conduit, with others becoming entrained within the final radius of the conduit at depth. Therefore additional waste packages would be exposed to varying stages of the eruption sequence. It is also possible that a conduit intersecting a repository could form in the separation distance between drifts, and although an intrusive event could occur, no waste packages would be directly intersected by the conduit. Volcanic conduits would be significantly smaller 300 m below the surface at repository depth than at ground surface (Fig. 2). This would minimize the number of waste packages that could be intersected by a conduit. Lithostatic pressure keeps the opening smaller at depth, whereas at the surface the vent periphery in the zone of fragmentation grows in diameter through active erosion by expelled tephra. As discussed previously, Valentine et al. [7] reported they have now better constrained the conduit size at depth based on studies at the Lathrop Wells cone.

Present information shows that dikes are more likely to be injected into pre-existing faults and tend to form in basins more often than on ranges. Conduits form along dikes, therefore if the

DOE continues to use a “setback” strategy from major faults (places waste tunnels at a minimum distance from faults), this would reduce the likelihood of a hypothetical extrusive event impacting the repository.

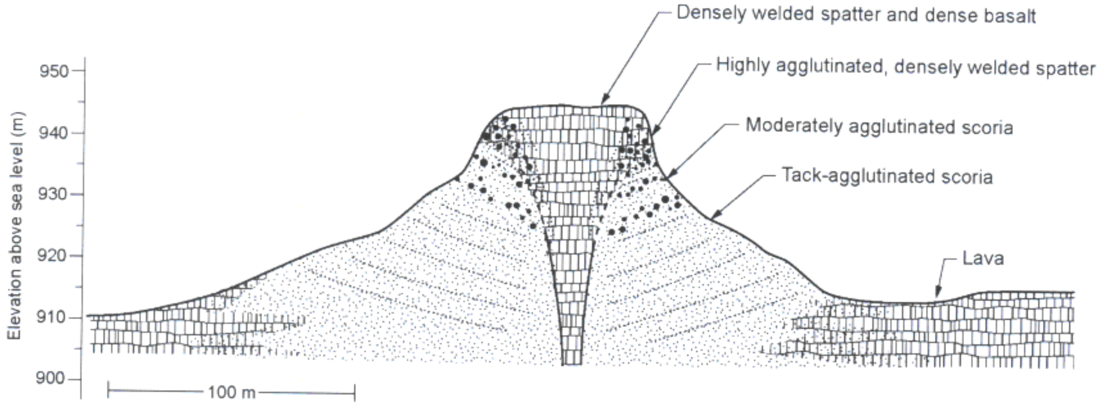

Fig. 2. Schematic cross-section through Shirtcollar Butte, Crater Flat, Nevada, a Pliocene (3.7 Ma) basalt volcano. The degree of fusing and welding of scoria increases up-section and grades into dense basalt on the top of the butte. [11]

The expected time of travel in a conduit from repository depth to the surface would be approximately one minute or less. This allows little time for erosion of ceramic pellets, but does permit rapid quenching of magma onto the relatively cold waste packages and their contents. The formation of a quench rind on waste pellets would protect them during their rapid transit to the surface within a flowing column of frothy magma. This protective quenching effect in volcanic conduits has not been considered in the DOE and NRC performance assessments.[8-10]

Since the time of Total-System Performance Assessment (TPA) version 3.2 [12, 13], the NRC has used relatively consistent assumptions about the size range of spent fuel particles that would hypothetically be incorporated in volcanic ash. Fuel particle sizes using a triangular distribution from 1-100 microns (Fig 3) are sampled in the TPA. For comparison, a grain of table salt is about 100 microns across, and a grain of talcum powder is about 10 microns across. The low end of the NRC size range is at 1 micron, which happens to be the wavelength of light in the near infrared band (just above the wavelength of visible light). A study by the Center for Nuclear Waste Regulatory Analyses (CNWRA) [14] suggested a triangular distribution from 0.01 to 1.0 cm (100 to 10,000 microns), based on the observed fracturing and crazing of irradiated fuel pellets, as shown in Fig. 4.

A variable range of spent fuel particle diameters is to be expected. However, in documenting the assumed distribution for the size range of spent fuel particle size, TPA 4.0, Mohanty et al. [15] cite an NRC handbook that evaluated the consequences of major accidents in nuclear fuel cycle facilities. Review of this report shows that it does not support the use of a greatly reduced size range for particle sizes. It instead suggests that a larger size range should be used for ejected fuel particles. Ayer et al. [16, pp. 4.87-4.103] present results of crush-impact experiments on glass, aggregates, and ceramics, including spent UO_2 fuel pellets. Fig. 5.a. is taken from this report, and shows results of crush-impacts on fuel pellets that had previously been irradiated. About 2% of the fuel (by weight) was reduced to particles smaller than 1000 microns. Reardon et al. [17] reported results of crushing tests at energies of 10 to 1000 J/gram using irradiated fuel (22 and 33 GWd/MTU KWO). At 10 J/gram, <30% of the mass of irradiated fuel was reduced to particle sizes <100 microns, and <10% of the mass was reduced to <10 microns. At 1000 J/gram, ~60% of the mass was reduced to less than 100 microns and <30% was reduced to under 10 microns. These size fractions do not consider the effects of fuel cladding or magma quenching on ejected waste particles in volcanism scenarios, which would significantly increase particle diameters.

Calculated doses are highly sensitive to assumptions about fuel particle size because of the strong dependence on respirability, which decreases sharply as particle diameters increase beyond 10 microns. The TPA code, version 4.1J, using several particle size distributions as input, was used by the ACNW&M staff to assess the sensitivity of dose estimates to fuel particle sizes assumed in the volcanism scenarios. Using a size range of 100-10,000 microns (also see test data set in Manteufel et al., [18] results in approximately a 200-fold reduction in calculated dose as compared to the range of 1 to 100 microns, which indicates significantly reduced consequences from extrusive volcanism. Using an intermediate fuel size range of 10-1000 microns reduces calculated dose by a factor of 2. [9]

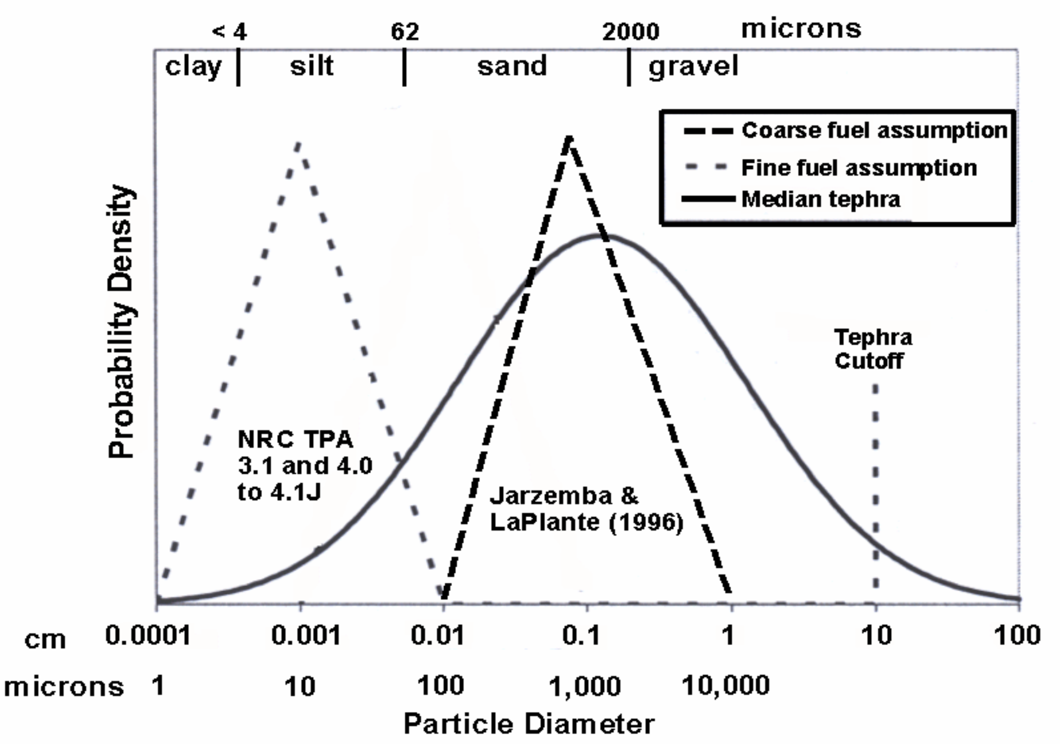

Fig 3. Median tephra diameter distribution plotted with spent fuel particle size distributions used in TPA versions 3.1 to 4.1. For comparison, the size distribution suggested by Jarzemba and LaPlante [14] is also shown. The Wentworth scale of particle sizes appears at top of figure for comparison. The intermediate size distribution used by Codell [9] is not shown, but is a triangular distribution that ranges from 10 to 1000 microns. The distribution for median tephra particle diameter is a sampled parameter in the TPA code. The distribution of tephra particle sizes was postulated by Hill et al. [19] based on data from the 1995 Cerro Negro eruption.[9] The tephra "cutoff" identifies the maximum particle size that can be transported through convective dispersal [15, p. A-165]. Particles larger than 10 cm would fall in close proximity to the volcanic vent.

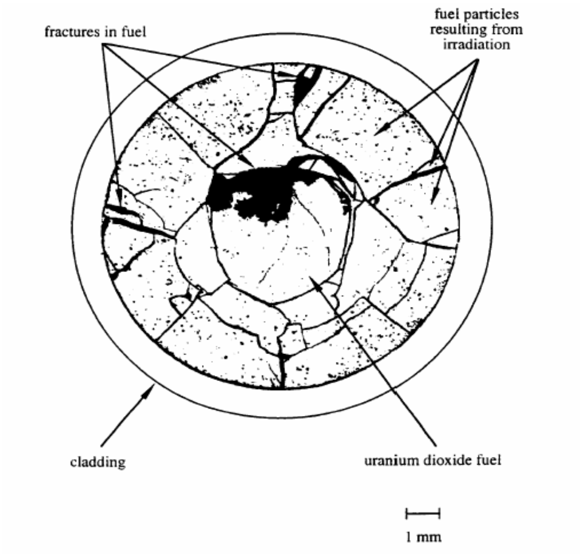

Fig. 4. Cross-section of a fuel pellet after irradiation in a reactor.[14]

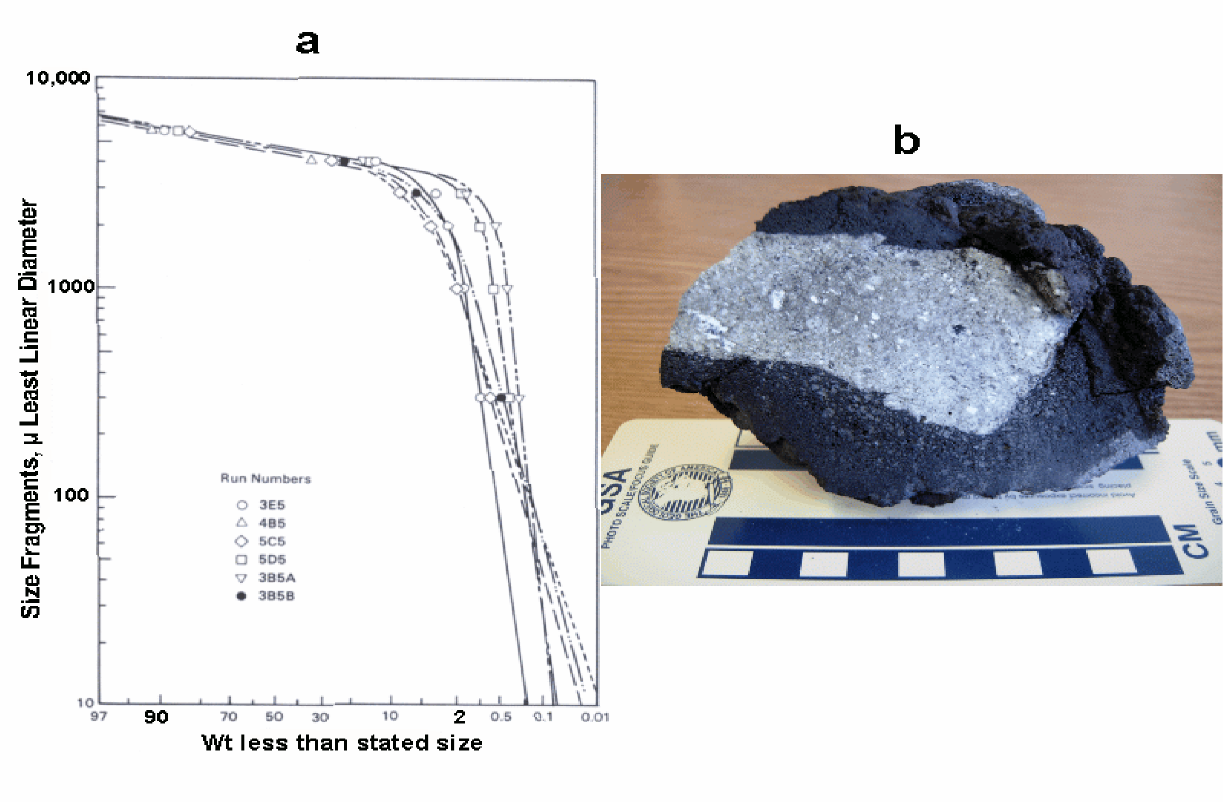

Fig. 5. Crush-impact experimental results and photo of basalt rind

a. Crush-impact experimental results - size distribution of fragments from fuel pellets irradiated to 6000 MWd/MTU. (Ayer et al., Figure 4.12 [16])

b. Tuff xenolith with basalt rind, collected from the scoria cone at Lathrop Wells. Scale is marked in cm.

The relative volume of ash deposits vs. volume of scoria cone and lava flows can be used to estimate practical limits on the fraction of ejected waste in the form of fallout that could be available for fluvial and eolian transport. The 80,000 year old Lathrop Wells Cone is larger in volume than the older Pleistocene-aged Red Cone and Black Cone in Crater Flat (see [7]). The Department of Energy (DOE) [20] estimate the total volume of eruptive products at Lathrop Wells at ~0.09 km^3 (cone, 0.02 km^3; lavas, 0.03 km^3; fallout, 0.04 km^3). Valentine et al. [21] estimated a larger fallout volume of 0.07 km^3. The fallout comprised approximately half of the eruptive products. Ash fallout (inferred violent Strombolian eruptive style) accounts for a fraction of total products of an individual volcano. At Lathrop Wells the fallout volume is about 1.4 times the cone plus lava volumes. Waste incorporated in lava flows or scoria cones would be protected from erosion and transport for many hundreds of thousands of years, as demonstrated by the million-year-old cones and flows in Crater Flat near Yucca Mountain. Over this time scale the lava flows experienced little erosion. The scoria cones have experienced erosion during the pluvial climates of the Quaternary, when the climate of Yucca Mountain was significantly wetter than today for most of the time. Valentine et al. [7] document that these cones are highly eroded, and only remnants of the inward dipping beds of the inner cones are preserved at Red and Black cones. However, entrainment of waste in scoria cones would immobilize the waste far beyond the time of peak risk from extrusive volcanism. The Electric Power Research Institute (EPRI) [22] also noted that waste could also be entrained within lava, as well as in tephra. The solidified lava presents a mechanically durable matrix for entrained and dissolved radionuclides. Both erosion and aqueous dissolution are mechanisms that may lead to subsequent release, but Quaternary age and older lava flows are well preserved in the arid environment surrounding Yucca Mountain.

At Lathrop Wells, lithic fragments of conduit wall rock (tuff) are commonly found embedded within the scoria that make up the cinder cone.[23] The nonwelded to partly welded tuff fragments were eroded from the walls of the volcanic conduit, vary in size from a fraction of a cm to 6 cm or larger, and have quenched rinds of basalt. Fig. 5.b. shows a xenolith 9 cm long that was collected by ACNW&M staff at Lathrop Wells. These expelled wall rock fragments are so abundant that they have been used to estimate the eroded volume of the Lathrop Wells conduit.[21] The size of the lithic fragments suggests that spent nuclear fuel pellets and fragments could be expelled in similar fashion during the cone-building phase of an eruption, intact and with protective quench rinds. The result is that entrained HLW would be likely to remain in relatively large fragments that would be deposited in or near a tephra cone, rather than as far-strewn, fine-grained ash. A xenolith 30 cm in diameter has been found at the Lathrop Wells cone.[23] The existence of this and many other xenoliths is further evidence that UO_2 pellets and fragments could be expected to survive relatively intact over the short conduit travel distance from repository depth to the surface (only ~300 m). This is especially true for the period of greatest hazard from a volcanic event (i.e., the first 1000 years) when waste packages and waste forms should still be relatively intact.

Based on available information about properties of UO_2 fuel and volcanic processes, including consideration of magma quenching and observations of xenoliths, there is no evidence that most of the spent fuel contained in HLW packages intersected by a volcanic conduit would be reduced to fine-grained material and subsequently erupted and transported as volcanic ash. A significant fraction of waste would likely be entombed in a scoria cone and lava flows. Use of a more realistic size range for spent fuel particle sizes would lead to substantially lower doses, based on analysis using TPA 4.1j. NRC has now updated this code and its accompanying user's guide. The revised code version is TPA 5.1.[24]

For an extensive review of technical views about hypothetical volcanism at Yucca Mountain, we refer readers to a report by NRC's Advisory Committee on Nuclear Waste and Materials (ACNW&M).[25]

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REFERENCES

1. K. S. NEUHAUSER, F. L. KANIPE, AND R. F. WEINER, 2000, “RADTRAN 5: Technical Manual” Report No. SAND2000-1256, Transportation Safety and Security Analysis Department, Sandia National Laboratory, Albuquerque, NM, 148 pp. (2000) [Available online at: https://radtran.sandia.gov/docs/SAND2000-1256.pdf].

2. M. P. LEE,., N. M. COLEMAN, AND T. J. NICHOLSON, , History of Water Development in the Amargosa Desert Area: A Literature Review, U.S. Nuclear Regulatory Commission, *NUREG-1710, Vol. 1*, February (2005)

3. J.M. FENELON and M. T. MOREO, Trend analysis of ground-water levels and spring discharge in the Yucca Mountain region, Nevada and California, 1960-2000, U.S. Geological Survey Water-Resources Investigations Report 02-4178, 97 pp. (2002) [available online at: http://pubs.usgs.gov/wri/wrir024178/wrir024178.pdf].

4. K. F. ECKERMAN and J. C. RYMAN, External Exposure to Radionuclides in Air, Water, and Soil, US EPA, Washington, DC. (1993)

5. K. F. ECKERMAN, R. W. LEGGETT, C. B. NELSON, J.S. PUSKIN, A.C.B RICHARDSON, Cancer Risk Coefficients for Environmental Exposure to Radionuclides. US EPA, Washington, DC (1999)

6. R. W. LEGGETT, and K. F. ECKERMAN, Dosimetric Significance of the ICRP’s Updated Guidance and Models, 1989-2003, and Implications for U.S. Federal Guidance. ORNL/TM-2003/207. Oak Ridge National Laboratory (2003)

7. G. A. VALENTINE, F. V. PERRY, D. KRIER, G. N. KEATING, R. E. KELLEY, A. H. COGBILL, Small-volume basaltic volcanoes: Eruptive products and processes, and posteruptive geomorphic evolution in Crater Flat (Pleistocene), southern Nevada, *GSA Bulletin*, v. 118, Nov.-Dec., pp. 1313-1330, doi:10.1130/B25956.1. (2006)

8. S. R. MOHANTY,. CODELL, J.M. MENCHACA, R. JANETZKE, M. SMITH, P. LAPLANTE, M. RAHIMI, A. LOZANO, System-Level Performance Assessment of the Proposed Repository at Yucca Mountain Using the TPA Version 4.1 Code. CNWRA Report 2002–05. Rev. 2. San Antonio, Texas, NRC Accession No. ML041350316. (2004)

9. R. B. CODELL, Alternative igneous source term model for tephra dispersal at the Yucca Mountain repository, Nuclear Tech., 48, 205-212 (2004)

10. DOE (U.S. DEPARTMENT OF ENERGY) Volcanic Events, Tech. Basis Doc. 13, Bechtel SAIC Co., LLC, Las Vegas, NV (2003) [Available at http://www.ocrwm.doe.gov/documents/38453_tbd/index.htm].

11. DOE (U.S. DEPARTMENT OF ENERGY), 2006, Probabilistic Volcanic Hazard Analysis Update Field Guide, May 1-4 (2006)
12. S. MOHANTY, Change pages to the Total-System Performance Assessment (TPA) Version 3.2 Code: Module Descriptions and User's Guide, January 11, 1999, CNWRA Report, NRC Accession No. ML033630530 (1999)
13. S. MOHANTY, S., and T. MCCARTIN, Total-System Performance Assessment (TPA) Version 3.2 Code: Module Description and User's Guide, CNWRA Report, NRC Accession No. ML040260387 (1998)
14. M. S, JARZEMBA, and P. A. LAPLANTE, Preliminary Calculations Of Expected Dose From Extrusive Volcanic Events At Yucca Mountain, CNWRA Report, NRC Accession No. ML040220041. (1996)
15. S. MOHANTY, T. J. MCCARTIN, D. W. ESH, Total-System Performance Assessment (TPA) Version 4.0 Code: Module Descriptions and User's Guide, CNWRA Report, NRC Accession No. ML031680620. (2002)
16. J.E. AYER, J. E., A. T. CLARK, P. LOYSEN, M. Y. BALLINGER, J. MISHIMA, P. C. OWCZARSKI, W. S. GREGORY, B. D. NICHOLS, Nuclear Fuel Cycle Facility Accident Analysis Handbook, NUREG-1320, U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards, Washington, DC. (1988)
17. P. C. REARDON, Y. R. RASHID, G. S. BROWN, On the particle size distribution of crushed spent fuel, Proceedings of the 3rd Intl. Conference on High Level Radioactive Waste Management, Vol. 1, pp. 137-142, Las Vegas, NV, April 12-16. (1992)
18. R. D. MANTEUFEL, R. D., R. G. BACA, S. MOHANTY, M. S. JARZEMBA, R. W. JANETZKE, S. A. STOTHOFF, C. B. CONNOR, G. A. CRAGNOLINO, A. H. CHOWDHURY, T. J. MCCARTIN, T. M. AHN, Total-System Performance Assessment (TPA) Version 3.0 Code: Module Descriptions and User's Guide, NRC Accession No. ML040200150 (1997)
19. B. E. HILL,, C. B. CONNOR, M. S. JARZEMBA, P. C. LA FEMINA, M. NAVARRO, W. STRAUCH, 1995 eruptions on Cerro Negro volcano, Nicaragua, and risk assessment for future eruptions, *Bull. Geol. Soc. of Am*. 110, 1,231-1,241. (1998)
20. DOE (U. S. DEPARTMENT OF ENERGY) Characterize Eruptive Processes at Yucca Mountain, Nevada. ANL-MGR-GS-000002, Rev. 01. (2003)
21. G. A. VALENTINE, D. J. KRIER, F. V. PERRY, G. HEIKEN, Eruptive and geomorphic processes at the Lathrop Wells scoria cone volcano, Journal of Volcanology and Geothermal Research 161, 57−80 (2007)
22. EPRI (Electric Power Research Institute), Scientific and Technical Priorities at Yucca Mountain, Report 1003335, December, (2003)
23. M. T. HEIZLER,., F. V. PERRY, B. M. CROWE, L. PETERS, R. APPELT, The age of the Lathrop Wells volcanic center: An ^{40}Ar/^{39}Ar dating investigation, *Jour. Of Geophys. Res*. 104, 767-804 (1999)
24. NRC (U.S. Nuclear Regulatory Commission), Total-System Performance Assessment (TPA) Version 5.1 Module Descriptions and User Guide, NRC Accession No. ML072710060025 (2007)

25. ACNW&M, Igneous Activity at Yucca Mountain: Technical Basis for Decisionmaking [White Paper], U.S. NRC, Washington, D.C. (2007) (http://www.nrc.gov/reading-rm/doc-collections/acnw/letters/2007/).

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