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subject: Low-Probability Rationale for Excluding Post-Closure Criticality at the Waste Isolation Pilot Plant along with Risk Perspective

ABSTRACT

The 1996 Compliance Certification Application to the United States Environmental Protection Agency (EPA) showed that both the probability and consequence of a post-closure criticality were low at the Waste Isolation Pilot Plant (WIPP), a bedded salt repository in southern New Mexico for disposing transuranic (TRU) waste from atomic energy defense activities. Most TRU waste destined for WIPP has low mass and concentration of fissile material. Furthermore, fissile solute has the natural tendency to disperse during transport over geologic time scales. As part of the periodic re-evaluation of WIPP about every 5 years, EPA asks for a renewed examination of features, events, and processes (FEPs) included or excluded from compliance calculations. Currently, some TRU waste is now packaged in criticality overpack containers that allow more mass and higher concentrations of plutonium in containers. Thus, an expanded evaluation of the criticality FEP after WIPP closure has been undertaken. This report first summarizes the formal qualitative low-probability rationale for screening post-closure criticality FEP presented in three related reports. Then, the paper updates past quantitative estimates of the low probability of post-closure criticality with an analogy to Oklo natural reactors. Next, the paper updates the low-consequence rationale. The direct consequences are very low because any post-closure criticality is isolated from humans, and the amount of fission products produced is much less than that already disposed at WIPP. The indirect consequences are imperceptible because the heat produced is less than already caused by normal decay of TRU waste, and any disruption of the repository is localized. Finally, the paper combines the quantitative estimates of low probability and low consequence to generate a weighted consequence to show that post-closure criticality has very low risk at WIPP. Hence, post-closure criticality is omitted from WIPP Compliance Re-certification Applications.

Keywords: post-closure criticality evaluation; features, events, and processes screening; transuranic radioactive waste disposal; safety assessment; performance assessment; Waste Isolation Pilot Plant

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FOREWARD

Several of the underlying nuclear calculations in reports referenced within this document were originally published by Oak Ridge National Laboratory (ORNL) to meet the requirements of the US Environmental Protection Agency's (EPA) implementing regulation, 40 CFR §194.32(e)(3). The ORNL calculations were relied on to justify the exclusion of nuclear criticality impacting the Waste Isolation Pilot Plant (WIPP) disposal system during the post-closure regulatory timeframe. This justification is performed in accordance with EPA "reasonable expectation" standard of proof given in 40 CFR §191.13(b) for the post-closure timeframe. This report is being issued outside of Sandia National Laboratories' Nuclear Criticality Safety Program that is governed under 10 CFR 830 and US Department of Energy (DOE) Order 420.1C, Chg. 3 without receiving that program's concurrence or dissension of the conclusions made within.

PREFACE

The important purpose of this report is to collect and summarize the qualitative reasoning presented in three reports and present a coherent formal low-probability rationale for excluding post-closure criticality from the 2026 Compliance Recertification Application for WIPP. Of lesser importance, this report also provides quantitative estimates of probability and consequence, which are combined as a complementary cumulative distribution function (CCDF) to provide a risk perspective.

The US Environmental Protection Agency (EPA) has regulatory authority for certifying the performance of the Waste Isolation Pilot Plant (WIPP) disposal system in isolating radionuclides over the next 10,000 years against its long-term environmental standard specified in 40 CFR 191. The US Department of Energy (DOE), responsible for WIPP, has designated Sandia National Laboratories (Sandia) to evaluate WIPP post-closure performance for EPA certification. Part of the performance assessment includes a formal analysis of all features, events, and processes (FEPs) that may impact WIPP isolation. EPA does not designate the post-closure criticality FEP for special consideration in 40 CFR 191. Rather, criticality is considered like all other FEPs.

Post-closure criticality in fissionable material disposed 600-m underground in bedded salt when humans are absent has been excluded from WIPP assessments since (1) the initial 1996 Compliance Certification Application to EPA, and (2) Compliance Re-certification Applications, conducted every 5 years thereafter, including the most recent Compliance Recertification Application in 2019. The EPA Standard, 40 CFR 191, is probabilistic and Sandia has developed a qualitative rationale that the occurrence of criticality has low probability in the post-closure timeframe, using EPA exclusion criteria specified in its implementing regulation, 40 CFR 194, at §194.32(e)(3) and the "reasonable expectation" standard of proof as described in §191.13(b).

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Tara LaForce, Mariah Garcia, and Anna Taconi of Sandia and G. Ross Kirkes of Piru Associates conducted the internal technical review. In addition, the author acknowledges those authors that contributed to the qualitative low-probability rationale described in the three reports summarized herein: (1) R.P. Rechard, B. Reedlunn, J.E. Bean, Jr., B.A. Day, and L.C. Sanchez, *Improbability of Post-Closure Criticality in Array of Transuranic Waste Containers after Compaction by Salt Creep at Waste Isolation Pilot Plant*; (2) R.P. Rechard, B.A. Day, B. Reedlunn, and J.E. Bean, Jr., *Improbability of Post-Closure Criticality in Compacted Criticality Control Overpacks after Room Closure at Waste Isolation Pilot Plant*; and (3) R.P. Rechard, S. King, and P.V. Brady. *Hydrologic and Geochemical Constraints on Post-Closure Criticality in Geologic Media near Waste Isolation Pilot Plant*.

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ACRONYMS AND INITIALISMS

CCA	Compliance Certification Application
CCDF	complementary cumulative distribution function (performance measure in EPA disposal standard at Title 40 Code of Federal Regulations Part 191)
CCO	criticality control overpack (container)
CFR	Code of Federal Regulations
CH-TRU	contact-handled TRU (waste)
CRA	Compliance Re-certification Application
DOE	US Department of Energy
EPA	US Environmental Protection Agency
EIS	Environmental Impact Statement for major federal projects required by *National Environmental Policy Act of 1969*
FEP	features, events (natural and anthropogenic phenomena of short duration), and processes (natural phenomena of long duration)
FGE	fissile gram equivalent (of ^{239}Pu)
HLW	high-level (radioactive) waste is "…the highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations…" [1, §2(12)] Although not used in this manner in this report, general articles regarding radioactive waste often use the term HLW to imply any combination of SNF and HLW that require disposal in a deep, geologic repository. NRC includes SNF in its definition of HLW
NRC	US Nuclear Regulatory Commission
PA	performance assessment is process of assessing whether a system or component meets a set of performance criteria. For US, the process is a stochastic simulation; the system is a deep geologic repository disposal system; the performance criteria are the long-term measures in the EPA post-closure environmental standard 40 CFR 191
POC	pipe overpack container
ORNL	Oak Ridge National Laboratory
RH-TRU	remotely handled TRU (waste)
RPPCR	replacement panel planned change request (PA analysis to EPA)
SNF	spent nuclear fuel, "…fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing"[1]
SPD	surplus plutonium disposition
SRS	Savannah River Site (which manufactures the diluted surplus plutonium)
TRU	transuranic (radionuclide waste)
US	United States
WIPP	Waste Isolation Pilot Plant (repository in southeastern New Mexico for TRU waste from atomic energy defense activities)

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I. INTRODUCTION

The Waste Isolation Pilot Plant (WIPP), a repository in bedded salt in southeastern New Mexico, is owned by the United States (US) Department of Energy (DOE) for disposal of transuranic (TRU) radioisotopes from atomic energy defense activities (Fig. 1). The US Environmental Protection Agency (EPA), as regulator, asks for periodic reviews of all features, events, and processes (FEPs) included or excluded from the periodic compliance evaluations for WIPP.[2] A renewed evaluation of post-closure criticality FEPs was undertaken for the 2026 Compliance Re-certification Application to EPA (CRA-2026) (i.e., low probability of assembling a critical mass after repository closure from fissile material in TRU waste disposed at WIPP).

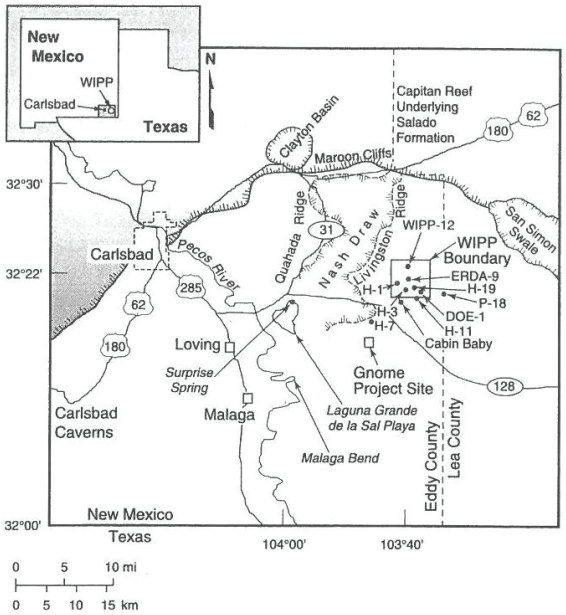


Fig. 1. WIPP TRU waste disposal facility 42 km east of Carlsbad in southeastern New Mexico.

I.A. Surplus Pu Disposition at WIPP

The renewed post-closure criticality evaluation[a] was expanded because DOE has disposed ~3.2 metric tons (t) of ^{239}Pu in pipe overpack container (POC) packages and decided in the 2010 Surplus Plutonium Disposition (SPD) Supplemental Environmental Impact Statement (EIS) and 2016 Record of Decision to dispose 6 t of surplus non-pit plutonium material at WIPP (after processing to meet WIPP waste acceptance criteria for contact-handled TRU waste).[4-8] The 6 t of contact-handled TRU waste was added to the WIPP inventory for the 2019 Compliance Re-certification Application to EPA (CRA-2019).[9] The recently completed and EPA approved Replacement Panel Planned Change Request (RPPCR-23) considers an additional 7.1 t.[10-14]

DOE has also decided to use the same process to dispose an additional 26.9 t of surplus Pu material at WIPP.[15-17] The surplus Pu material is to be disposed as contact-handled TRU waste in criticality control overpack (CCO) containers with higher initial concentration and higher fissile mass than considered in the 1996 Compliance Certification Application to EPA (1996 CCA).[18] Disposal of 7.1 t and 26.9 t (34 t total) of surplus Pu in additional WIPP panels is considered in CRA-2026[19;20] and will be considered in a supplemental environmental impact statement to expand the disposal area of the underground facility (but not increase the legislated maximum TRU waste volume).

Two performance assessments (PAs)/sensitivity analysis were performed for both RPPCR-23 and CRA-2026: (1) PA for an interim repository layout consisting of 12 panels (designated RPPCR-23-12P[21] and CRA-26-12P), and (2) PA for final repository layout consisting of 19 panels (designated RPPCR-23-19P[10] and CRA-26-19P when it is necessary to be specific).

Because 19 panels are necessary to accommodate the full SPD inventory, we emphasize the final state CRA-26-19P when quantitatively estimating probability or consequences in §V through §XI. The interim, 12-panel repositories are more difficult to make a quantitative probability estimate of criticality because the number of containers required for the mass of surplus Pu included is not easy to reconcile with the 12 panels modeled (e.g., although RPPCR-23-12P has partial SPD inventory, CRA-26-12P has full SPD inventory).

I.B. Performance Criteria for Waste Disposal at WIPP

In response to the Congressional requirement for EPA to set standards for nuclear waste disposal in the *Nuclear Waste Policy Act of 1982*,[1] EPA promulgated a radiation protection standard in Title 40 Code of Federal Regulations Part 191 (40 CFR 191).[22;23] EPA requires a PA to evaluate compliance with its standard. The PA is to[22, §§191.12(q)] (1) include pertinent FEPs, and sets of FEPs (called scenarios[b]) of possible future disposal system

[a] We refer to the analysis here as a criticality evaluation to examine the probability of criticality in the post-closure timeframe (i.e., post-closure criticality evaluation) when humans are absent from the sealed and inaccessible deep geologic repository. We use the term nuclear criticality safety analysis when we wish to describe a rule-based approach to determine if criticality is incredible when humans are present during the current timeframe (e.g., a criticality analysis outside reactors using the standard ANSI/ANS 8.1-2014).[3]

[b] The term scenario has various meanings. The dictionary definition most like the meaning intended here is[24] "an outline or model of an expected or supposed sequence of events." The US Nuclear Regulatory Commission (NRC) defines a scenario as[25] "a well-defined, connected sequence of FEPs that can be thought of as an outline of a possible future condition…" The International Atomic Energy Agency (IAEA) states,[26] "A scenario is a postulated or assumed set of conditions and/or events…" Within the WIPP Project, a scenario is a set of FEPs for a possible future condition but does not include the timing or ordering of

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conditions, (2) evaluate the effects of the FEPs and scenarios through an estimate of corresponding probabilities and consequences, and (3) estimate the cumulative release of radionuclides, including uncertainties.

In the *WIPP Land Withdrawal Act* of 1992, Congress designated that EPA regulate WIPP.[27] In response, EPA promulgated WIPP-specific certification criteria in 40 CFR 194 and requires that DOE document the continued compliance of WIPP with 40 CFR 191 about every 5 years.[28;29] CRA-2019 was the fourth re-certification application submitted to EPA. CRA-2026 will be the fifth.[c]

I.C. Approach for Screening Post-Closure Criticality at WIPP

Although not always cast as FEPs and scenarios, an analyst must decide what to include in the computational model. Because PA analysis is used as part of a regulatory decision, the task of including or excluding FEPs and scenarios is formal. The formal process, designated as scenario development, is to demonstrate, for screening and modeling, that all important FEPs have been included in the PA. Hence, the scenario development process includes (1) identifying a universe of FEPs relevant to the WIPP disposal system, (2) selecting FEPs that might reasonably contribute to radionuclide releases, and (3) forming scenarios from sets of FEPs, and aggregating scenarios into classes for which consequences and probabilities are similar and can be reasonably estimated. The scenario consequences are usually estimated through mathematical models that introduce time and order of events and processes acting on the features. The WIPP Project identified 245 FEPs,[d] of which 152 FEPs were omitted and 93 FEPs were included in mathematical models for the 1996 CCA and subsequent re-certifications.[18, App. SCR.2.2.3;29;32;33]

In discussing criticality in a geologic repository, we seek the probability and consequences of assembling a critical configuration of fissile mass. Prior to disposal, the emphasis is on an initiating event, such as an accident during operations, that causes a criticality; thus, we speak of a critical event (and possibly a corresponding event class). After disposal and repository closure, however, we speak of a criticality scenario (or class of criticality scenarios[e]) because the emphasis is on a set of processes, such as fissile mobilization, transport, and deposition acting to assemble a critical configuration of fissile mass in some feature of the disposal system, such as a disposal room.

EPA does not single out the post-closure criticality scenario class for special consideration when evaluating FEPs, scenarios, or scenario classes in either 40 CFR 191 or 40 CFR 194.[22;23;28;29] Rather, criticality is evaluated within the probabilistic regulatory framework and considered along with the 245 FEPs identified for the WIPP disposal system.[f] In the WIPP FEP database, the criticality consisted of a scenario on the influence of criticality heat (FEP W14) and a scenario on the influence of criticality explosions (FEP W28).[g]

In addition, a rationale based on low consequence or low probability rationale is equally valid in showing a FEP or scenario is sufficiently small to exclude from consideration in WIPP PAs; no regulatory preference exists in the US. The 1996 CCA formally relied upon a low-probability rationale to eliminate the two criticality scenario classes. However, a rationale for low consequences from (a) low added heat, (b) minor steam explosive disruption of deep repository, and (c) imperceptible increased radionuclide release was also included in supporting documentation to provide a broad perspective that the overall criticality risk was very low.[37]

The paper first summarizes the qualitative arguments of the low probability of criticality in disposal rooms, the underground facility, and the geologic barrier used in the formal screening rationale. The paper then provides a quantitative estimate of the low probability of criticality. The quantitative estimate outside the disposal rooms is based on an analogy to Oklo natural reactors. Next, the paper updates the low-consequence rationale.[h]

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events and processes. Once a mathematical model of the disposal system has been developed, timing and order of events and processes are introduced and described as a computational scenario.

[c] Starting with CRA-2026, EPA has directed DOE to certify compliance every 5 years after the previous EPA completeness determination.[30] CRA-2019 was certified complete on 26 November 2021.

[d] The analysis for the proposed repository for commercial spent nuclear fuel at Yucca Mountain adopted and greatly expanded the WIPP approach for identifying FEPs and scenarios. In the 2008 license application to NRC, 374 FEPs were formally screened; 222 FEPs were excluded; and 152 FEPs were retained.[31, Table 1]

[e] NRC defines scenario class as[25] "a set of related scenarios sharing sufficient similarities that they can be aggregated for the purpose of screening analysis…" For the developed mathematical model, a future of the disposal system is a point in the parameter space and a scenario or scenario class is a subset of the parameter space with similar characteristics. No sharp distinction exists between scenario and scenario class rather a continuum exists. Here, the terms distinguish between a set of FEPs useful for conceptual discussion and a set of FEPs useful for screening in the WIPP PA.

[f] EPA did not identify the criticality scenario class for special consideration when evaluating the post-closure behavior in the site-specific standard for the Yucca Mountain repository (40 CFR 197)[34;35] even though EPA had the opportunity to do so when EPA used criticality as a FEP screening example in the preamble for 40 CFR 197.

[g] The WIPP FEP database does not distinguish between individual feature, events, processes, scenarios, or scenario classes. All are simply designated as "FEPs." However, the database does categorize them as human-induced FEPs, natural FEPs, and waste/repository-induced FEPs (such as criticality FEPs W14 and W28).[36, Table 2]

[h] In the United Kingdom, the Nuclear Decommissioning Authority (implementer of nuclear waste policy) requires both a low-probability and a low consequence rationale for evaluating criticality in a geologic

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Finally, the paper combines the quantitative estimates of low probability and low consequence to generate a weighted consequence (as demonstrated in 2015[37;39]) to show that criticality has very low risk at WIPP.[i] Hence, criticality was not included in CRA-2019 or CRA-2026.[9, App. SCR-2019]

This paper draws upon information contained in four companion reports. Two companion reports update the qualitative description of the low probability of criticality from (a) compaction of TRU waste drums, boxes, pipe overpack containers,[41] and (b) criticality control containers in disposal rooms through salt creep.[42;43] A third companion report updates the qualitative description of fissile mobilization followed by deposition in other areas of the underground facility and geologic barrier from hydrologic and geochemical processes.[44] The neutronic criteria necessary for criticality after fissile deposition in geologic media is discussed in a fourth paper.[45-47]

II WIPP DISPOSAL SYSTEM

II.A Transuranic Waste

In its radiation protection standard 40 CFR 191, EPA requires deep geologic disposal of waste material contaminated with α-emitting TRU isotopes with an activity > 3.7 MBq/kg (>100 nCi/g) and half-life of >20 years. Two categories of TRU waste generated from atomic energy defense activities are allowed in the *Waste Isolation Pilot Plant Land Withdrawal Act*: [27;29] contact-handled transuranic (CH-TRU) and remotely handled transuranic (RH-TRU) waste. Most TRU waste disposed at WIPP in the past has consisted of a variety of organics, inorganics, and solidified materials contaminated with TRU radionuclides.

Rather than consisting of material contaminated with TRU radionuclides, surplus Pu material is processed to meet WIPP acceptance criteria for CH-TRU waste[8] by taking oxidized Pu and diluting it with an adulterant such that it cannot be readily diverted for nefarious purposes. Because bounding estimates were used in the 1996 CCA, and because estimates for CRA-04 and thereafter greatly decreased the ^{239}Pu inventory, the disposal of 6.0 t of surplus Pu in CCOs, as evaluated in CRA-2019,[48] represented only a small increase in total ^{239}Pu (1 t increase over the total 13 t in the 1996 CCA) and the Pu fissile mass equivalence was still less than originally planned in 1996 (Table I). The disposal of 13.1 t of surplus Pu in CCOs is modeled in RPPCR-23, for a total of 35 t ^{239}Pu (Table I),[10;12] and the disposal of 34 t of surplus Pu in CCOs in CRA-26-19P, for a total of 67.2 t ^{239}Pu,[49] are notably larger than the 13 t in the 1996 CCA, but as shown herein, the criticality scenario class is still not important when assessing WIPP performance.

The projected emplaced ^{235}U enrichment of CH-TRU at WIPP closure of 1.8% for CRA-2019, 0.35% for RPPCR-23-19P, and 0.26% for CRA-26-19P has remained less than the 4.9% projected in the 1996 CCA. The RH-TRU ^{235}U enrichment of 8.4% for CRA-2019/CRA-26-19P and 8.6% for RPPCR-23-19P at WIPP closure are only somewhat greater than the 6.5% enrichment projected in the 1996 CCA (Table I).

II.C. Geologic Characteristics

The 600-m-thick Salado Formation hosts the WIPP repository 654 m below the surface (Fig. 2). Near the repository, the Salado consists of nearly horizontal (<1° regional dip) halite (NaCl), argillaceous halite, and occasional interbeds of clay and anhydrites ($CaSO_4$) of the Late Permian Period (~255 million years old or 255 Ma).[33, Fig. 4]

The Rustler Formation overlies the Salado (Fig. 2). The 7.3-m thick Culebra Dolomite Member of the Rustler Formation, 216 m below the surface, is the most likely pathway for transporting radionuclides away from the repository after an inadvertent human intrusion into the repository (see §III.B), because it is the most transmissive saturated stratigraphic unit above the WIPP repository.[29;32] The Culebra consists mostly of dolomite with minor amounts of gypsum, quartz, and clay.

disposal system for radioactive waste; specifically, demonstration that "the possibility of a local accumulation of fissile material such as to produce a neutron chain reaction is not a significant concern" and a requirement that the "environmental safety case should also investigate, as a 'what if', the impact of a postulated criticality on the performance of the disposal system").[38] Here, "what-if" cases are not scenarios. Instead, they are cases specified by the regulator (or perhaps implementor) that take the disposal system beyond the realm of a probable limit to explore consequences and test disposal system robustness.

[i]DOE described this approach in the Safety Assessment Report for the proposed repository at Yucca Mountain as follows:[40,§2.2.1] "FEP screening may include assessing both the likelihood of the FEP occurring and the potential consequences of the FEP were it to occur because, `consistent with the definition of a performance assessment (proposed 10 CFR 63.2),` both aspects enter into the evaluation of radiological exposure to the RMEI [reasonably maximally exposed individual] and radionuclide releases to the accessible environment."

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Table I. Projected uranium and plutonium at closure in selected certifications and change request for replacement panels at WIPP.

	1996[a] CCA[18]		CRA[b]-2004[50;51]		CRA[c] -2009[52;53]		CRA-2019[48]		RPPCR -23-19P[11;12]		CRA-26-12P[20]		CRA-26-19P[19;54]	
Radioisotope	**CH** (kg)	**RH** (kg)	**CH** (kg)	**RH** (kg)	**CH** (kg)	**RH** (kg)	**CH** (kg)	**RH** (kg)	**CH** (kg)	**RH** (kg)	**CH** (kg)	**RH** (kg)	**CH** (kg)	**RH** (kg)
Uranium														
^{233}U	860	16	130	3.5	16	5.3	11	1.8	41	14	32	1.7	37	13
^{234}U	75	6.9	45	6.0	49	0.83	77	1.6	106	3.1	104	1.1	118	3.2
^{235}U	5 900	2 100	610	440	2 000	33	2 100	860	1 171	918	750	541	807	945
^{238}U	120 000	31 000	73 00	390 000	81 000	880	117 000	9 300	342 520	9 833	285 300	5 263	321 230	10 400
Enrichment ^{233}U+^{235}U	4.9%	6.5%	1.0%	0.11%	2.5%	4.1%	1.8%	8.4%	0.35%	8.6%	0.27%	9.3%	0.26%	8.4%
Plutonium														
^{238}Pu	15	0.09	73	0.16	86	0.30	55	1.3	74	1.2	80	0.3	92	1.5
^{239}Pu	13 000	170	11 000	87	8 200	47	14 000	68	35 000	62	56 510	30	67 200	73
^{240}Pu	920	22	470	7.5	630	4.4	1 400	14	3 038	16	4 092	5.8	4 860	20
^{241}Pu	2.2	0.13	5.0	0.23	4.9	0.04	18	0.44	4.2	0.06	4.7	0.02	5.6	0.08
^{242}Pu	310	0.04	6.8	0.12	19	0.32	38	4.0	62	4.9	62	1.0	73	6.1
^{239}Pu fissile kg mass equivalent[d]	16 700	1 560[e]	11 200	370[e]	9 590	73.0	15 500	624[e]	35 900	670[e]	57 200	380[b]	67 900	697[b]
Enrichment ^{239}Pu	90%	88%	95%	92%	92%	90%	90%	78%	92%	74%	93%	81%	92%	73%

[a] EPA-requested PAVT-1997 for evaluating the 1996 CCA used the same inventory[55]
[b] Inventory masses were updated and differ somewhat for EPA-requested PABC-2004 analysis for evaluating CRA-2004[51]
[c] EPA-requested PABC-2009 analysis used the same inventory.[56]
[d] Pu fissile mass equivalence is the mass of ^{239}Pu plus factors for other fissionable masses: specifically, 0.113·^{238}Pu, 0.0225·^{240}Pu, 2.25·^{241}Pu, 0.0075·^{242}Pu, 0.9·^{233}U, 0.643·^{235}U, 0.015·^{237}Np, 0.0187·^{241}Am, 34.6·^{242m}Am, 0.0129·^{243}Am, 15·^{245}Cm, 0.5·^{247}Cm, 45·^{245}Cf, and 90·^{251}Cf. The factors derive from comparing the minimum critical mass of 0.45-kg ^{239}Pu (for a slurry, which includes bias and 0.02 margin on k_{eff}) to the minimum critical mass of other fissile isotopes.[3,§5.2;57,Table XVI]
[e] Pu fissile kg mass equivalence for RH-TRU primarily derives from 0.643 ^{235}U

II.D. Repository Design

In the original design of the WIPP underground facility, the excavated disposal region of 4.42×10^5 m^3 was divided into 8 panels (of which 6 panels were filled as of the beginning of 2014) plus 2 smaller panels composed of the 4 central connecting drifts (with a combined volume for the 2 small panels a factor ~1.5 larger than a standard panel—Fig. 2). In February 2014, however, a drum from Los Alamos National Laboratory burst when improperly filled with an organic rather than inorganic inert filler. Both ^{241}Am and ^{239}Pu were released that contaminated some of the underground. DOE has abandoned the southern equivalent panel and the closures between Panels 3, 4, 5, and 6 in the southern portion of the repository.[58]

At least 2 replacement panels (as addressed in supplementary environmental assessment[59] and RPPCR-23[13]) and up to 7 more panels (to be addressed in future EIS) will be excavated to the west of Panel 8. The excavation is to accommodate space lost from[60,Figure 2] (a) the April 2014 radiation contamination to avoid undue worker exposure;[61] (b) disposal areas abandoned because of the inability to rock bolt ceilings in existing excavations during the 3-y closure after the April 2014 accident to avoid undue rockfall hazards, and (c) packing inefficiencies throughout repository (Fig. 2). Neither the expansion to ~8.59×10^5 m^3 for 2 panels (nor the future expansion to 9 more panels) changes the maximum TRU waste volume of 1.75564×10^5 m^3 (6.2×10^6 ft^3) authorized for disposal in the *Waste Isolation Pilot Plant Land Withdrawal Act*.[27]

A full panel is divided into 7 rooms (Fig. 2). The nominal volume of a room is 6585 m^3, including the connecting drifts to form a square bracket shape. Ideally, 10 908 55-gallon drums can be placed per room.[62] On average, ~5% of the disposal room volume is backfilled with bags of magnesium oxide.[41, Table VI;62] Magnesium oxide (MgO) acts as a buffer to control pH of any brine that enters the disposal rooms. The MgO also combines with any CO_2 formed during degradation of organic matter, such that highly soluble Pu carbonate species are not formed.[41]

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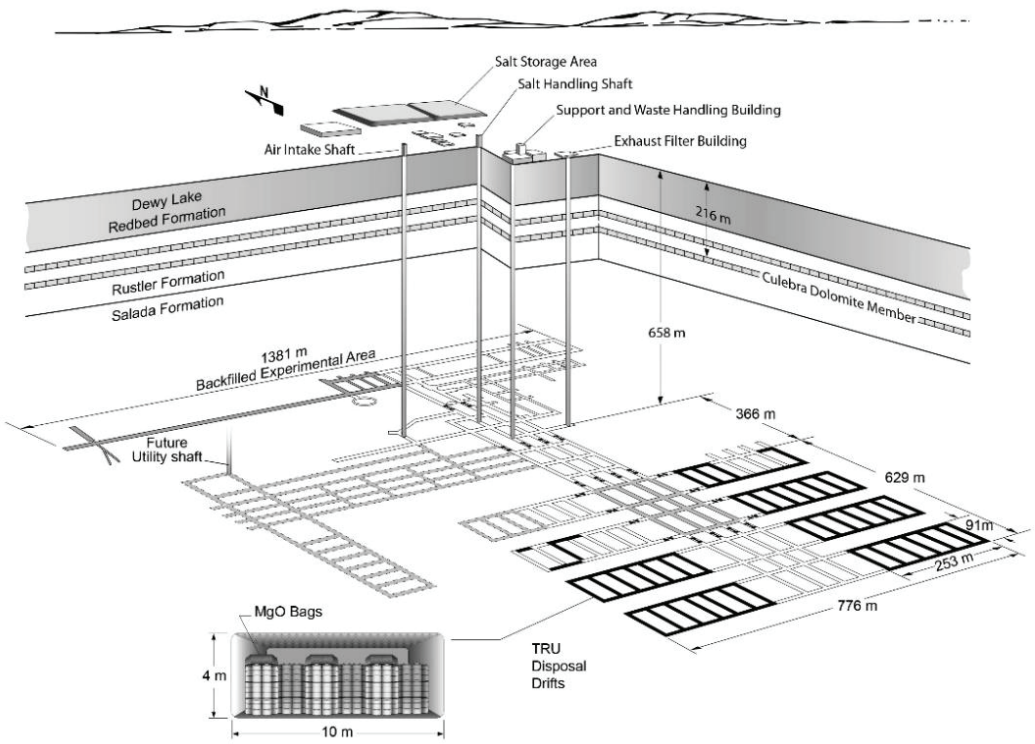


Fig. 2. Transuranic waste disposal area of the WIPP repository has 8 panels, one equivalent panel in the north central region; at least 2 replacement panels and perhaps 7 additional panels with same disposal volume will be constructed to the west.[10]

III. SCREENING POST-CLOSURE CRITICALITY

III.A. Scenario Classes of WIPP PA

In 40 CFR 191, EPA selected three indicators of potential health impacts at the disposal system boundary: (1) cumulative release ($R_{total}(\mathbf{p})$) of long-lived radionuclides to a hypothetical large population in the Containment Requirements (§191.13), (2) dose to individuals in the Individual Protection Requirements (§191.15), and (3) groundwater concentration in the Groundwater Protection Requirements (§191.16).

The cumulative release $R_{total}(\mathbf{p})$ for the set of model parameters $\mathbf{p}$ is [22;23]

$$R_{total}(\mathbf{p}) = \frac{1}{f_{actvty}} \sum_{r=1}^{n_r} \frac{1}{L_r} \int_0^{\Im} \int_{x^{ae}} \mathrm{E}_r(t, \mathbf{x}|\mathbf{p}) \mathrm{d}\mathbf{x} \mathrm{d}t \qquad (1)$$

where $\mathrm{E}_r(\sim)$ is the exposure consequence model that calculates the flux of the n_r radionuclides r across the accessible boundary (as represented by the boundary integral x^{ae}) during the regulatory period ($\Im$) for all the scenarios imagined and retained. The $R_{total}(\mathbf{p})$ is normalized by (a) EPA limits (L_r) specified in 40 CFR 191 for n_r α-emitting TRU radionuclides with half-lives ($t_r^{1/2}$) >20 years, and (b) activity of TRU radionuclides placed in the repository, expressed as a waste factor ($f_{actvty} = \Sigma W_r / 10^6 \mathrm{Ci}$) (i.e., allowable release is proportional to disposed waste[63-65]).

The regulated measure of the cumulative release $R_{total}(\mathbf{p})$ is the expected (mean) cumulative release. By specifying the mean as the performance measure,[34, p. 32125] EPA implied a probabilistic stimulation.[j] The expected release $\bar{R}_{total}$ can be expanded to include the expectation from aleatoric $\mathbf{a}$ and epistemic $\mathbf{e}$ uncertain parameters (i.e., $\mathbf{p} = \{\mathbf{e}^e, \mathbf{e}^p, \mathbf{a}\}$) where epistemic parameters are associated with both exposure models and probability models:

$$\bar{R}_{total}(\mathbf{p}) = \mathcal{E}\{R_{total}(\mathbf{p})\} = \mathcal{E}^E\{\mathcal{E}^A\{R_{total}(\mathbf{e},\mathbf{a})\}\} \qquad (2)$$

$$= \mathcal{E}^E\left\{\sum_{j=1}^{n_{\mathcal{A}}} R_{total}(\mathbf{e}^e, \mathbf{a}_j) \wp\{\mathbf{e}^p, \mathbf{a}_j\}\right\} \qquad (3)$$

[j] EPA is more direct in the site-specific standard for the Yucca Mountain repository [34, p. 32125] "By specifying the mean as the performance measure and probability limits for the processes and events to be considered, and in concert with the intent of our 'reasonable expectation' approach in general, we have implied that probabilistic approaches for the disposal system performance assessments are expected."

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Scenario classes can be formed to describe the aleatoric uncertainty.[66, Fig. 3.2-2;67, Table 6] Two general scenario classes can be formed from the events in the 93 retained FEPs for WIPP: (1) undisturbed conditions (A_U); and (2) human disruption (A_H). To these two retained scenario classes, we conceptually add the criticality scenario class (A_C—formed from two criticality scenario subclasses mentioned in Section 1.B (i.e., $\mathcal{A}_{W14} + \mathcal{A}_{W28}$).

In summary, the expected consequence, expressed as cumulative release, is the sum of three incremental consequences that comprise the aleatoric uncertainty:

$$\bar{R}_{total} = \bar{R}_U + \bar{R}_H + \bar{R}_C \quad (4)$$

$$\approx \bar{R}_U + \bar{R}_H \quad (5)$$

Herein, we show that Eq. (5) is a reasonable approximation for $\bar{R}_{total}$ since the incremental probability-weighted consequences from the criticality scenario class ($\bar{R}_C$) are so small relative to probability-weighted consequences from the other scenario classes. Specifically, the criticality scenario class has low risk because post-closure criticality has both low probability and low consequence.

Although the undisturbed scenario is traditionally retained in Eq. (4), no large driving force exists for the movement of radioisotopes without human intrusion to disrupt and allow brine to pass through the repository, as demonstrated in the first PA in 1989 and thereafter.[29;66;68;69] For example, diffusion through the salt is an included process but not sufficient for radionuclides to reach the accessible environment. Also, generation of hydrogen from anoxic corrosion is an included process that creates pressure in the disposal region that conceivably could drive small concentrations of radionuclides and any disposed hazardous chemicals through shaft seals to the surface and along subsurface anhydrite layers to edge of the disposal system underground prior to intrusion. However, these potential releases have been below regulatory concern in the past,[18;70 71] and do not occur within 10^4 years in current analysis (i.e., CRA-2019, RPPCR-23, and CRA-2026).[9, §PA-7.2] Hence, the human disruptive scenario is fundamental to the movement and assembly of fissile material beyond the disposal rooms.[k]

III.B. Inadvertent Human Intrusion Event

In 40 CFR 191,[22;23;73] EPA requires DOE demonstrate that the closed WIPP repository will comply with the performance criteria after hypothetical human disruption of the repository (A_H). In 40 CFR 194,[28] EPA narrowed the focus of regulatory interest to four human disruptions of the WIPP disposal system: adverse effects from (1) fluid injection for enhanced deep oil and gas recovery in wells outside land withdrawal boundary (LWB) that causes fluid injection into repository (A_{HF}); (2) development of existing and future oil and gas wells outside LWB that influences Culebra dolomite flow through seepage and subsidence; (3) potash mining in McNutt Potash Zone above repository both inside and outside LWB that influences Culebra dolomite flow; and (4) inadvertent intrusion into the repository via an exploratory borehole using present drilling technology (A_{HI}—as described further in §V.D and §VI.D.1).

The influence of fluid injection into the repository and the influence of oil and gas development on flow in the Culebra dolomite are events that are screened out of the PA analysis.[9, App. SCR] The influence of potash mining on flow in the Culebra dolomite strata is included in PA analysis[l] and included as part of qualitative criticality screening in a companion report as summarized in §IV.I,[44] but the influence on fissile deposition next to an exploratory borehole is minor.

Of the four human disruptions EPA identified, intrusion by an exploratory borehole is most pertinent to post-closure criticality. The short-term result of intrusion by an exploratory borehole is entrainment of radionuclides into the drilling fluid and their immediate release at the surface. At later times, releases may occur through the abandoned borehole. In the stylized calculation, the borehole, filled with material that has the permeability of silty sand, creates an advective path from the repository to a transmissive zone in the Culebra dolomite above the repository but retains the remainder of the natural barrier, where radionuclides will likely be dispersed during transport.

III.C. Criticality Scenario Class Probability and Consequence

To demonstrate that the influence of criticality is small requires expanding $\bar{R}_C$ into its probability and consequence components, using several approximations implied in EPA regulatory guidance. By analogy with Eq. (2),

[k] Other FEPs that disrupt the repository are considered during FEP screening (e.g., Ref[9, App. SCR-2019]). For example, other disruptive events include earthquake risk, which is described by several FEPs, such as small seismic activity event (included), but most related FEPs such as regional tectonics or fault movement, have low probability in the region forming the Delaware basin. Other disruptive processes include breccia pipes causing large dissolution about the repository, such as deep dissolution, breccia pipes, and collapsed breccia, that were demonstrated to have low probability when evaluating site suitability in the early 1980s.[9, App. SCR-2019;72].

[l] Two potash mining subclasses are considered in the WIPP PA: partial mining (i.e., mining of the economical potash reserves) and full mining (i.e., mining of all known potash including that inside LWB) of NcNutt Potash Zone in Salado Fm above the repository.

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$$\bar{R}_C = \mathcal{E}\{R_C(\mathbf{p})\} = \mathcal{E}^E\{\mathcal{E}^A\{R_C(\mathbf{e},\mathbf{a})\}\} \quad (6)$$

Approximating the aleatoric expectation of criticality by summing criticality computational scenarios yields[m]

$$\bar{R}_C = \mathcal{E}^E\left\{\sum_{m=1}^{n_{CS}} \mathcal{R}_m^{CS}(\mathbf{e}^e) \bullet \wp\{\mathcal{A}_m^{CS}(\mathbf{e}^p)\}\right\} \quad (7)$$

As elaborated in §III.E, EPA guidance implies that epistemic means of the probability and consequences of FEPs and scenario class provide an adequate estimate for screening, hence, we will estimate means

$$\bar{R}_C = \sum_{m=1}^{n_{CS}} \mathcal{E}^E\left\{\mathcal{R}_m^{CS}(\mathbf{e}^e) \bullet \wp\{\mathcal{A}_m^{CS}(\mathbf{e}^p)\}\right\} \quad (8)$$

Also, the expectation with respect to the epistemic uncertain parameters will be understood to simplify the notation (i.e., $\bar{\wp}\{\mathcal{A}_m^{CS}\}$ is understood to mean $= \mathcal{E}^E\{\wp\{\mathcal{A}_m^{CS}(\mathbf{e}^p)\}\}$) thus

$$= \sum_{m=1}^{n_{CS}} \bar{\mathcal{R}}_m^{CS} \bullet \bar{\wp}\{\mathcal{A}_m^{CS}\} \quad (9)$$

The potential bound on the criticality computational scenarios is

$$< \sum_{m=1}^{n_{CS}} \bar{\mathcal{R}}_m^{CS} \bullet \sum_{m=1}^{n_{CS}} \bar{\wp}\{\mathcal{A}_m^{CS}\} \quad (10)$$

$$= \bar{R}_C^{-} \bullet \bar{\wp}\{A_C\} \quad (11)$$

where $\bar{R}_C^{-}$ is the expected *conditional* consequence of the criticality scenario class and equal to the sum of the conditional computational criticality subclasses m ($\sum_{m=1}^{n_{CS}} \bar{\mathcal{R}}_m^{CS}$); $\bar{\wp}\{A_C\}$ is the expected probability of the criticality scenario class and equal to the sum of the criticality computational subclasses m ($\sum_{m=1}^{n_{CS}} \bar{\wp}\{\mathcal{A}_m^{CS}\}$). Both expectations are with respect to the epistemic uncertain parameters.

The inequality of Eq. (10) assumes the expectation described in Eq. (9) can be sufficiently bound by the product of the sum of the consequences and the sum of the scenario class probabilities, without considering any potential interplay between the individual conditional consequence $\bar{\mathcal{R}}_m^{CS}$ and the probability $\bar{\wp}\{\mathcal{A}_m^{CS}\}$. For example, the evolution of the criticality consequences is reasonably independent of the probability of the criticality computational scenarios, which is only approximately true on a macroscale. Both the conditional consequence ($\bar{R}_C^{-}$) and the probability of the criticality scenario class ($\bar{\wp}\{A_C\}$) contribute to the risk (i.e., probability-weighted consequences); thus, probability, consequence, or risk may be used to determine whether it is necessary to consider criticality in the PA.[n]

III.D Criteria for Excluding Criticality Scenario Class

In Appendix C of 40 CFR part 191[22;23] and in 40 CFR §194.32,[28;29] EPA provides three criteria for excluding a FEP or a scenario class, such as criticality, from the PA over the 10^4-year regulatory period: One exclusion criterion is based on regulatory fiat (e.g., guidance excluding purposeful human mining of the repository). A second criterion is the estimation of FEP or scenario class probability, such as $\bar{\wp}\{A_C\}$, and exclusion by low probability (i.e., "…performance assessments need not consider categories of events or processes that are estimated to have less than one chance in 10,000 of occurring over 10,000 years").[23, App. C] In practice FEPs and scenario classes are excluded via (a) a qualitative rationale (based on degrees of belief) that the scenario class is improbable because of site, waste, or repository characteristics, or (b) a quantitative demonstration that the probability is less than 10^{-4} in 10^4 years.[o] Herein, the qualitative rationale that the criticality scenario class is improbable is summarized from three companion reports[41;42;44] and a quantitative demonstration is made that the probability of criticality is $<10^{-4}/10^4$ y (Eq. (13)).

[m] Similar to scenarios and scenario class, a continuum exists between the criticality scenario class and criticality computational scenarios. Here, the terms distinguish between a broad set of FEPs used for screening discussion and fine groupings of FEPs that are useful for probability and consequence estimation.

[n] In Yucca Mountain PA, DOE combined probability and consequence qualitative reasoning to omit precipitation leaching radionuclides from ash (deposited after a volcano erupted through the proposed repository) into groundwater that then flowed to the accessible environment. Specifically, in FEP 1.2.04.07.0B, Ash Redistribution in Groundwater:[74, p. 6-164] "…Thus, the probability-weighted consequences of leaching from ash would be less than the probability-weighted consequences of exposing the same number of waste packages to direct seepage." NRC accepted this approach.[75, p. 2-14] Furthermore, NRC also referred to a probability-weighted consequence argument in regards to Yucca Mountain FEP 1.2.10.01.0A, Hydrologic Response to Seismic Activity, the NRC staff wrote:[75, p. 2-17] "…the NRC staff finds that the risk (probability-weighted consequences) would be negligible because the likelihood of earthquakes with magnitudes large enough to induce changes in the water table is small (less than about 10^{-6}/y)."

[o] EPA's most recent statement of the quantitative probability criteria in the site-specific regulation for the Yucca Mountain repository, 40 CFR 197, is that the probability is *very unlikely*, where *very unlikely* is defined by EPA and NRC as "those that are estimated to have less than one chance in 100,000,000 per year of occurring."[76, §63.342(a)] This most recent EPA probability criterion of 10^{-8}/y emphasizes that the underlying frequency for screening is constant; hence, the probability screening criterion over 10^4 years is 10^{-4} and over 10^6 years is 10^{-2}. Expressing the probability criterion as 10^{-4} in 10^4 years in 40 CFR 191[22, App. B;23, App. C] emphasizes that the probability of interest is over 10^4 years.

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A third criterion is exclusion of the criticality scenario class because of low consequence, $\overline{R}_C$ (i.e., "…reasonable expectation that the remaining probability distribution of cumulative releases would not be significantly changed by such omissions"). Exclusion of a criticality scenario by a low consequence argument is to be documented, but no criterion for significance is provided (such as a percentage of the total dose). This approach is reasonable because a limit of acceptable insignificance would need to be tied to the measure selected for comparison, and secondary measures that influence the performance measure indirectly may be useful for a screening scenario class via a low-consequence rationale. This paper updates an indirect measure in the low-consequence rationale previously presented for the 1996 CCA.

As practiced by the WIPP Project, those FEPs and scenario classes that primarily provide a beneficial function but are omitted for modeling simplification are also excluded under the third criterion. Hence, the third criterion is actually a "low or beneficial consequence criterion" at WIPP. As described in §VII.C, criticality in a ^{239}Pu assembly has benefits, but the benefits are not included.

III.E. Approximation of Mean Probability and Consequence of Criticality

In 40 CFR 191, EPA invoked "reasonable expectation" as the standard of proof for compliance with EPA limits in the Containment Requirements specified in §191.13(a)). Reasonable expectation connotes a flexible standard of proof and use of central estimates when encountering unknowns.[p] Specifically, for the Containment Requirements EPA noted [65, §191.13 (b)]:

> …Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames. Instead, what is required is a reasonable expectation, on the basis of the record before the implementing agency, that compliance with 191.13 (a) will be achieved.

Furthermore, EPA noted in the guidance to 40 CFR 191, App. C

> *Compliance with Section 191.13.* The Agency assumes that, whenever practicable, the implementing agency will assemble all of the results of the performance assessments to determine compliance with §191.13 into a "complementary cumulative distribution function" that indicates the probability of exceeding various levels of cumulative release…

In 40 CFR 194, EPA stated "Finally, the CCA must demonstrate that the mean of the population of CCDFs [complementary cumulative distribution functions] meets the containment requirements of §191.13…"

Consistent with the use of reasonable expectation and mean results in a PA, EPA guidance implies a mean estimate of a FEP or scenario class probability, such as criticality, provides an adequate estimate for screening. Consequently, EPA does not expect nor does the WIPP Project provide worse-case scenarios that combine unrealistic combinations of imagined events to assemble fissile material in order to bound the probability of criticality after WIPP closure.[q]

Although the mean is formally evaluated in a WIPP PA, the mean is approximated for FEP screening (e.g., $\overline{\wp}\{\mathcal{A}_m^{CS}\}$ of Eq. 9). Our approach here is to use bounding results to argue that the probability and consequence are very small. However, the purpose is not to produce a bound on the distribution of the probability (i.e., $^{\max}\overline{\wp}\{A_C\}$) or consequence $^{\max}\overline{R}_m^{CS}$ of the criticality scenario class but rather ensure that the lack of criticality does indeed bound a reasonable estimate of mean behavior and would do so in the future even with possible changes in repository design and containers.

IV. FORMAL LOW-PROBABILITY RATIONALE FOR SCREENING CRITICALITY

IV.A. Criticality Scenario Categories

The absence or presence of sufficient moderator is one condition used to define criticality computational scenarios and organize the screening argument (Fig. 3). An effective moderator reduces the neutron energy to the thermal range (i.e., slows down the neutrons) and thereby increases the probability of absorption by nearby fissile material; and thus criticality. The presence of sufficient moderation can be further subdivided into the abundance of moderation from brine inundation of the disposal room or presence of other hydrogenous material (such as plastics) inside the WIPP disposal container.

A second condition for organizing the screening argument is the speed of assembling the fissile material

[p] EPA elaborated upon reasonable expectation as the standard of proof in the site-specific standard for the Yucca Mountain disposal system, 40 CFR 197, as follows:[34, §197.14;77]: "Characteristics of reasonable expectation include that it: (a) Requires less than absolute proof because absolute proof is impossible to attain for disposal due to the uncertainty of projecting long-term performance; (b) Accounts for the inherently greater uncertainties in making long-term projections of the performance of the Yucca Mountain disposal system; (c) Does not exclude important parameters from assessments and analyses simply because they are difficult to precisely quantify to a high degree of confidence; and (d) focuses performance assessment and analyses upon the full range of defensible and reasonable parameter distributions rather than only upon extreme physical situations and parameter values."

[q] The use of the mean probability for screening FEPs is emphasized by NRC in the Yucca Mountain Review Plan: [25, 2.2-14] "…the mean of the distribution range is to be used to screen an event from the performance assessment…"

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into a critical configuration (Fig. 3). Three speeds of fissile assembly are considered: (a) slow refers to assembly processes that occur over geologic time, such as salt creep closure of a WIPP disposal room; (b) fast refers to assembly processes that occur over a short time, such as gravity-driven room collapse; and (c) explosive refers to assembly processes that occur in microseconds.

Assembly of the fissile material into a critical configuration is required because insufficient fissile material exists in any individual container to cause criticality. This condition is enforced to ensure safety during transportation and WIPP operations by in-depth nuclear criticality safety analysis that follow established protocols as set forth by NRC 10 CRF 71 and DOE 10 CFR 830 regulations, ANSI/ANS-8 series consensus standards (e.g., Ref[3], and WIPP WAC[8]). To cause criticality after WIPP closure, either (1) the array of containers in the disposal room must be compacted such that fissile separation is no longer maintained, or (2) fissile material in each container must be mobilized, transported, and deposited in a critical configuration in another location (through precipitation, adsorption, or colloid aggregation).

Criticality involving little or no moderation in the WIPP disposal system is difficult to conceive. WIPP containers have some hydrogenous material such as organic material in the form of polyethylene plastic bags to prevent external contamination when loading containers. The containers also often have inorganic material with absorbed moisture (e.g., zeolites), water of hydration (e.g., clay), or hydrated metal ions ion (e.g., $CoCl_2 \cdot 6H_2O$). Furthermore, magnesium oxide (MgO), which acts as a moderator, is used throughout the disposal region. Finally, much of the WIPP disposal system may be saturated with brine, such as in Culebra dolomite strata, or partially saturated, such as brine seepage into a disposal room. Hence, unmoderated branches are readily dismissed and discussed first.

IV.B. Unmoderated Explosive Assembly

An unmoderated, explosive assembly of fissile material is essentially a nuclear weapon, which requires special design features;[78] it is a situation that cannot occur by natural processes in the mostly saturated, moderated environment at WIPP.[r]

The neutron multiplication factor (k_{eff}) is an index of criticality and conceptually the ratio of the number of neutrons in one generation to the number of neutrons present in the previous generation. k_{eff} of unity indicates a system is critical. Although $k_{eff} > 1$ is a necessary condition for an atomic explosion, it alone is not sufficient. Special conditions must exist such that the assembly becomes supercritical and the rate of increase in k_{eff} is very rapid. Without special conditions, much can disrupt the increase of neutrons such as waste impurities, other isotopes, and other neutron absorbing radionuclides mixed with the fissile material.

IV.C Unmoderated Fast Mechanical Assembly

Rockfall in the WIPP disposal in which an array of containers is compacted sufficiently such that fissile separation between containers is not maintained potentially results in a fast assembly of fissile material. As described more thoroughly below in §IV.E (fast assembly with moderation), a salt block falling onto an array of POCs or CCOs does not cause them to buckle, crush, or cluster together.[43;79;80] Hence, rockfall does not promote a critical configuration, whether the container is moderated or not.

IV.D. Unmoderated Slow Assembly

No credible method exists to mobilize, transport, and slowly assemble fissile material beyond a disposal room without brine in the saturated environment of WIPP.[44;78] Certainly, gradual closure from salt creep and subsequent container compaction represents a slow assembly inside a disposal room. Yet, rooms filled with containers without hydrogenous material and rooms without MgO are improbable in the WIPP disposal system. Unmoderated fissile material with a slow rate of assembly would roughly correspond to conditions in experimental breeder reactors, which requires human intervention.[78;81]

[r] An energetic auto-catalytic event speculated for highly specific configurations of ^{239}Pu is discussed in the moderated branch with slow hydrologic/geochemical assembly, §IV.H

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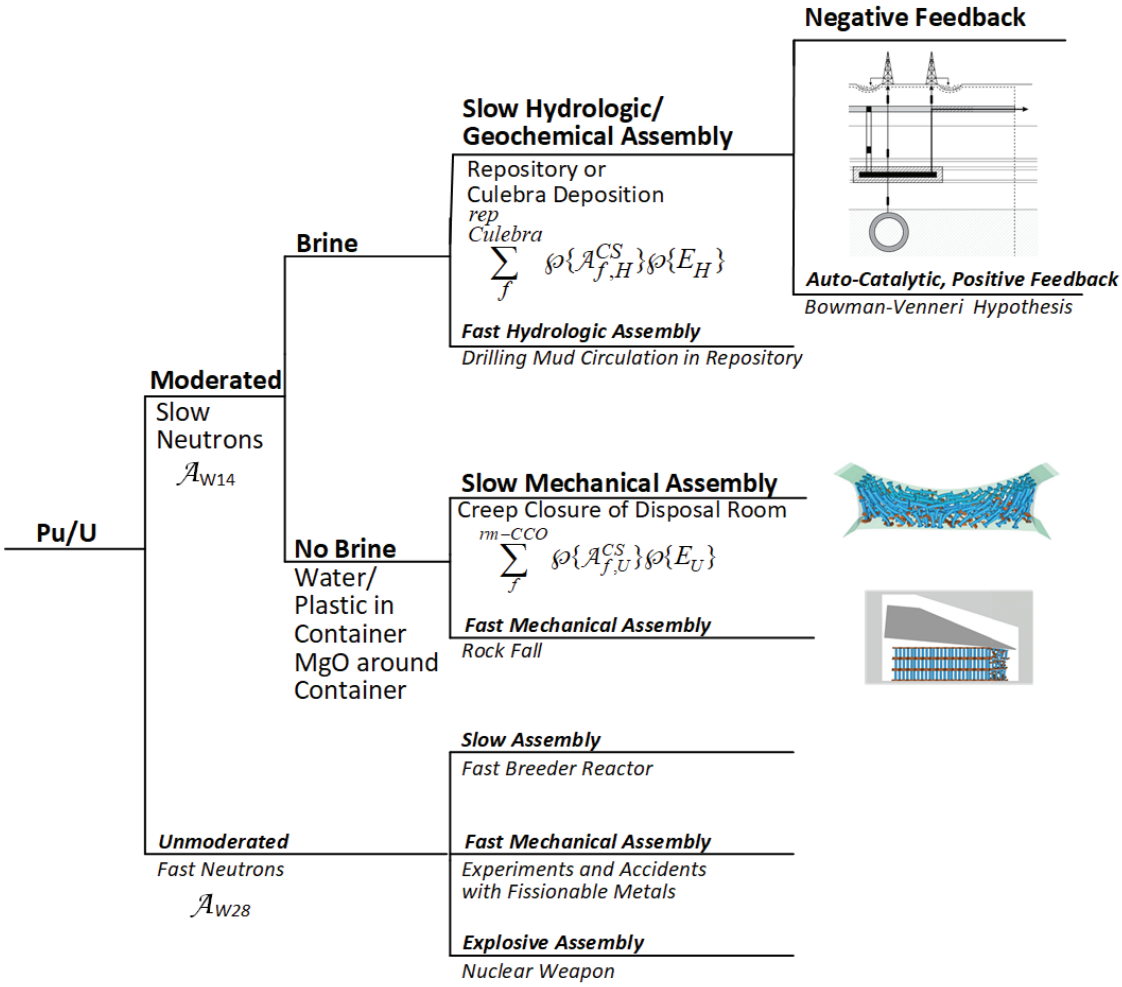


Fig. 3. Categories of criticality for organizing screening argument based on moderation and assembly speed;[78, Fig. 7] all branches are formally dismissed but the probability of criticality from slow geomechanical assembly and slow hydrologic/geochemical assembly with negative feedback are examined quantitatively in §VI and §V.

IV.E. Fast Mechanical Assembly of Moderated Container

High-fidelity geomechnical simulations (using the Sandia Sierra/Solid Mechanics finite-element code system[82]) were conducted of rockfall in a room full of POCs or CCOs to determine if fissile separation between containers is maintained.[41;42;79;80] POCs and CCOs were selected since all POCs and CCOs in a room can respectively dispose the maximum 200 and 380 fissile gram equivalents (FGE) ^{239}Pu, unlike other WIPP containers, which can only dispose 325 FGE in, for example, group of seven drums.[41, Table IV]

The rock fall analysis applied several conservatisms.[43;79;80] The analysis considered one large salt block falling onto empty POCs or CCO s (with weak material strength) that were stacked three high with each layer offset 2.54 cm from the layer below. The MgO on top of the stacks were omitted and the rockfall initiated before any closure from salt creep had occurred in order to maximize the fall distance and, thus, the velocity of the salt block. Conservatively, the salt block was not allowed to fracture, and the salt block size was the largest that had been observed at WIPP. The observed salt block had separated at Anhydrite Layer b/Clay Seam G about 2 m above the disposal room in the lower horizon such that larger salt blocks were unlikely.[42, Fig. 4]

Although only CCO model results are shown here (Fig. 4), POCs and CCOs have several similarities such that they behave similarly during rock fall.[41;43] For example, both POCs and CCOs consist of an outer 55-gallon carbon-steel drum that overpacks an inner stainless-steel pipe for waste that is stabilized by plywood.

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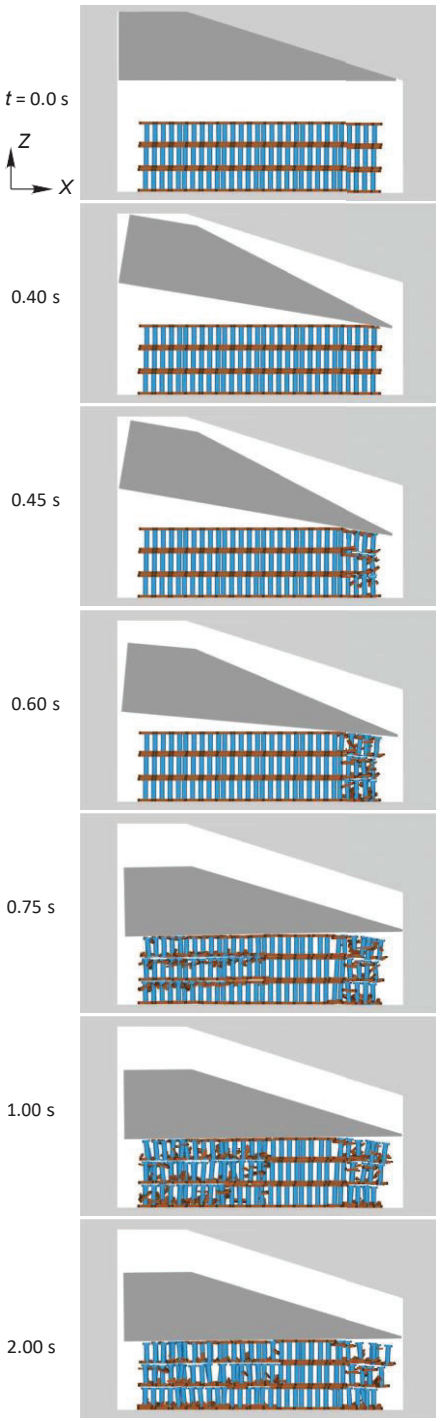


Fig. 4. Roof fall onto three tiers of CCOs emplaced in WIPP disposal room does not greatly disrupt hexagonal array. Brown discs represent top and bottom plywood stabilizer for blue stainless steel criticality control container inside 55-gallon CCO shell (which is hidden for visualization).[43, Fig. 4;79;83, Fig. 5]

Neither a salt block that uniformly released from the ceiling and fell mostly flat or a block that unzipped from the ceiling and thus had rotation at impact caused POCs or CCOs to buckle, crush, or cluster together.[79;80;83;84, Table 1] Because separation of fissile material is maintained in POCs and CCOs, rockfall does not promote a critical configuration, whether the container is moderated or not.

IV.F. Fast Hydrologic Assembly

Fast fissile assembly with brine-moderated neutrons might conceivably be the result of inadvertent drilling intrusion that causes vigorous mixing of a slurry of fissile material (and possibly suspended colloidal particles) in the repository or in the drilling mud. However, a solution of dissolved Pu or U formed under repository conditions is not critical; the difference between the mean Pu^{III} concentration for CRA-2026 (both 12 panel and 19 panel repositories) and the critical limit for Pu in components within the repository such as concrete, clay, or rust saturated with Castile brine is at least 4 orders of magnitude; i.e., 8.8×10^{-4} kg/m^3 (3.7×10^{-3} mM in Fig. 5) versus 8.8 kg/m^3 (§IV.I).

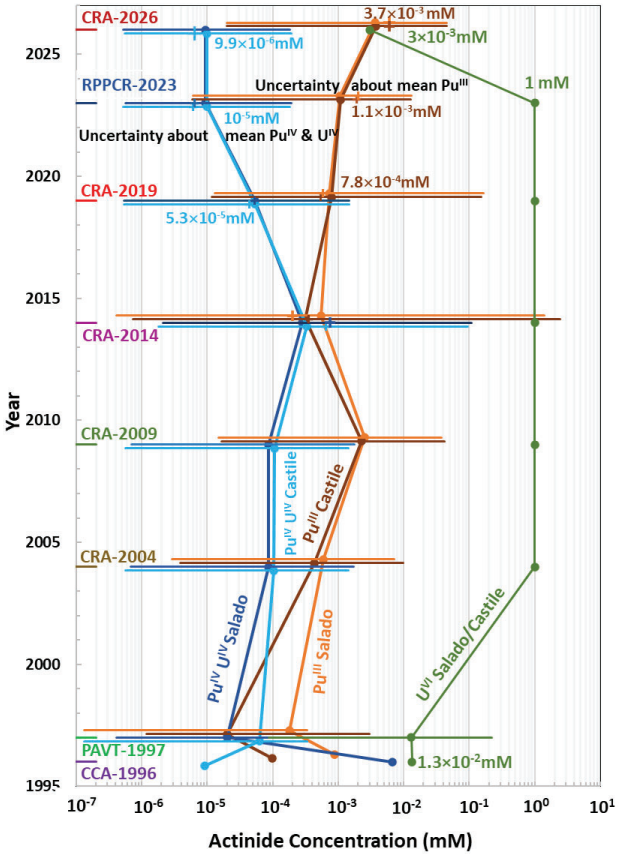


Fig. 5. Mean and range of actinide III, IV, and VI solution concentration (without colloids) for minimum mixing volume in disposal rooms for WIPP certifications.[44, Fig. 5]

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Rather, the solution must be concentrated through a geochemical process (not simple settling of a slurry solution) as in the branch with assembly by slow hydrologic/geochemical processes, described in §IV.H. Nonetheless, the fission consequences of fast hydrologic assembly are used as bounds on transient criticality events later in §IX. This type of criticality excursion would be similar to critical accidents of aqueous fissile solutions in nuclear fuel processing plants,[78;81;85] which ranged between 10^{15} to 4×10^{19} fissions with 5.8×10^{18} mean and 8.2×10^{17} median.[78;81;86;87] Human exposure to deadly radiation at the surface is a serious effect of a criticality accident since the mean energy released is not great: about 181 MJ or 50 kW-h.[s]

IV.G. Slow Mechanical Assembly of Moderated Container

Gradual room closure from salt creep and subsequent container compaction represents a slow geomechanical assembly. Two types of quantitative modeling demonstrate the low probability of criticality: geomechanical modeling and neutron/photon transport modeling. The room closure was evaluated with high-fidelity geomechanical models of a disposal room filled with POCs or CCOs.[41;42;79;80] Although brine may seep into the room over time, only hydrogenous material inside the container was modeled. This assumption adds conservatism because the presence of brine promotes generation of gas by metal corrosion and, thus, reduces the amount of room closure from gas pressure. Furthermore, the absorption of neutrons by chlorine in brine reduces the likelihood of criticality.

Geomechanical models predict that most closure occurs within the first 200 years prior to any extensive container corrosion, which could spill container contents. However, the coordinate positions of the inner stainless-steel pipe in a POC or inner container in a CCO that were used in subsequent criticality evaluations were at 1000 years, when room closure had asymptotically approached maximum compaction (Fig. 6). At 1000 years, clearly most inner containers of a CCOs are on their side, and mostly a single layer at the room center.

Neutron/photon transport models by Oak Ridge National Laboratory (ORNL), with spheres of 200 FGE ^{239}Pu as oxide (PuO_2) placed at the predicted irregular spacing, demonstrated that an array of POCs was not critical when surrounded by salt and magnesium oxide.[41;43]

The probability of criticality in POCs is an upper bound for the probability of criticality in other containers. That is, POCs can transport 200 FGE ^{239}Pu per container and 1400 FGE ^{239}Pu in a bundle of seven POCs disposed in a room. In comparison, other containers transport less fissile material in bundle of seven containers because of fissile limits on transportation. For example, a bundle of seven 55-gallon drums disposed in a room contains a maximum equivalent plutonium content of 325 FGE ^{239}Pu.[41]

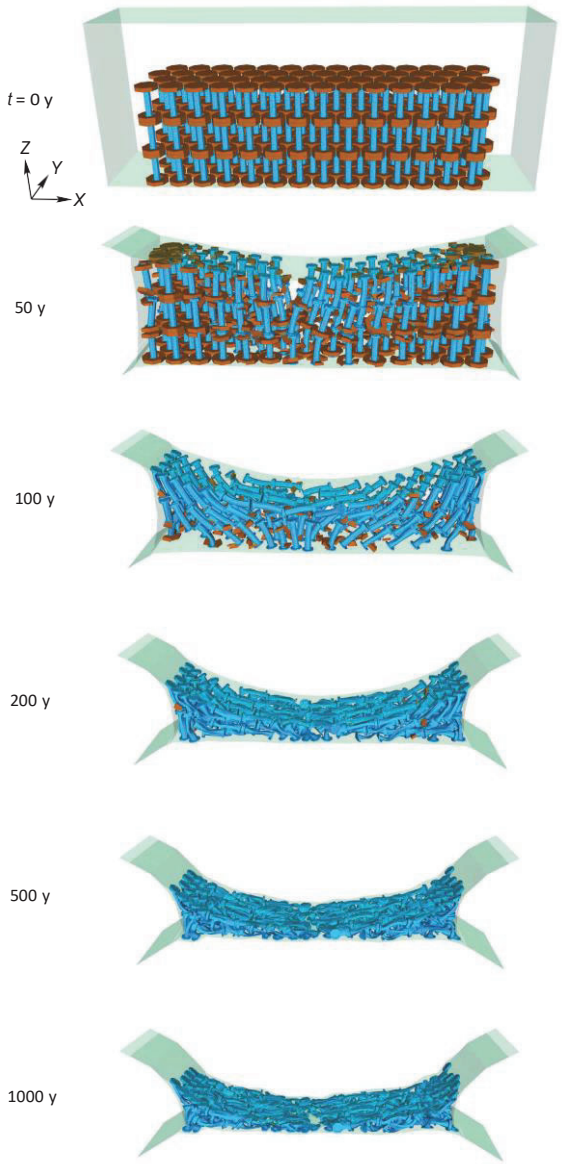


Fig. 6. Compacted array of inner containers in CCOs in a disposal room in upper salt horizon in southern portion of WIPP underground facility is not critical provided hydrogenous mass controlled or boron carbide mixed with fissile contents.[84, Fig. 9]

[s] Conversion assumes 195 MeV/fission useful energy: one ^{235}U fission = 3.124×10^{-17} MJ = 8.679×10^{-18} kW-h = 3.616×10^{-25} GW-d = 3.902×10^{-28} t ^{235}U burnup.[39, Table V]

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ORNL criticality models of spheres composed of the maximum 380 FGE ^{239}Pu for CCOs (almost double the FGE ^{239}Pu in a POC) at the predicted irregular spacing are also not critical provided the mass of hydrogenous material shipped in a CCO (usually plastics) is controlled or boron carbide (a neutron poison) is mixed with the fissile contents,[43] as specified in the WIPP Waste Acceptance Criteria (WAC).[8] The probability of criticality when the boron carbide is accidently missing or the hydrogenous mass is not controlled is estimated below in §IV.

IV.H. Slow Hydrologic/Geochemical Assembly within Repository

Mobilization of fissile material in a container, transport, and deposition in another location represents slow hydrologic/geochemical assembly. Dissolution followed by precipitation, adsorption, and/or colloid aggregation is only possible after brine seepage into a disposal room. Neither deposition in the underground facility nor deposition in the Culebra dolomite of the geologic barrier above the repository is likely to form a critical fissile assembly,[44] as summarized here.

Prior to intrusion, the hydrologic unfavorable conditions include (1) short-term gradient often causes seepage *into* disposal rooms (e.g., mean brine inflow of 27 000 m^3 and maximum inflow of 31 800 m^3 in CRA-2019);[44, Table VIII] and (2) brine seepage is completely consumed in some simulations.

Before and after intrusion, the unfavorable geochemical conditions include[44] (1) mean dissolved concentration of 8.8×10^{-4} kg/m^3 for ^{239}Pu^{III} at least 4.5 orders of magnitude less than critical concentration of 30.2 kg/m^3 in Castile brine (Fig. 8); (2) dissolved concentration of 2.4×10^{-6} kg/m^3 for ^{235}U^{IV} (CRA-2026—Fig. 5) at least 9 orders of magnitude less than critical concentration of 1550 kg/m^3 in Castile brine (Fig. 8); (3) reducing agent such as iron (Fe^0) and MgO reactant well distributed, on a macroscopic scale throughout the waste repository, which keeps brine chemistry fairly uniform with no preference for precipitation; (4) molecular diffusion is sufficient to prevent micro-environments from persisting within the repository brine chemistry; (5) adsorptive material for fissile material, such as rust and MgO, are well distributed throughout waste and repository; (6) fissile adsorption on a homogeneous mixture of rust is not critical; (7) substrates for colloid formation are well distributed throughout repository; and (8) no bioaccumulation of fissile material occurs by microbes.

After human intrusion, brine flow may move fissile material within the repository. However, the addition of copious amounts of Castile brine from a hypothetical brine reservoir below the WIPP does not substantially change pH, ionic strength, or the reduction-oxidation potential within the repository and promote sufficient precipitation, adsorption or colloidal aggregation to cause criticality (i.e., the solution concentration in Salado or Castile brine is similar for Pu^{III} and Pu^{IV} because the iron/lead in containers and the added MgO buffer the solution—Fig. 5).

IV.I. Slow Hydrologic/Geochemical Assembly in Culebra Dolomite Strata

Hydrologic conditions constrain the deposition location of fissile material released outside of the repository through an intrusion borehole.[44] The relatively greater permeability favors movement of fissile material to the Culebra Dolomite strata above the repository rather than to other strata. For undisturbed conditions of the Culebra dolomite strata (and after hundreds of years after abandoning an intrusion borehole), brackish water tend to flow into rather than out of Culebra; thus, little likelihood exists for deposition in adjacent strata (see also §VI.D).

Within the Culebra dolomite, the probability of criticality is low because of nine unfavorable deposition conditions:[44] (1) absence of strong reductants (or oxidants) in Culebra to promote precipitation; usually low masses of fissile material transported from the repository because of the low solubility of ^{239}Pu and U fissile material under reducing geochemical conditions; (2) general absence of uranium ore deposits in evaporates, such as dolomite, because carbonate tends to increase rather than decrease solubility; (3) general inability of uranium to deposit at a critical density of 240 kg/m^3 (or 9.0 kg/m^3 as 3.7% enriched ^{235}U) since concentrations found in most economically mineable ores are far less (i.e., typical uranium ore deposits in sandstone in the US vary between 1.8 and 5.3 kg/m^3 or 1000 to 3000 ppm);[33;88;89] (4) general inability of plutonium to deposit at a critical density of between 12 and 20 kg/m^3 (5900 and 9900 ppm),[46] since the deposition density higher than normally occurs in uranium ore bodies; (5) a mixing zone in Culebra dolomite that is too large to reach critical limits of 3.7 kg/m^3 for ^{239}Pu (Fig. 7) and 190 kg/m^3 as uranium (or 9.5 kg/m^3 as ^{235}U) for 5% enriched UO_2 (Fig. 8) because vast amounts of brine are usually necessary to transport low-soluble fissile material; (6) a mixing zone in the Culebra dolomite that is spread out because of the wide variation of brine flux up the intrusion borehole over time; (7) sorption concentration on Culebra dolomite for bounding ^{239}Pu and ^{235}U solubility is less than not critical limits of 3.7 kg/m^3 for ^{239}Pu (Fig. 7) and 190 kg/m^3 for ^{235}U (Fig. 8); and (8) control of filterable mineral and microbial colloids by solution concentration (i.e., equilibrium thermodynamics), which cannot exceed critical asymptotic limits.

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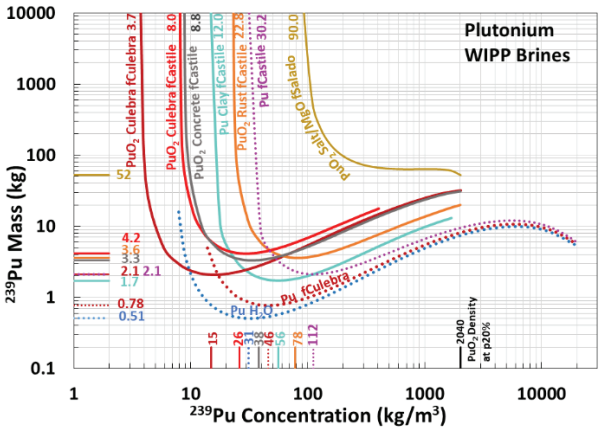


Fig. 7. Critical limits for plutonium deposited in homogeneous spherical shape in various materials at 20% total porosity saturated with water and WIPP brines.[45, Fig. 35;46, Fig. 28]

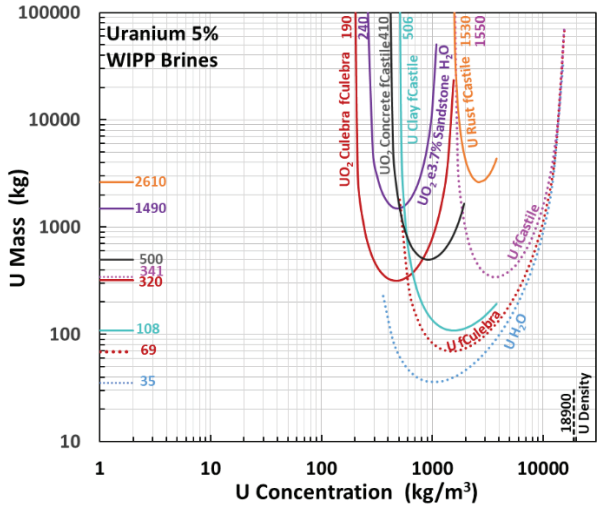


Fig. 8. Criticality limits for 5% enriched U deposited as homogeneous spherical shape in various material with 20% total porosity saturated in water and WIPP brines.[45, Figs. 34&36;46;47, Fig. 6]

IV.I.1. Geochemical Assembly with Negative Feedback

Conceptually, two types of assemblies may form from slow hydrologic/geochemical processes mobilizing, transporting, and depositing the fissile material (Fig. 3):[t] (1) a critical assembly with negative feedback as the criticality heats the fissile material and vaporizes the brine moderator such that the neutron chain reaction rapidly shuts down, and (2) a critical assembly with auto-catalytic, positive feedback as water is driven from surrounding fractures such that the neutron chain reaction continues long enough that the material surrounding the fissile material melts (discussed below in §IV.I.2).

A moderated, slow rate of assembly with negative feedback is represented by the Oklo natural reactors in uranium ore deposits in Gabon, Africa. The critical assembly formed when massive amounts of dissolved uranium in fresh water flowed through the porous sandstone, was reduced by trapped oil, and precipitated as lenticular deposits.[95] These conditions are very different from those in the WIPP disposal system, which lacks massive amounts of dissolved fissile material, lacks a strong reductant such as trapped oil, and includes the carbonate dolomite, which tends to increase solubility. Although thought to be a possible common occurrence soon after their discovery,[96] the Oklo natural reactors remain unusual; no other uranium deposits of the Proterozoic System of the Precambrian Era show evidence of forming natural reactors.

IV.I.2. Geochemical Assembly with Auto-Catalytic Positive Feedback

In late 1994, Bowman and Venneri[97] hypothesized several situations of Pu deposited in an unsaturated fracture system in volcanic tuff that could release substantial energy through positive feedback (i.e., autocatalytic behavior). In general, the configurations were either dry and under-moderated or wet and over-moderated. The dry, under moderated configuration requires a larger amount of fissile material than the wet, over moderated configuration,[90] which makes the dry, under moderated situation less likely. More importantly, the dry configuration is not possible in the brine saturated environment at WIPP with much moderating MgO and hydrogenous material, as already mentioned in §IV.B, §IV.C, and §IV.D concerning unmoderated fissile assemblies, and so it is not discussed further.

In 1996, Kastenberg et al.,[90;98-100] more closely examined potential consequences of an over-moderated ^{239}Pu deposition in fractures in the unsaturated zone of the volcanic tuff. Kastenberg et al.[90] envisioned a process initiated by sporadic deposition of fissile material in fractures of the unsaturated zone of volcanic tuff until the fissile assembly is almost critical when wet. Later, natural drying of the fissile material in the fractures and then continued natural drying of pores in the matrix in the unsaturated zone creates an assembly that is more reactive than the wet fracture assembly and thus could

[t] An alternative, previously used by the author, was to classify the critical assembly with positive feedback as a type of explosive assembly.[78, Fig. 7] With this approach, however, the low probability arguments for screening the critical assembly with negative feed must be repeated for screening the critical assembly with positive feedback. For example, Kastenberg et al.,[90] and other authors,[91-94] qualitatively refute the likelihood of assembling a critical heterogeneous configuration of fissile-filled fracture lattice with large ^{239}Pu mass capable of positive feedback, based on site characteristics. These qualitative arguments are mostly the same arguments for refuting the likelihood of assembling an Oklo-type configuration with negative feedback.

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go critical because of the moderating effects of the silicon in the tuff. Further drying from the criticality makes the assembly even more reactive (i.e., auto-catalytic behavior).

The hypothesized sequence of events is not possible at WIPP.[90] Certainly sorption, precipitation, and colloid filtering could deposit ^{239}Pu in the Culebra dolomite fracture system such that criticality can occur. However, natural drying of a large deposited fissile mass, as hypothesized by Kastenberg et al.,[90] to start and sustain the sequence of events is not possible in the *saturated* zone of the repository or Culebra dolomite at WIPP. Rather for dry out to occur in the saturated zone, intense heat from criticality must occur.[u] However, as a critical fissile assembly dries, the assembly becomes subcritical and the reaction stops until the fractures re-saturate. That is, the assembly must go critical in a mode with negative fissile material feedback and cannot jump to a mode with positive feedback. Consequently, the probability of a criticality with positive feedback is much less and, thus, bounded by the probability of criticality with negative feedback (§IV.I.1)

V. LOW PROBABILITY OF CRITICALITY IN DISPOSAL ROOMS

V.A. Computational Scenarios Formed from Moderated, Slow-Assembly Categories

We divide the slow-assembly, moderated criticality categories of §IV.G, §IV.H, and §IV.I into computational scenarios ($\mathcal{A}_m^{CS}$) based on pertinent events and features: Two events e are considered for WIPP: human disruption (designated H) and no disruption (designated U); hence, $e = \{H,U\}$.

Three feature/locations are considered. The first and second feature/locations considered are the underground repository facility (designated *rep*) and the Culebra dolomite above the repository in the natural geologic barrier (designated *Culebra*). The third feature/location is the disposal room with three container types: drum packages, POCs, and CCOs. Hence, $f = \{$*Culebra, rep, rm-drum*, *rm-POC*, and *rm-CCO*$\}$).

In the 1996 CCA, the fissile loading was similar and diffuse throughout all containers; thus, the probability of criticality scenario inside the rooms was practically zero (i.e., $\bar{\wp}\{E_{rm-drum,U}^{compact}\} \approx 0$).[33;39] But with the addition of POCs and CCOs, $\bar{\wp}\{E_{rm-POC,U}^{compact}\}$ and $\bar{\wp}\{E_{rm-CCO,U}^{compact}\}$ are potentially non zero;[v] hence, the container type is an important aspect of the criticality rationale. However, the container type is only important in the underground facility prior to extensive degradation because Pu release to the geologic barrier is solubility controlled.[44]

Other feature/locations considered in the 1996 CCA include the disturbed rock zone around the repository, anhydrite marker beds in the Salado, and the small diameter abandoned exploratory borehole. However, these feature/locations are not identified here since the amount of contaminated brine inflow (and subsequent fissile deposition) is bounded by fluid flow into the repository and the Culebra.[33, §IV.B;37,§3.5]

Feature/location is not always a convenient means of defining a scenario class in a PA since location is not associated with aleatoric uncertainty; rather, the likelihood of radionuclides such as fissile material residing in a specific location is modeled as part of epistemic uncertainty. Here, however, it useful to subdivide the criticality scenario class by location even though it is not possible to assign a distinct probability to each location.[w] The probability of fissile material in other areas of underground facility of the repository and the geologic barrier of the disposal system (i.e., $\wp\{E_{rep}\}$ and $\wp\{E_{Culebra}\}$) are eventually about one, but the probabilities do differ in the first 10^4 y.

In summary, the probability of criticality after slow assembly of the fissile material is expressed as the sum of the probability of criticality for each environment location feature f and initiating event e:

$$\bar{\wp}\{A_C\} = \sum_{m=1}^{n_{CS}} \bar{\wp}\{\mathcal{A}_m^{CS}\}$$

$$= \sum_{f}^{\substack{rm-CCO \\ rm-POC \\ rm-drum \\ rep \\ Culebra}} \sum_{e}^{\substack{U \\ H}} \bar{\wp}\{\mathcal{A}_{f,e}^{CS}\}\wp\{E_e\} \qquad (12)$$

where E_e designates an initiating event $e = \{H,U\}$).

Eq. (12) can be simplified because criticality conditions inside the room mostly consider undisturbed conditions (first term of Eq. (13) and discussed further in §IV.A) because an inadvertent human intrusion introduces brine into the room, which, in turn, greatly

[u] Drawdown from a water well is not considered.[90, p.304] Drilling a water well effectively places the boundary of the accessible environment at the water well, which would of necessity occur near the disposal area (if sufficient deposition of fissile material is to occur [44]) rather than at the legislated WIPP land withdrawal boundary. As noted in §III.B, EPA specified the four human disruptions of the WIPP disposal system that were of regulatory interest. Other speculative drilling disruptions to the disposal system such as long-term use of a water well (not just exploration) in the LWA marked by passive controls (and, thereby, bypassing the Culebra dolomite portion of the WIPP disposal system) are not required in 40 CFR 191 or 40 CFR 194.[23;28]

[v] The 2015 demonstration of combining probability and consequence used the results of the 1996 CCA, which did not include an estimate of the criticality probability/consequences in compacted CCOs.[39]

[w] The international generic FEP list compiled by the Nuclear Energy Agency for deep geologic disposal of radioactive waste identifies two criticality FEPs by location:[101] 2.3.6.6 Criticality [waste package] and 3.2.6.5 Criticality [elsewhere].[102]

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decreases the probability of criticality after compaction. Criticality conditions outside the room only consider disturbed conditions (second term of Eq. (13) and discussed further in §V.A), because an inadvertent human intrusion is necessary to promote mobilization and migration of fissile material:

$$\bar{\wp}\{A_C\} \approx \sum_{f}^{\substack{rm-CCO\\rm-POC\\rm-drum}} \bar{\wp}\{\mathcal{A}^{CS}_{f,U}\}\wp\{E_U\} + \sum_{f}^{\substack{rep\\Culebra}} \bar{\wp}\{\mathcal{A}^{CS}_{f,H}\}\wp\{E_H\} \quad (13)$$

The sum of computational scenarios to determine the total probability of criticality is strictly true only for disjoint (mutually exclusive) computational scenarios. While the events and container types are disjoint, the locations considered are not. However, the overlap of scenarios and, thereby, the double counting of probability is small, because the probability of criticality in either location is so small and independent. For example, the probability of the union of the computational scenarios in the repository and Culebra dolomite for disturbed conditions in the second term of Eq. (14) is

$$\bar{\wp}\{\mathcal{A}^{CS}_{rep,H} \cup \mathcal{A}^{CS}_{Culebra,H}\} = \bar{\wp}\{\mathcal{A}^{CS}_{rep,H}\} + \bar{\wp}\{\mathcal{A}^{CS}_{Culebra,H}\} - \bar{\wp}\{\mathcal{A}^{CS}_{rep,H} \cap \mathcal{A}^{CS}_{Culebra,H}\} \quad (14)$$

Because $\mathcal{A}^{CS}_{rep,H}$ and $\mathcal{A}^{CS}_{Culebra,H}$ are independent (i.e., criticality in the repository would not preclude criticality in the Culebra dolomite), the last term of Eq. (14) is

$$\bar{\wp}\{\mathcal{A}^{CS}_{rep,H} \cap \mathcal{A}^{CS}_{Culebra,H}\} = \bar{\wp}\{\mathcal{A}^{CS}_{rep,H}\}\bar{\wp}\{\mathcal{A}^{CS}_{Culebra,H}\} \quad (15)$$

Yet, the product, $\bar{\wp}\{\mathcal{A}^{CS}_{rep,H}\}\bar{\wp}\{\mathcal{A}^{CS}_{Culebra,H}\}$ is small relative to $\bar{\wp}\{\mathcal{A}^{CS}_{rep,H}\} + \bar{\wp}\{\mathcal{A}^{CS}_{Culebra,H}\}$ because $\bar{\wp}\{\mathcal{A}^{CS}_{rep,H}\}$ and $\bar{\wp}\{\mathcal{A}^{CS}_{Culebra,H}\}$ are both so small. Hence, Eq. (14) is approximated as

$$\bar{\wp}\{\mathcal{A}^{CS}_{rep,H} \cup \mathcal{A}^{CS}_{Culebra,H}\} \approx \bar{\wp}\{\mathcal{A}^{CS}_{rep,H}\} + \bar{\wp}\{\mathcal{A}^{CS}_{Culebra,H}\} \quad (16)$$

V.B. Types of Criticality

Two potential extremes of criticality are (1) one transient critical event (also called rapid transient[38]), or (2) numerous critical events in cyclic steady-state (also called quasi steady state[38]). The number of fission consequences from these two extremes are discussed in §VII.B. Long-term, cyclic, steady state may seemingly be less probable than one transient criticality. Yet cyclic steady-state criticality occurred at Oklo, as described in §V.C. The moderator was water at Oklo. The moderator would be the dilute Culebra brine in the Culebra and Salado brine elsewhere in the underground facility. The later heating of brine could deposit Cl^- which would complicate criticality. Also, the moderator in the disposal room would primarily be plastics, which could also add complications. Nevertheless, the author does not try to enumerate the difference; rather the probability of criticality is for one or more critical events.

V.C. Favorable Compaction Conditions in Disposal Room

For criticality to occur in an array of containers in the disposal rooms requires favorable salt-creep compaction. If one expands the criticality computational scenario inside the disposal room (Eq. (13)) to include the compaction process ($E^{favorable}_{f,e}$), then

$$\bar{\wp}\{\mathcal{A}^{CS}_{rm-CCO,U}\}(1-\wp\{E_H\}) = \bar{\wp}\{\mathcal{A}^{CS}_{rm-CCO,U} \,|\, E^{favorable}_{rm-CCO,U}\} \bullet \wp\{E^{favorable}_{rm-CCO,U}\}(1-\wp\{E_H\}) \quad \text{.....(17)}$$

where $\bar{\wp}\{\mathcal{A}^{CS}_{rm-CCO,U} \,|\, E^{favorable}_{rm-CCO,U}\}$ is the conditional probability of criticality for criticality computational scenario $\mathcal{A}^{CS}_{f,U}$ given favorable compaction conditions of package *CCO* in the disposal room for the undisturbed scenario; $\wp\{E^{favorable}_{rm-CCO,U}\}$ is the probability of favorable compaction conditions for *CCO* in disposal room for the undisturbed scenario; and the term $1-\wp\{E_H\}$ is the probability of the undisturbed scenario. Eq. (17) only considers CCOs in the room. As noted in IV.G, an analysis of compacted POCs, using a geomechanical model of gradual room closure from salt creep combined with a criticality model of spheres of fissile material at the compacted spacing shows $\wp\{E^{favorable}_{rm-POC,U}\}$ is very small and so is omitted in Eq. (17).

As also noted in IV.G, analysis of CCOs at the predicted compacted spacing found that $\wp\{E^{favorable}_{rm-CCO,U}\}$ of Eq. (17) is also very small, provided (a) hydrogenous mass (usually water and plastics) shipped in CCOs <1.5 kg or (b) boron carbide (B_4C) mass >10 g mixed with the fissile contents and hydrogenous material mass <2.8 kg).[8;43]

V.D. Probability of Undisturbed Scenario

At WIPP, the probability of undisturbed scenario (i.e., $1-\bar{\wp}\{E_H\}$ in Eq. (18)) is based on the Poisson discrete distribution function with an average rate of intrusion of $\bar{\lambda}^H_{drill}$. For $\Im$ years, the probability of no intrusion is

$$1-\bar{\wp}\{E_H\} = P\{0:\bar{\lambda}^H_{drill}\Im\} = \frac{(\bar{\lambda}^H_{drill}\Im)^0}{0!}\exp\{-\bar{\lambda}^H_{drill}\Im\} = \exp\{-\bar{\lambda}^H_{drill}\Im\} \quad (18)$$

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For CRA-2019, the probability of no intrusion into the disposal rooms over 10^4 years ($\Im$) is 1.6×10^{-5} (Eq. 18)).[x] The CRA-2019 intrusion rate $\bar{\lambda}^{H}_{drill}$ of 1.04×10^{-3} y^{-1} is based on a drilling frequency of 99 boreholes/km^2 over 10^4 years and a 0.1115-km^2 disposal area in the 10 original panels.[9, §33.3.2]

For RPPCR-23-19P, the drilling frequency is the same but for a disposal area of 0.1355 km^2 for 12 active panels (10 original plus 2 new panels); thus, the probability of no intrusion over 10^4 years is 1.6×10^{-9}.

For the final state of the WIPP repository in CRA-26-19P, the probability of no intrusion over 10^4 years is 5.9×10^{-16}, which is based on the same drilling frequency of 153.4 boreholes/km^2 over 10^4 years and a disposal area of 0.2286 km^2 for 19 panels (10 original plus 9 new panels). Hence, in CRA-2019, RPPCR-23, and CRA-26-19P, the probability of no intrusion is practicality zero.

However, most CCO compaction occurs in the first 1000 years and the probability of no intrusion is greater during this period (Fig. 9). The probability of no intrusion in the first 1000 years is 0.33 for CRA-2019, 0.26 for RPPCR-23-12P, and 0.030 for CRA-26-19P.

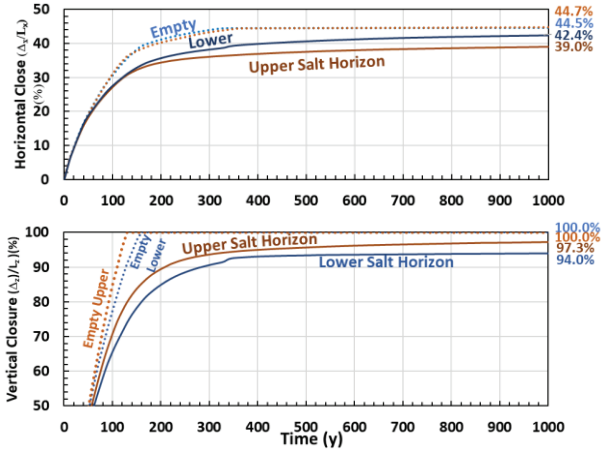


Fig. 9. Horizontal and vertical room closure at mid-height and mid-width mostly complete by 300 years but continues to 1000 years for CCOs initially emplaced in triangular array in upper and lower salt horizons.[84, Fig. 10]

V.E. Probability of Criticality with Favorable Conditions

Whether an assembly of fissile regions is critical depends upon the generation and interaction of neutrons with matter within and outside the assembly, which for a finite heterogeneous system, depends upon four general parameter categories (1) type, mass, and form of fissile material (i.e., 380 FGE ^{239}Pu as PuO_2); (2) material mixed with the fissile material and its overall concentration (e.g., moderating hydrogenous material such as water and plastics, miscellaneous non-hydrogenous filler); (3) nearby material and its concentration outside the fissile array (e.g., reflecting stainless steel, MgO, salt, and brine); and (4) shape of individual CCOs and array configuration of fissile regions and, thereby, neutron leakage (e.g., spherical or cylindrical fissile region, and irregular, nonuniformly compacted configuration of CCOs initially emplaced as either a hexagonal or triangular array). The neutron multiplication factor (k_{eff}) is a measure of this interaction.

If the parameters in the first category are fixed, the irregular CCO configuration is very important and determined by high-fidelity geomechanical modeling of salt creep closure of a room segment filled with 153 CCOs. The WIPP disposal panels are in two different but nearby horizons of the geologic strata of the Salado Formation. The 2 replacement panels and up to 9 additional panels for CCOs would likely be excavated in the lower horizon to the west of existing panels (Fig. 2). The geomechanical modeling established a reasonable compacted, irregular configuration of CCOs in the lower repository horizon for subsequent criticality evaluation with 380 FGE ^{239}Pu placed in spheres at the deformed centers of the CCOs.

The probability of criticality conditional on favorable conditions (i.e., $\bar{\wp}\{\mathcal{A}^{CS}_{rm-CCO,U} \,|\, E^{favorable}_{rm-CCO,U}\}$ in Eq. (17)) was determined from the criticality evaluation of k_{eff} using the SCALE neutron/photon transport model.[103] The criticality evaluation established that the system reactivity of the irregular, non-uniformly compacted array is due to reactivity in small, local areas, rather than global behavior of the entire system. Specifically, high neutron flux was only in local areas. Several measures of the spacing in the CCO configuration, as determined from the geomechanical modeling, were evaluated (e.g., nearest neighbor, simple CCO concentration, and relative weighted CCO concentration). High relative weighted concentration corresponded well to three high neutron flux areas of the criticality evaluation on the left side of the compacted CCOs in the lower repository horizon (Fig. 10). Thus, the locations of high relative weighted concentration (where *high* relative weighted concentration was defined as the tail of the distribution) were used to estimate percentage of containers that might go critical should favorable conditions exist. The distribution tail of the relative weighted concentration consisted of ~10% of the CCOs (specifically, 15 out of 153 CCO containers in the simulation designated by all 12 outlined red triangles, 2 purple squares, and 1 purple diamond). Hence,

[x] The drilling frequency in the 1996 CCA was 46.8 boreholes/km^2 over 10^4 years. Hence, the Poisson intrusion rate into the disposal rooms was 5.22×10^{-4} y^{-1}. Other intrusion rates can be calculated from (1) the area of the RH waste in the panel walls, which was 0.01576 km^2, (2) the entire enclosed area of the 8 disposal panels, which was 0.6285 km^2.

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$\bar{\wp}\{\mathcal{A}^{CS}_{rm-CCO,U} \,|\, E^{favorable}_{rm-CCO,U}\}$ was set at 10%. But a smaller value is reasonable: The distribution tail of the relative weighted concentration in the upper horizon is ~5% of the CCOs (8 out of 153 CCOs). [43, Fig. 37;84, Fig. 29]

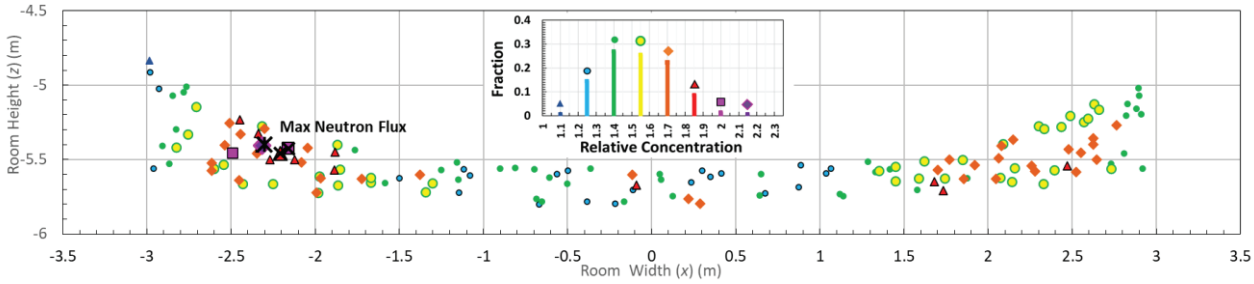


Fig. 10. Side view of the spatial distribution of relative weighted concentration at 1000 years for CCOs emplaced in lower bedded salt horizon; high neutron flux corresponds to distribution tail of relative weighted concentration.[43, Fig. 35;84, Fig. 27]

V.F. Probablity of Favorable Compaction Conditions

The criticality evaluation of CCOs established that the hydrogenous material must be limited or boron carbide mixed with CCO contents to ensure subcriticality. In turn, there is the potential for a human error to create favorable compaction conditions when boron carbide is erroneously omit $p\{E^{missB_4C}_{CCO}\}$ and the hydrogenous material content is erroneously assessed as low $p\{E^{highH}_{CCO}\}$. That is,

$$p\{E^{favorable}_{rm-CCO}\} = p\{E^{missB_4C}_{CCO} \cap E^{highH}_{CCO}\} = p\{E^{missB_4C}_{CCO}\}p\{E^{highH}_{CCO}\} \quad (19)$$

where $p\{\cdot\}$ is used rather than $\wp\{\cdot\}$ to indicate a small group of containers rather than all containers. Because the acquisition of containers with B_4C is separate from assessing the hydrogenous material, the events are independent in Eq. (19). The conditional probability for a criticality in small group of containers is

$$p\{\mathcal{A}^{CS}_{rm-CCO,U}\} = p\{\mathcal{A}^{CS}_{rm-CCO,U} \,|\, E^{missB_4C \cap highH}_{CCO}\} \cdot p\{E^{missB_4C}_{CCO}\}p\{E^{highH}_{CCO}\} \quad (20)$$

V.F.1. Possibility of Mistake in Loading Boron Carbon

For the diluted surplus Pu manufactured at SRS, the probability of mistakenly omitting 10-g boron carbon (B_4C) in a CCO is taken as 1.25×10^{-7} (i.e., $p\{E^{missB_4C}_{CCO}\}$ per container—Table II), which is the same probability assigned for mistakenly omitting boron carbon in disposal packages for the proposed YM repository.[104, Table 4.1-1;105, Fig. 6-9;106] The probability of mistakenly omitting B_4C was based on a human factor analysis of the probability of humans selecting the wrong material during manufacture of the procured handling container (i.e., "convenience can") for the CCO in nuclear facilities (10^{-4}) and the probability that an independent inspection does not detect the error (1.25×10^{-3}).[y]

V.F.2. Possibility of Mistake in Estimating Hydrogenous Material

For diluted surplus Pu from SRS, acceptable knowledge, which is any information about the process used to generate the waste,[43,§VIII.C] can demonstrate that the diluted surplus plutonium has <700 g hydrogenous material. First, the manufactured PuO_2 has an initial moisture content <10 g. Second, the adulterant used to dilute the PuO_2 is not hydroscopic and is easily bounded by 240 g. Third, the plastic bagging used to limit contamination in the two handling convenience cans is <400 g.[108, App. A] The 700 g is less than one half of the 1500 g of hydrogenous material needed to promote criticality in an irregular, compacted array of CCOs in a WIPP disposal room.[43,Table III] Furthermore, acceptable knowledge from process controls could also show that the diluted surplus Pu from SRS, has >2000 g filler, since the adulterant filler is ~3480 g.[108, App. A] Hence, any mistake in estimating hydrogenous material in CCOs from SRS, would require a procurement error, which would have a probability similar to B_4C (i.e., $p\{E^{highH}_{CCO}\}$ per container is 1.25×10^{-7}—Table II).

[y] In Swain and Gutzman,[107] the probabilities are given as nominal (represented here as median) and an error factor (EF) to calculate the 5th (i.e., μ/EF) and 95th percentile (μEF). Usually, the distribution is considered log normal, thus, the mean values are determined as

$$\mu = \exp\{\mu(y) + \frac{1}{2}\sigma^2(y)\} \text{ where } \quad \sigma(y) = \frac{\ln(L)}{1.645} \quad \text{and} \quad L = \sqrt{95^{th}\text{ percentile} / 5^{th}\text{ percentile}} = \sqrt{\frac{\mu L}{\mu / L}}$$

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V.G. Overall Criticality Probability in Disposal Room

The probability that at least two mistakes occur for a repository disposing of N_{CCO}^{WP} CCOs is given by the binomial distribution B with N_{CCO}^{WP} trials:

$$\bar{\wp}\{A_{rm-CCO,U}^{CS}\} = \bar{\wp}\{n_C > 0\} = 1 - B\{a = 1; p\{\mathcal{A}_{rm-CCO}^{CS}\}, N_{CCO}^{WP}\} \quad (21)$$

where $p\{\mathcal{A}_{rm-CCO,U}^{CS}\}$ is the probability for *small group* of containers and a is the number of combinations (here, two to evaluate the probability of at least two mistakes). Because $p\{\mathcal{A}_{rm-CCO}^{CS}\}N_{CCO}^{WP}$ is so small and N_{CCO}^{WP} so large, the binomial can be estimated by the Poisson distribution with λ equal to $p\{\mathcal{A}_{rm-CCO}^{CS}\}N_{CCO}^{WP}$. That is,

$$\bar{\wp}\{\mathcal{A}_{rm-CCO,U}^{CS}\} \approx 1 - P\{0; p\{A_{rm-CCO,U}^{CS}\}N_{CCO}^{WP}\} \approx p\{A_{rm-CCO,U}^{CS}\}N_{CCO}^{WP} \quad (22)$$

The probability can be expressed as a linear function of N_{CCO}^{WP} because $p\{\mathcal{A}_{rm-CCO}^{CS}\}$ is so small. Substituting Eq. (18) into Eq. (22) yields

$$\bar{\wp}\{\mathcal{A}_{rm-CCO,U}^{CS}\} \approx \left[p\{\mathcal{A}_{rm-CCO,U}^{CS} \middle| E_{CCO}^{missB_4C \cap highH}\} \bullet p\{E_{CCO}^{missB_4C}\} p\{E_{CCO}^{highH}\} \right] N_{CCO}^{WP} \quad (23)$$

For CRA-2019, 15 800 packages (N_{CCO}^{WP}) are necessary to ship 6.0 t of the non-pit Pu currently part of the WIPP inventory, 34 500 CCOs are necessary to ship 13.1 t of Surplus Pu analyzed in RPPCR-23-19P, and 105 300 CCOs are necessary for all 40 t of Surplus Pu for CRA-26-19P (Table II).

Consequently, the quantitative estimate of the probability of ^{239}Pu criticality in the disposal rooms is 8.2×10^{-12} in CRA-2019 and 4.9×10^{-12} in CRA-26-19P when B_4C is included in the CCO and the hydrogenous material is known to be < 700 g (Table II). The probability of ^{235}U criticality in the disposal rooms is a factor of 0.643 smaller at 5.3×10^{-12} in CRA-2019 and 3.2×10^{-12} in CRA-26-19P. The decay of ^{239}Pu would produce 100% enriched ^{235}U in the CCO. Thus, the reduction in probability of criticality is estimated by the ratio of the minimum critical mass of ^{239}Pu and minimum critical mass of ^{235}U (i.e., 0.643 from Table I).

The WIPP WAC was modified in 2023 for accepting surplus plutonium waste in CCOs.[8] This modification is reflected in CRA-26-19P. Three options were defined to provide flexibility in using CCOs with other miscellaneous generic waste forms besides surplus ^{239}Pu from SRS. The probability of ^{235}U criticality in the CCOs ($\bar{\wp}\{\mathcal{A}_{rm-CCO,U,^{235}U}^{CRA-2026}\}$) possibly increases to 6.5×10^{-6}, because only one of the two constraints for surplus ^{239}Pu from SRS would be required (Table II): either (1) B_4C content greater than 10 g, or (2) hydrogenous content less than 1.5 kg limit, as follows.

Option A specified use of 10-g B_4C; hence, the probability of an error is 1.25×10^{-7} (Table II). Option B omitted use of B_4C and instead required assessing the hydrogenous content of the CCO. Option C omitted use of B_4C and required assessing both the hydrogenous content and miscellaneous filler content of the CCO. Options B and C are combined for the probability evaluation because the important measure is the hydrogenous content. The probability of an error in estimating hydrogenous content is 1.25×10^{-7} (Table II).

The quantity of other miscellaneous waste forms that might use CCOs in the future is unknown, but the surplus Pu and other TRU destined for WIPP will mostly fill the disposal area; thus, the volume must be less than in a waste panel. A reasonable estimate is the 26 800 POCs used to package the 3.1 t of plutonium residues emplaced at WIPP (Table II), which is slightly more than 2 rooms in a panel.[41,Fig. 6]

Table II. Probability of criticality scenario subclass over 10^4 years from assembly of fissile material by compaction of CCOs in disposal room.

	Count[a] N_{CCO}^{WP}	**Probability of Criticality given Favorable Conditions** $p\{\mathcal{A}_{rm-CCO}^{CS}\}N_{CCO}^{WP}$	**Probability of B_4C Missing** $p\{E_{CCO}^{missB_4C}\}$	**Probability of Hydrogenous >1.5 kg** $p\{E_{CCO}^{highH}\}$	**Probability of Undisturbed based on Probability at 1000 y** $1-\bar{\wp}\{E_H'\}$	**Probability Overall for ^{239}Pu over 10^4 y** $\bar{\wp}\{\mathcal{A}_{rm-CCO,U,^{239}Pu}^{CS}\}$	**Probability[b] Overall for ^{235}U over 10^4 y** $\bar{\wp}\{\mathcal{A}_{rm-CCO,U,^{235}U}^{CS}\}$
CRA-26-19P							
Surplus Pu (40 t)	105 300	0.10	1.25×10^{-7}	1.25×10^{-7}	0.030	4.9×10^{-12}	3.2×10^{-12}
Option A (generic)	26 800[c]	0.10	1.25×10^{-7}	1	0.030	1.0×10^{-5}	6.5×10^{-6}
Option B or C	26 800[c]	0.10	1	1.25×10^{-7}	0.030	1.0×10^{-5}	6.5×10^{-6}
CRA-2019							
Surplus Pu (6 t)	15 800	0.10	1.25×10^{-7}	1.25×10^{-7}	0.33	8.2×10^{-12}	5.3×10^{-12}

[a] The counts assume each CCO contains 380 FGE to maximize fissile mass in a room or panel of repository. However, DOE currently plans to use a nominal loading of 330 FGE per CCO. Thus, 18 200 CCOs would be required in CRA-2019 and 121 200 CCOs in CRA-26-19P.
[b] Based on ^{239}Pu equivalence to 0.643 ^{235}U in Table I
[c] Quantity of plutonium residues packaged in POCs and emplaced in WIPP is used as surrogate for miscellaneous unknown waste stream[41,Fig. 6]

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VI. LOW PROBABILITY OF CRITICALITY IN CULEBRA GEOLOGIC BARRIER

VI.A. Possibility of Favorable Hydrologic/Chemical Conditions in Culebra

For criticality to occur in a fissile deposit in the geologic barrier of the WIPP disposal system requires favorable hydrologic mobilization and favorable geochemical deposition where the geochemical processes can include precipitation, sorption, or colloid aggregation/filtration ($E_{f,e}^{hydro\cap chem}$). If one expands the criticality computational scenario outside the room (Eq. (15)) to include favorable hydrologic and geochemical processes ($E_{f,H}^{hydro\cap chem}$), then

$$\sum_{f}^{rep\ Culebra} \bar{\wp}\{\mathcal{A}_{f,H}^{CS}\}\wp\{E_H\} = \sum_{f}^{rep\ Culebra} \bar{\wp}\{\mathcal{A}_{f,H}^{CS}\,|\,E_{f,H}^{hydro\cap chem}\}\bar{\wp}\{E_{f,H}^{hydro\cap chem}\} \quad (24)$$

where $\bar{\wp}\{\mathcal{A}_{f,H}^{CS}\,|\,E_{f,H}^{hydro\cap chem}\}$ is the conditional probability of criticality for criticality computation scenario $\mathcal{A}_{f,H}^{CS}$ given favorable hydrologic and geochemical conditions in location f after human intrusion; $\bar{\wp}\{E_{f,H}^{hydro\cap chem}$ is the probability of favorable hydrologic and geochemical conditions in location f after human intrusion; and the repository feature is considered to encompass mobilization throughout the repository including portions of the disposal room. Undisturbed conditions are not included because of the general lack of favorable hydrologic conditions prior to inadvertent human intrusion. Furthermore, the probability of one or more human intrusions into the repository is practically one over the 10^4-year regulatory period.

As noted in §IV.I, favorable hydrologic/geochemical conditions are generally absent within the Culebra dolomite; thus, the probability of criticality ($\bar{\wp}\{E_{Culebra,H}^{hydro\cap chem}\}$) is very small in Eq. (24).[44] Absent these hydrologic/geochemical constraints, the probability of criticality is estimated in the next sections for a favorable depositional environment in the Culebra dolomite (i.e., $\bar{\wp}\{\mathcal{A}_{Culebra,H}^{CS}\,|\,E_{Culebra,H}^{hydro\cap chem}\}$).

VI.B. Formulation of Criticality Probablity Given Favorable Conditions

If one assumes that the probability model for deposition in the geologic barrier given favorable conditions is a Poisson process, the formation-rate of critical deposits (i.e., failure-rate function) is defined by[109]

$$r(t) = \frac{-\mathrm{d}(\ln(1-F(t|M))}{\mathrm{d}t} \quad (25)$$

where t is the time elapsed since the disposal system was closed and $F(t|M)$ denotes the cumulative distribution function for the first time, T, when criticality occurs (i.e., $F(t|M) = \wp\{\mathcal{A}_{e,f}^{CS}(t, m(t), \mathbf{e})\}$ t≤T, conditional on the mass of fissile material (M) deposited. The formation rate function can be integrated to give

$$F(t|M) = 1-\exp\{-\int h_e(t;\mathbf{e}))\mathrm{d}t\} \quad (26)$$

The simplest form of $h_e(t;\mathbf{e})$ is a constant rate of formation

$$h_e(t;\mathbf{e}) = \dot{r}(\mathbf{e})m_e^{r_{out}}(t;\mathbf{e}) \quad (27)$$

where $\dot{r}(\mathbf{e})$ is the rate of forming a critical assembly.

Substituting Eq. (27) into Eq. (26), the mean probability of criticality in either the Culebra dolomite or repository in WIPP (i.e., location $f \Leftarrow Culebra$ or $f \Leftarrow rep$), as estimated from the mass of radionuclide r released, is

$$\bar{\wp}\{\mathcal{A}_{f,H}^{CS}\,|\,E_{f,H}^{hydro\cap chem}\} = 1-\exp\left\{-\dot{r}(\mathbf{e})\int_0^{\Im} m_{e,f}^{r_{out}}(t;\mathbf{e})\mathrm{d}t\right\} \quad (28)$$

For the situation at WIPP, the time of intrusion was assumed to occur early in the regulatory period (between 350 and 1000 years) (Table V), such that the dependence of $m_{e,f}^{r_{out}}(t;\mathbf{e})$ on time could be neglected. Then,

$$\bar{\wp}\{\mathcal{A}_{f,H}^{CS}\,|\,E_{f,H}^{hydro\cap chem}\} = 1-\exp\left\{-\dot{r}(\mathbf{e})M_{f,H}^{r}(\mathbf{e})\Im\right\} \quad (29)$$

$$\approx \dot{r}(\mathbf{e})M_{f,H}^{r}(\mathbf{e})\Im \quad \text{(For small argument)} \quad (30)$$

and

$$\bar{\wp}\{\mathcal{A}_{f,H}^{CS}\,|\,E_{f,H}^{hydro\cap chem}\} \approx \bar{\dot{r}}\bar{M}_{f,H}^{r}\Im \quad (31)$$

where $\bar{\dot{r}}$ is the expected formation rate over the epistemic uncertainty ($\mathcal{E}^E\{\dot{r}(\mathbf{e})\}$), and $\bar{M}_{f,H}^{r}$ is the expected mass release after human intrusion ($\mathcal{E}^E\{m_{e,f}^{r_{out}}(t;\mathbf{e})\}$).

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VI.C. Rate of Forming Natural Critical Assembly Based on Oklo

Analogy with the Oklo natural reactors can be used to estimate the rate of forming a critical assembly in the geologic barrier in the first 10^4 years. The value of $\bar{r}$ is bound by the product of the "microscopic efficiency" of natural concentration processes as estimated from the Oklo natural reactors. If the disruptive event produces favorable hydrologic and geochemical conditions on the scale of the repository, then a natural analogue where globally favorable conditions are known to have occurred, such as the Oklo ore body, can be used to approximate chance favorable conditions.[33,§V.B;78, §4.1.1;95;96;110,§6.3;111]

$$\bar{r}_{RN-geo} = \bar{r}^{Oklo}_{LEU,sand} f_{RN-geo} \quad (32)$$

where $\bar{r}^{Oklo}_{LEU,sand}$ is the rate of formation of low enriched uranium (LEU) in sandstone and hydrocarbons, and f_{RN-geo} is a factor that compares the minimum critical mass at Oklo with the minimum mass of the fissile radionuclide (including its enrichment) in the pertinent geologic media, as discussed below.

The Oklo ore body is one of six in the Francevillian Basin in the Republic of Gabon, Africa. The most important four ore deposits are in the northwestern edge of the basin: Maunana, Boyindzi, Oklo, and Okélobondo. Maunana was the first ore deposit discovered in 1956 and produced 5 700 t uranium. Boyindzi, though initially mined open pit, was being mined underground in 1989 with an estimated 3 100-t uranium endowment. Oklo was also initially mined open pit but was being mined underground in 1989 with an estimated 17 300-t uranium endowment. Okelobondo, a southern extension of Oklo, had only been explored with an estimated 7 400-t uranium endowment. Two other ore deposits are in the central part of the basin: Mikouloungou and Bangombe. In 1989, Mikouloungou had been partially mined with an estimated uranium endowment of 4700 t. Bangombe, had only been explored with an estimated 3000-t uranium endowment. The total uranium economically viable endowment estimated in 1989 was 41 200 t.[111] In 1999 when mining operations ceased, the Francevillian Basin had produced 28 000 t uranium.[112] All the ore deposits had been partially mined except Bangombe, which had an new estimated endowment of only 100 to 200 t.[113]

The Oklo ore body consists mostly of low grade (0.2-1 wt. % uranium) in sandstone strata that formed ~2.15×10^9 years ago (2.15 Ga).[112] Following subsidence of the sandstone formation and invasion of the ocean, a black shale formation was deposited (2.14 Ga). High concentrations of uraninite (UO_2) (>20 wt. % uranium) were formed 2.05 Ga as uranium-rich water came in contact with fault-trapped hydrocarbons (between 2.099 Ga and 2.036 Ga) from the black shale.[112]

In the Oklo ore body, lenticular regions within the high concentration of uraninite were discovered between 1972 and 1991 to have operated as natural reactors 1.95 Ga,[114] when natural uranium had a content of ~3.68 wt. % ^{235}U.[z] Also, one natural reactor was discovered in the Okélobondo area 0.5 km south of Oklo,[116] and one reactor discovered in 1986 in the Bangombé deposit 25 km southeast of Oklo. Although 18 reactor zone can be assigned (1-16 zones at Oklo, and one zone each at Okélobondo and Bangombé), only 16 reactor events are reported here because Reactors 3 through 6 at Oklo are now considered to be 2 reactors (3-4 and 5-6).[114] The number of reactor events may be less in that Reactors 11, 12, and 14 were identified by borehole analysis and not confirmed by mining (Table III).[117]

The Oklo phenomenon remains unusual because other existing uranium deposits of the Precambrian Era show no evidence of forming natural reactors. For example, the richest uranium ore deposit in the world at Cigar Lake in Canada has been present for ~1.3 Ga but shows no sign of criticality.[118;119]

Table III. Estimated Durations of Seven Reactor Zones at Oklo

Reactor Zone	Borehole/ Drift	Neutron Fluence (10^{21}n/cm^2)	^{235}U Fissioned from ^{239}Pu	Duration (ka)
2	SC-36	1.362	0.49	620[a]
7	GL-2481	0.22	0.53	350[a]
9	GL-13	0.75	0.80	220[b]
10		0.67	0.35	148
	SF-84-1469	*0.52*	*0.46*	*156*[c,d]
	SF-84-1480	*0.80*	*0.30*	*143*[c,d]
	SF-84-1485	*0.62*	*0.38*	*156*[c,d]
	SF-84-1492	*0.56*	*0.38*	*198*[c,d]
	D-81N	*0.85*	*0.24*	*85*[a]
13	SD-37	0.78	0.11	24.2[c]
Okélobondo	OK-84	0.33	0.70	270[a]
Bangombé	BA-145	0.31	0.48	110[c,e]
Average		**0.63**		**249**

[a]Ref[114, Table 1]; also Ref [115]
[b]Ref[120]; also reported as 320 ka in Ref[114, Table 1] based on range of 64 to 556 ka
[c]Ref[121, Table 4]
[d]Reported as 190 ka in Ref[114, Table 1]
[e]Reported as 300 ka in Ref[114, Table 1]

[z]An age of 1.95 Ga is most frequently cited but depends upon the U/Pb age and the assumption of no U migration. For example, the U/Pb age of Reactor 13 is 8.7 Ga assuming some migration of U. Similarly, a separate analysis of Reactor 2, with some migration, yields an estimate of 1.8 Ga[115]

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An upper bound on the rate of forming the reactors at Oklo is the time required to form the uranium-rich layer, which is about 100 Ma (2.05 – 1.95 Ga). The operating life of the natural reactors is reasonable lower bound because the early functioning of the reactors assisted in their formation. That is, convective circulation of water heated by the natural reactor continued to concentrate the ore in the reactor (up to 60 wt. %). Furthermore, up to 3 t ^{239}Pu created in the reactors, formed by neutron capture of ^{238}U,[122] decayed and supplemented the originally deposited ^{235}U in the reactor (i.e., only 2% to 6% of the ^{239}Pu is thought to have directly fissioned[123]). The reactors may have operated for 24.2 ka to 620 ka. This paper uses an average estimate of 249 ka (Table III).

While the reactors operated, quartz (SiO_2) in the sandstones was dissolved, thereby forming clays, which enclosed the natural reactors. Also, the hydrocarbons, which had caused the highly concentrated uranium, formed bitumen deposits around some of the natural reactors. Therefore, the rate $\bar{r}_{LEU,sand}$ is 2.29×10^{-9} events/t-y with 3.7 wt. % ^{235}U (i.e., $\bar{r}_{LEU,sand} = 16$ events/(28000 t-249 ka)).[aa]

Conceptually, this rate factors in microscopic inefficiencies found in nature when macroscopic physical, hydrologic, and geochemical conditions are generally favorable. For fissile material with less favorable conditions, the rate would presumably be less. For fissile material at higher enrichment, the rate would presumably be greater.

Specifically, for 3.68% enriched uranium in homogeneous Oklo sandstone at 30% porosity, the minimum critical mass is 500 kg (Fig. 11).

For Pu at 100% enrichment in Culebra dolomite at 20% total porosity (with 4% fracture porosity and 17% matrix/vug porosity) without general background fissile material, the minimum critical mass is 2.1 kg (Fig. 11). The rate would increase to 5.5×10^{-7} t^{-1}y^{-1}(Table IV) when one assumes a similar reduction of 240 (i.e., 500/2.1) in required mass occurs in a natural ore body for 100% enriched Pu in dolomite.[bb]

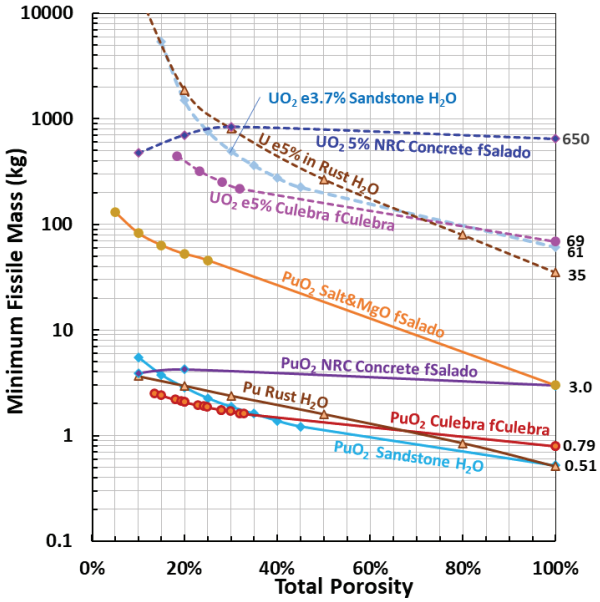


Fig. 11. Variation of minimum critical mass with total porosity for 3.7% and 5% enriched UO_2 and 100% enriched PuO_2 in homogeneous sandstone, Culebra dolomite, rust, concrete, and salt.[45, Fig. 37;47, Fig. 29]

VI.D. Fissile Release to Culebra

VI.D.1 Human Intrusion Release Scenarios

In the WIPP PA, human intrusion is divided into a drilling intrusion through repository to underlying brine pocket in the Castile Formation (A_{E1}); intrusion into the repository that misses underlying brine pocket (A_{E2}), and two intrusions the latter of which intersects an underlying pressurized brine pocket (A_{E2E1}).[29;44, Table IX;124;125] The largest releases to the Culebra typically occur from the drilling intrusion into the Castile brine pocket in scenario A_{E1} and scenario A_{E2E1} (Fig. 12).[126]

In scenario A_{E2E1}, an inadvertent intrusion into the repository occurs sometime after closure. The driller plugs the borehole using concrete (present-day technology) and abandons it. A second intrusion borehole into repository occurs 1000 years later but continues into a hypothetical underlying Castile brine pocket. The driller again plugs the borehole. Releases over the long term occur from hypothetical degradation of the concrete seal 200 years later. The concrete plug in the lower portion of second borehole fails (i.e., borehole

[aa] Here we are estimating the mean $\bar{r}_{LEU,sand}$. A similar value of 10^{-9} events/t-y for $\bar{r}_{LEU,sand}$ results when solely using the extensively studied Reactor 2, with duration of 620 ka (Table III).[39, §A.III] In contrast, the criticality screening rationale for the 1996 CCA used a bounding formation rate ($^{\max}\bar{r}_{LEU,sand}$) of 3.75×10^{-8} events/t-y based on a 150-ka duration calculated from the maximum power output of 17 kW/reactor using the information readily available on 6 reactors in 1996 (150 ka is also the duration of Reactor 10—Table III). The 6 reactors were associated with 800 t of uranium.[33;110]

[bb] A similar comparison of critical masses is also used to calculate the fissile mass equivalent of various fissile masses. Specifically, Pu fissile mass equivalence is the mass of ^{239}Pu plus factors for other fissionable masses (e.g., 0.113·^{238}Pu or 0.643·^{235}U in Table I). The factors derive from comparing the minimum critical mass of 0.45-kg ^{239}Pu in a slurry (which includes bias and 0.02 margin) to the minimum critical mass of other fissile isotopes.[3,§5.2;57,Table XVI]

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permeability set to permeability of sand), which allows brine flow through a portion of the repository and mobilizes radionuclides. The radionuclide laden flow then continues up the first intrusion borehole into the overlying Culebra dolomite.

Salt creep eventually reduces the permeability of the intrusion boreholes by up to 5 orders of magnitude;[127, Fig. 8] however, for modeling intrusion scenarios into the Castile brine pocket, the permeability is only reduced a factor of ten 1200 years after the initial intrusion but still effectively isolates the Castile brine pocket. [127, Table 1]

In the WIPP PA, the three intrusion scenarios (A_{E1}, A_{E2}, and A_{E2E1}) were further divided into computational scenarios based on the time of intrusion and type of calculation. The largest releases occur from intruding into the repository 100 years after closure. Here, we use the largest release from the brine-flow (BF) calculation from the repository up the borehole (i.e., computational scenario A_{E2E1}-BF-t100).

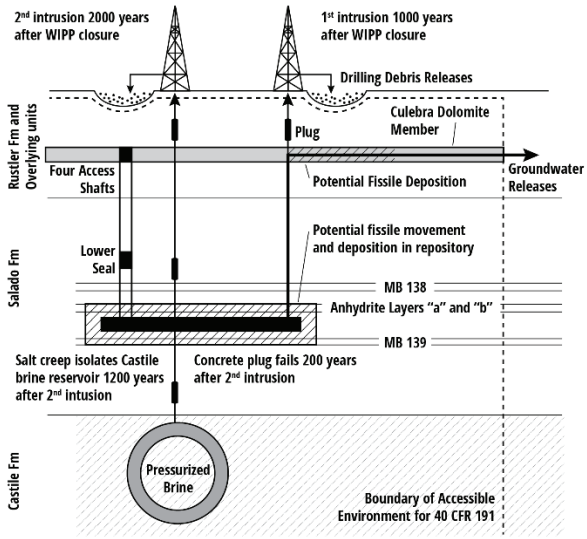


Fig. 12. Hypothetical future release of radionuclides to the Culebra Dolomite Member of Rustler Fm after two human intrusions into repository where second intrusion intersects a pressurized brine reservoir in the Castile Fm (Scenario A_{E2E1}).[33, Fig. 2;66, Figure 5.1-2]

VI.D.2 Plutonium Release to Culebra

In the WIPP PA, three replications of the calculations, each with a different starting random number, were run to evaluate potential variation in results. In each replicate, the ^{239}Pu releases are approximately log normally distributed. Hence the largest releases are several orders of magnitude greater than the mean.

For CRA-26-19P conditional on A_{E2E1} occurring with intrusion at 100 years, the ^{239}Pu mean release is 4.3×10^{-4} kg for all three replicates (Fig. 13), compared to the 4.7 kg mean release of ^{239}Pu in the 1996 CCA. The maximum is 7.7×10^{-3} kg. Both values are less than the minimum critical mass of 2.1 kg of Pu in Culebra dolomite with Culebra brine (Fig. 7). Therefore, criticality in the Culebra dolomite is not considered further for CRA-2026 (both 12 panel and 19 panel repositories).

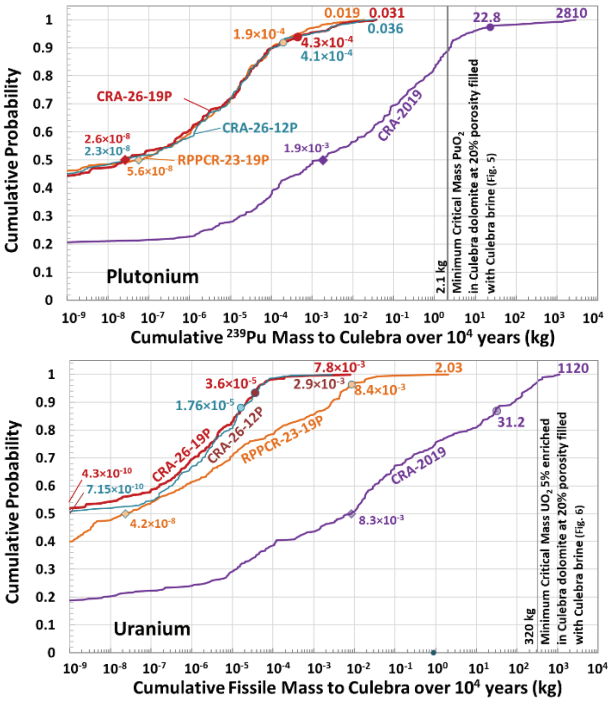


Fig. 13. Distribution of ^{239}Pu and ^{235}U releases to Culebra dolomite in CRA-26-19P, CRA-26-12P, RPPCR-23-19P, and CRA-2019 for 300 replicates for computational scenario with intrusion into underground facility and Castile pressurized brine reservoir 100 years after closure (Scenario A_{E2E1}-BF-t100).[44, Fig. 14]

For CRA-2019, the mean release is 22.8 kg ^{239}Pu for all three replicates of A_{E2E1}-BF-t100 (Fig. 13), which is a factor of 5 larger than the 4.7 kg mean release of ^{239}Pu in the 1996 CCA.

VI.D.3 Uranium Release to Culebra Dolomite

The mean ^{235}U release to the Culebra dolomite in CRA-26-19P is 3.6×10^{-5} kg, with a maximum of 7.8×10^{-3} kg (Fig. 13). Both the mean and maximum are less than the 320 kg minimum mass required for criticality in Culebra dolomite with Culebra brine for 5% enriched uranium (Fig. 8); thus, uranium criticality in the Culebra dolomite is not discussed further for CRA-2026.

The mean ^{235}U release to the Culebra dolomite in CRA-2019 is 31.2 kg with a maximum of 1120 kg. Although much of the ^{235}U is eventually from the decay of ^{239}Pu, the fissile transport through the underground

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facility and up the intrusion borehole would blend the ^{235}U with the transporting ^{238}U. After 10^4 years, the average enrichment is ~4.5% in CRA-2019 (Table I).

VI.E. Mistakely Observing Unfavorable Hydrologic and Geochemical Conditions in Culebra

The 1996 CCA only evaluated the conditional probability of critically given favorable hydrologic and geochemical conditions (i.e., $\bar{\wp}\{\mathcal{A}^{CS}_{Culebra,H} \,|\, E^{hydro\cap chem}_{Culebra,H}\}$). Here, we want to estimate the probability of criticality in the Culebra in order to combine with criticality in room and a repository panel. Hence, $\bar{\wp}\{E^{hydro\cap chem}_{Culebra,H}\}$ must be evaluated. To specify a degree of belief about the presence of favorable hydrologic/geochemical conditions for deposition of fissile material in the Culebra dolomite, we make an estimate of the probability that the WIPP project mistakenly missed the presence of favorable hydrologic/geochemical conditions in the Culebra dolomite.

The probability estimate is 10^{-5} (Table IV), which is an order of magnitude greater than used for the mistake in using B_4C in a CCO, because the evaluation is of a natural system that is not designed. The probability is not larger because of the extensive peer review of the Culebra characterization for the initial 1996 CCA, the continued monitoring of Culebra conditions during WIPP operations, and the periodic peer review about every five years.

VI.F. Quantitative Estimate of Criticality Probability in Culebra

For CRA-2026 and RPPCR-23, not enough fissile mass reaches the Culebra to form either a ^{239}Pu or ^{235}U criticality assembly (Fig. 13).

For CRA-2019, the quantitative probability of ^{239}Pu criticality under favorable conditions in the Culebra dolomite ($\bar{\wp}\{\mathcal{A}^{CS}_{Culebra,H} \,|\, E^{hydro\cap chem}_{Culebra,H}\}$) is 1.5×10^{-7} over 10^4 years ($\mathfrak{T}$) for a maximum Pu release ($\bar{M}^{r}_{f,H}$) of 2810 kg for all replicates for computational scenario with intrusion into repository and Castile pressurized brine reservoir 100 years after closure (i.e., $\bar{\wp}\{\mathcal{A}^{CS}_{Culebra,H} \,|\, E^{hydro\cap chem}_{Culebra,H}\} \approx \bar{r}^{Oklo}_{LEU,sand} f_{RN-geo} \bar{M}^{r}_{f,H} \mathfrak{T}$). The probability of ^{235}U criticality under favorable conditions is 3.2×10^{-10} based on the maximum 1120 kg of ^{235}U (Fig. 13) brought to the Culebra (Table IV).

Table IV. Probability of criticality after fissile material deposited in Culebra dolomite for CRA-2019 and CRA-26-19P

Analysis	Fissile Material	Adjust Factor (Fig. 11) $f_{RN\text{-}geo}$	Adjusted Rate $\bar{r}_{LEU,sand} f_{RN-geo}$ ($t^{-1}y^{-1}$)	Mass Available (Fig. 13) $\bar{M}^{r}_{f,H}$ (kg)	Conditional Probability[a] (over 10^4 y given favor conditions) $\bar{\wp}\{\mathcal{A}^{CS}_{f,H} \,|\, E^{hydro\cap chem}_{f,H}\}$	Error in Finding Favorable Conditions	Probability after Intrusion (over 10^4 y) $\bar{\wp}\{\mathcal{A}^{CS}_{f,H}\}$
CRA-26-19P	^{239}Pu	500/2.1	5.5×10^{-7}	3.1×10^{-2}	0	10^{-5}	0
	^{235}U e5%	500/400	2.9×10^{-9}	7.8×10^{-3}	0	10^{-5}	0
CRA-2019	^{239}Pu	500/2.1	5.5×10^{-7}	2810	1.5×10^{-2}	10^{-5}	1.5×10^{-7}
	^{235}U e5%	500/400	2.9×10^{-9}	1120	3.2×10^{-5}	10^{-5}	3.2×10^{-10}

[a] In 2015 demonstration using the 1996 CCA, the conditional probability of criticality in ^{235}U was estimated at 4.4×10^{-7} for the Culebra dolomite geologic barrier.[39, Table II]

VII. LOW PROBABILITY OF CRITICALITY IN UNDERGROUND FACILITY

VII.A. Adjusted Rate of Criticality

Hydrologic and geochemical constraints limit the possibility of criticality elsewhere in the repository (i.e., $\bar{\wp}\{E^{hydro\cap chem}_{f,H}\}$ is likely very small in Eq. (24) as described in §IV.H). However, the probability of criticality is estimated here for a more favorable deposition environment in the repository (i.e., $\bar{\wp}\{\mathcal{A}^{CS}_{f,H} \,|\, E^{hydro\cap chem}_{f,H}\}$).

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Rust from degraded CCOs, concrete in various locations about the repository, or a mixture of salt and MgO around CCOs are plausible materials for deposition of mobilized and transported ^{239}Pu in the repository. For $^{239}PuO_2$ deposited in rust, f_{RN-geo} is 167 because the minimum mass 3 kg in rust at 20% porosity is much smaller than the 500 kg of UO_2 in Oklo sandstone (Fig. 11). Hence, $\overline{\dot{r}}_{Pu,rust}$ is 3.8×10^{-7} $t^{-1}y^{-1}$ (Table V). For criticality of 100% enriched $^{239}PuO_2$ at 10% porosity in concrete, f_{RN-geo} is 125 because the minimum mass is 4 kg in concrete at 10% porosity (Fig. 11). Hence, $\overline{\dot{r}}_{Pu,concrete}$ is 2.9×10^{-7} $t^{-1}y^{-1}$. For $^{239}PuO_2$ deposited in mixture of salt and MgO, f_{RN-geo} is 3.85 because the minimum mass 130 kg in salt/MgO mixture at 5% porosity (Fig. 11). Hence, $\overline{\dot{r}}_{Pu,salt\&MgO}$ is 8.8×10^{-9} $t^{-1}y^{-1}$.

The methodology is similar for UO_2 in rust, but for 5% enriched U the rate of formation is 3.8 orders of magnitude lower for rust ($\overline{\dot{r}}_{U,rust}$) and 2 orders of magnitude lower for concrete ($\overline{\dot{r}}_{U,concrete}$) (Table V). The adjusted rate for ^{235}U deposition in salt/MgO is too small to consider.

VII.B. Mistakely Observing Unfavorable Hydrologic/Geochemical Conditions in Underground

Again, we make an estimate of the probability that the WIPP project mistakenly missed the presence of favorable hydrologic/geochemical conditions throughout the repository during the initial characterization over 23 years between initial site selection in 1974 and submission of the 1996 CCA,[29] continued monitoring of conditions over the next 28 years between 1996 and 2024, and subsequent peer review during the recertification of WIPP in 2004, 2009, 2014, and 2019. The probability estimate for a mistake in evaluating the WIPP underground engineered system is 10^{-6}, which is one order of magnitude greater than for the precisely controlled procurement of CCOs, and one order of magnitude less than for Culebra dolomite characterization (Table IV).

VII.C. Fissile Material Mobilized and Criticality Probability in Underground

The amount of fissile material mobilized, transported, and deposited elsewhere in the repository is set at the amount of waste in CCOs in a panel, like the situation in WIPP performance assessments. In CRA-26-19P, the 40 t of surplus Pu in 105 300 containers (Table II) is more than enough to fill a panel of 76 360 CCOs; thus, the ^{239}Pu mass is 2.9×10^{4} kg, based on 0.38 kg/CCO.

For CRA-26-19P, the probability of criticality in the underground facility is 2.0×10^{-7} (Table V), based on combining the adjusted rate of criticality, mass available, and probability of mistakenly missing the presence of favorable conditions for both ^{239}Pu and ^{235}U fissile material.

The amount of ^{235}U that is produced from decay of 2.9×10^{4} kg ^{239}Pu over 10^{4} y is ~7250 kg in CRA-26-19P. Thus, the probability of criticality in ^{235}U in the underground is 2.2×10^{-10} (Table V)

In CRA-2019, the 6 t of surplus Pu in 15 800 CCOs only partially fills a panel. Thus, the amount of ^{239}Pu in a panel is 6000 kg. The corresponding probability in ^{239}Pu is 4.1×10^{-8} (Table V). The amount of ^{235}U that is produced from decay of 6000 kg ^{239}Pu over 10^{4} y is ~1500 kg. Thus, the correspond probability in ^{235}U is 4.6×10^{-11} (Table V) in CRA-2019.

A reasonable minimum for the amount of fissile material mobilized, transported, and deposited elsewhere in the repository is the same amount that eventually goes up the borehole and is released to the Culebra dolomite, as discussed above in §IV.D: maximum of 3.1×10^{-2} kg ^{239}Pu and 7.7×10^{-3} kg ^{235}U for CRA-26-19P and 2810 kg ^{239}Pu and 1120 kg ^{235}U CRA-2019 (Fig. 13). For CRA-26-19P, the corresponding ^{239}Pu probabilities for the repository is over 10^{4} years ($\Im$) are 2.1×10^{-13} (versus 2.0×10^{-7} in Table V); the corresponding ^{235}U probabilities for the repository are 2.4×10^{-16} (versus 2.2×10^{-10} in Table V).

For CRA-2019, the fissile mass released to the Culebra dolomite is of the same order of magnitude as present in a panel; hence, the probability of criticality in the underground does not change much: 1.9×10^{-8} (versus 4.1×10^{-8} in Table V) for ^{239}Pu and 3.4×10^{-11} (versus 4.6×10^{-11} in Table V) for ^{235}U.

VII.D. Quantitative Estimate of Criticality Probability in Underground

For CRA-26-19P, the probability of post-closure criticality is 2.0×10^{-7} over 10^{4} years (Table V), which is the combination of the probability in the underground for both ^{239}Pu and ^{235}U with the inconsequential probability of criticality in compacted CCOs (3.2×10^{-12}—Table II) and zero probability in the Culebra dolomite (Table IV).

For CRA-2019, the probability of post-closure criticality is 2.35×10^{-7} over 10^{4} years (Table V).

Table V. Probability of criticality over 10^{4} years after fissile material mobilized and deposited elsewhere in underground facility for CRA-2019 and CRA-26-19P.

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Analysis	Fissile Material	Location in Repository	Adjust Factor (Fig. 11) $f_{RN\text{-}geo}$	Adjusted Rate $\overline{\dot{r}}_{LEU,sand} f_{RN-geo}$ ($t^{-1}y^{-1}$)	Mass Available $\overline{M}^{r}_{f,H}$ (kg)	Conditional Probability (over 10^4 y given favor conditions) $\overline{\wp}\{\mathcal{A}^{CS}_{f,H} \mid E^{hydro\cap chem}_{f,H}\}$	Error in Finding Favorable Conditions	Probability after Intrusion (over 10^4 y) $\overline{\wp}\{\mathcal{A}^{CS}_{f,H}\}$
CRA-26-19P	^{239}Pu	Rust (p20%)	500/3.0	3.8×10^{-7}	2.9×10^{4}	1.1×10^{-1}	10^{-6}	1.1×10^{-7}
		Concrete (p10%)	500/4.0	2.9×10^{-7}	2.9×10^{4}	8.3×10^{-2}	10^{-6}	8.3×10^{-8}
		Salt&MgO (p5%)	500/130	8.8×10^{-9}	2.9×10^{4}	2.6×10^{-3}	10^{-6}	2.6×10^{-9}
						^{239}Pu Subtotal for Repository Scenario		2.0×10^{-7}
						^{239}Pu Subtotal for Repository, Culebra, CCO Compaction Scenarios		2.0×10^{-7}
	^{235}U e5%	Rust	500/1870	6.1×10^{-10}	7250	4.4×10^{-5}	10^{-6}	4.4×10^{-11}
		Concrete	500/470	2.4×10^{-9}	7250	1.8×10^{-4}	10^{-6}	1.8×10^{-10}
						^{235}U Subtotal for Repository Scenario[a]		2.2×10^{-10}
						^{235}U Subtotal for Repository, Culebra, CCO Compaction Scenarios		2.2×10^{-10}
						Total for all Scenarios and Fissile Material		2.0×10^{-7}
CRA-2019	^{239}Pu	Rust	500/3.0	3.8×10^{-7}	6000	2.3×10^{-2}	10^{-6}	2.3×10^{-8}
		Concrete	500/4.0	2.9×10^{-7}	6000	1.75×10^{-2}	10^{-6}	1.7×10^{-8}
		Salt&MgO	500/130	8.8×10^{-9}	6000	5.3×10^{-4}	10^{-6}	5.3×10^{-10}
						^{239}Pu Subtotal for Repository Scenario		4.1×10^{-8}
						^{239}Pu Subtotal for Repository, Culebra, CCO Compaction Scenarios		2.3×10^{-7}
	^{235}U e5%	Rust	500/1870	6.1×10^{-10}	1500	9.2×10^{-6}	10^{-6}	9.2×10^{-12}
		Concrete	500/470	2.4×10^{-9}	1500	3.65×10^{-5}	10^{-6}	3.65×10^{-11}
						^{235}U Subtotal for Repository Scenario[a]		4.6×10^{-11}
						^{235}U Subtotal for Repository, Culebra, CCO Compaction Scenarios		3.7×10^{-10}
						Total for all Scenarios and Fissile Material		2.35×10^{-7}

[a]In 2015 demonstration using the 1996 CCA, the conditional probability of criticality in ^{235}U was estimated at 4.0×10^{-8} for the underground facility. The rate of criticality in the underground facility ($\overline{\dot{r}}_{LEU,sand} f_{RN-geo}$) was lower but the available ^{235}U mass was much larger than more realistically estimated here.[39, Table II]

VIII. SCREENING CRITICALITY VIA CONSEQUENCES

VIII.A. Consequence Screening Approach

The consequence criterion for screening a FEP or scenario class, such as criticality, can be met in several ways:[31] (a) a reasoned rationale that inclusion of a scenario class would not influence timing or magnitude of the performance measure, (e.g., subsidence in formations far from repository); (b) directly calculating the performance measure from the scenario class and showing that it is sufficiently small (e.g., the calculated releases when including leakage into the repository from flooding of a nearby oil well in secondary recovery operations), or (c) calculating a secondary intermediate measure that is indirectly related to the primary performance measure (e.g., number of fissions produced in a computational scenario of criticality, as used in this paper).

To exclude criticality using a low-consequence rationale in a practical sense, one assumes criticality is possible and evaluates the incremental consequence of the criticality relative to the expected performance measure (or some secondary measure). For some FEPs and scenario classes, it may be possible to show that the maximum conditional consequence, *unweighted* by its probability, is trivial within the regulatory period, such that it is not necessary to calculate $\overline{\wp}\{A_j\}$ in order to show that the increment of the performance measure is unimportant. (i.e., $\overline{\mathcal{R}}_j << \overline{R}_{total}$ where $\overline{\mathcal{R}}_j$ is the cumulative releases of computational scenario j unweighted by its probability and $\overline{\mathcal{R}}_j << \overline{R}_{total}$ is total cumulative release consequences). An example of an unweighted trivial consequence $\overline{\mathcal{R}}_j$ is that of a meteor impact at the surface on the closed underground facility 658 m below surface (Fig. 2). Earth destroying asteroids are not included; hence, probability still enters into the rationale indirectly.[cc]

Likewise, the difficulty when estimating criticality consequences is that the consequences are a strong function of the processes that assemble the fissile mass that, in turn, establish the initial and

[cc] Thus, an additional practical screening criterion is omission of FEPs that cause catastrophes that greatly exceed consequences from the release of radionuclides from the repository.

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boundary conditions under which a nuclear reaction would occur. For example, the initial conditions establish the maximum energy release in a single transient criticality (similar to the situation that occurs in a criticality accident). Likewise, the boundary conditions, which couple the heat energy from the criticality with the thermal-hydrologic response of the system, determine the operation of cyclic steady-state criticality (similar to situation at the Oklo natural reactors).[33,§V.D;78, §4.1.1;95;96;110,§6.3;111;128]

When evaluating consequences of a criticality, the initial and boundary conditions of the fissile configuration analyzed must have a reasonable possibility of occurring. Thus, consequences and probability cannot be cleanly separated. The inability to reach a consensus on what constitutes reasonable conditions for a criticality scenario class can cause difficulties, as evident from the controversy related to consequences from a transient criticality in the tuff geologic barrier at the proposed Yucca Mountain repository.[39;78;90-93;97;106]

One may avoid much of the controversy, however, by presenting the probability-weighted consequences (i.e., risk) that have been calculated. The product of the expected consequence from criticality and its probability is very small relative to the total consequence because the probabilities are very low (i.e., $\bar{R}_C < R_C^{-} \bullet \bar{\wp}\{A_C\} << \bar{R}_{total}$). Consequently, the risk of criticality provides a useful viewpoint this is discussed in §XII.

When calculating the risk product, one is in essence conducting a mini-PA to provide a rough estimate of the incremental consequence of criticality to show that $\bar{R}_C$ is inconsequential. Certainly, the mini-PA may span the spectrum from a simple bounding estimate of $\bar{R}_C$ using the product of R_C^{-} and $\bar{\wp}\{A_C\}$ (Eq. (11)) to an elaborate analysis that calculates an approximation of $\bar{R}_C$ by calculating many $\sum_{m=1}^{n_{CS}} \bar{\mathcal{R}}_m^{CS} \bullet \bar{\wp}\{\mathcal{A}_m^{CS}\}$ pairs (Eq. (9)).

Although a consequence rationale can involve the complicated coupling of salt-creep analysis and thermal analysis with criticality evaluation,[dd] here, we use rough analytical estimates.[106;131]

VIII.B. Types of Consequences from Criticality

On the surface in the presence of humans, the usual consequence of interest is the direct dose from neutrons and gamma rays during a critical event. For criticality in a closed repository, the consequences are delayed. Consequences from a critical event might include (a) increased actinides and fission products produced by the event and ultimately the increased hazard from radionuclide release at the disposal system boundary, and/or (b) compromising the isolating and stabilizing functions of the disposal system such as damaging the engineered or geologic barriers through the release of kinetic energy or through additional of heat energy.

For the discussion, this paper selected the total fissions produced for use in a screening rationale as a measure of the criticality consequences. As with cumulative releases ($\bar{R}_C$) the total fissions of the criticality scenario class ($\bar{F}_C$) increases (1) directly via the criticality event, and/or (2) indirectly by compromising the isolating and stabilizing functions of the repository and promoting early release of fission products contained in the repository. For WIPP, the consequences are cumulative over the regulatory period ($\Im$=10^4 y), (i.e., $\Sigma\bar{F}_C \equiv \int_0^{\Im} \bar{\mathcal{F}}_C(t)\mathrm{d}t$).

The potential direct fission consequences and indirect disruptive consequences from both types of criticalities are evaluated below after a discussion of the decreased health hazard from plutonium fissions.

VIII.C. Decrease in Hazard from Plutonium Fission

Fissions from both fissile U and Pu criticality are included when evaluating the additional fissions made available by *indirect* disruptive consequences. However, to properly account for the increased radiologic hazard, only the fissions from ^{235}U criticality are considered when evaluating the *direct* health consequence because criticality involving ^{239}Pu is beneficial in that the total hazard of the fission radionuclides produced in the criticality is less than the original hazard of ^{239}Pu radionuclide after 110 years.[37;78] To demonstrate this point, the integral of the EPA performance measure (Eq. (1)) is equated to $S_r(\mathbf{p})$, that is,[37;78]

[dd] The direct evaluation of the effect of the increased heat and actinide/fission product inventory requires elaborate models and coupling of these models. This coupling of the nuclear dynamics and resulting heat energy with the thermal-hydrology of the unsaturated zone in the geologic barrier was first explored for DOE-managed spent nuclear fuel in the proposed Yucca Mountain repository in volcanic tuff in 1995.[129, Vol. 2 Fig. 10-5] More recently, an analysis has examined the coupling of a steady-state and transient criticality inside a large dual-purpose canister for commercial spent nuclear fuel with heat and fluid flow around the canister in hypothetical alluvial and shale repositories.[130]

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$$R_{total}(\mathbf{p}) = \frac{1}{f_{actvty}} \sum_{r=1}^{n_r} \frac{1}{L_r} S_r(\mathbf{p}) \quad (33)$$

For a waste consisting only of ^{239}Pu, R_{total} is $R_C^{^{239}Pu}$ and equal to unity when $S_{^{239}Pu} = f_{actvty} L_{^{239}Pu}$. If f_w is also unity, then $S_{^{239}Pu} = L_{^{239}Pu}$. $L_{^{239}Pu}$ is 100 Ci for ^{239}Pu, which is equivalent to 1.6 kg. To identify the consequences of the fission of ^{239}Pu, all 1.6 kg of ^{239}Pu was converted to its fission radionuclide products.[132] Then the contribution to $R_C^{^{239}Pu}$ of each fission product was calculated as a function of time as the fission products decay. After 110 years, the contributions to R_C^{239Pu} from the fission products are less than the initial 1.6 kg of ^{239}Pu (Table VI).

Thus, if a subsurface criticality occurs with ^{239}Pu and the fission products are not substantially more mobile than ^{239}Pu (which is valid for the reducing environment at WIPP), then the hazard is less than before criticality, based on the current estimates of the health hazard of the fission products relative to plutonium. A similar benefit occurs when using Pu in mixed oxide fuel in nuclear reactors or proposals to transmute Pu in nuclear reactors or accelerators (e.g., as proposed in 2007 US Global Nuclear Energy Partnership).

Table VI. Summed EPA units of fission products of ^{239}Pu at various times.[37, Table 7;39, Table III;78, Table II]

Elapsed time since fission (y)	Summed EPA Units of ^{239}Pu Fission Products[a,b] ($R_C^{^{239}Pu}$)
0	1.0000
0.003	11.1790
10	8.8538
100	1.1047
110	0.8794
1000	0.0004
10000	0.0003

[a]Based on release limits (surrogate of health hazard) in 40 CFR 191 (Eq. (33)) for fissions products of one initial EPA unit of ^{239}Pu

[b]Release limit for ^{239}Pu ($L_{^{239}Pu}$) is 100 Ci; $t^{1/2}_{^{239}Pu}$ is 2.406 × 10^4 y; mass $M_{^{239}Pu}$ is 1.60091 kg

IX. STEADY-STATE FISSION CONSEQUENCES OF CRITICALITY

IX.A. Steady-State Fissions in Disposal Rooms Prior to Mobilization

About 8.4×10^{24} total cumulative fissions are possible after a cyclic, steady-state criticality in CCOs in the disposal rooms ($\Sigma\bar{\mathcal{F}}^{CS}_{rm-CCO,U}$) for CRA-26-19P and 1.3×10^{24} fissions for CRA-2019. The probability-weighted cumulative ^{235}U fission consequences are very small: 1.35×10^{16} and 3.6×10^{15} fissions, respectively for CRA-26-19P and CRA-2019 in Table VII).

The conditional state-state fissions ($\Sigma\mathcal{F}^{CS}_{rm-CCO,U,^{235}U}$) are based on the product of (a) 10^4-y duration ($\mathfrak{I}$); (b) ^{235}U mass available; and (c) average ^{235}U consumption rate. For CRA-26-19P, the available ^{235}U mass in a disposal room is estimated as 10^3 kg (Table VII), based on 10% of the 105 300 CCOs in room (§IV.F—Table II) each with 0.38 kg ^{239}Pu of which ~25% decays over 10^4 years after WIPP closure.

$$\bar{F}^{CS}_{rm-CCO,U,^{235}U} = \Sigma\mathcal{F}_{rm-CCO,U,^{235}U} \bullet \bar{\wp}\{\mathcal{A}^{CS}_{rm-CCO,U,^{235}U}\}$$
$$= \mathfrak{I} M^{favor}_{rm-CCO,U,^{235}U} \bar{\dot{r}}^{Uburn} \bullet \bar{\wp}\{\mathcal{A}^{CS}_{rm-CCO,U,^{235}U}\} \quad (34)$$

As described in §IV.C, up to ~10% of CCOs may go critical under favorable conditions inside the disposal area. For CRA-2019, the available ^{235}U mass in CCOs disposed in a room is 150 kg ($M^{favor}_{rm-CCO,U,^{235}U}$—Table VII).

The average ^{235}U consumption rate ($\bar{\dot{r}}^{Uburn}$) of 8.4×10^{20} fissions/y-t-^{235}U is estimated as follows: Six closely grouped natural reactor zones in the Oklo ore body were extensively studied in the 1970s. Researchers estimated that ~6 t of ^{235}U was consumed out of the surrounding ~800 t of high-grade uranium ore with an enrichment of ~3.68%.[95;122] The circulation of heated water possibly contributed to the continued formation of the fissile assembly, but here, the author assumes that the entire mass was initially available such that the burn-up consumption of ^{235}U was 20.4%, based on consumption of 6 t of ^{235}U out of a total of 29.4 t (i.e., 3.68% of 800 t) over the 6.2×10^5-y duration of the Oklo Reactor 2 (Table III). Thus, the estimate of annual fissions per mass of ^{235}U is 20.4%(2.563×10^{27} fissions/t ^{235}U)/6.2×10^5 y) or 8.4×10^{20} fissions/y-t-^{235}U.

The WIPP WAC allows for some miscellaneous fissile material to be disposed in CCOs.[42;43] This miscellaneous fissile volume is constrained to a few rooms, as noted earlier in §IV.F, since surplus Pu and other TRU destined for WIPP will mostly fill the disposal area. Here, the mass is set at 255 kg in 26 800 CCOs (number of POCs used to dispose Pu residues—Table II); thus, the conditional steady-state fissions are 2.1×10^{24} (Tables II and VII). The probability of ^{235}U criticality in the CCOs ($\bar{\wp}\{\mathcal{A}^{CRA-2026}_{rm-CCO,U,^{235}U}\}$) increases to 6.5×10^{-6}; thus, the number of probability-weighted ^{235}U fissions in a room possibly increases to 1.4×10^{19} (Table VII), because only one of two constraints

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would be required: either (1) B_4C content greater than 10 g, or (2) hydrogenous content less than 1.5 kg limit.

Table VII. Mean conditional and probability-weighted cumulative ^{235}U fission consequences of steady-state criticality in rooms, underground facility, and geologic barrier over 10^4-y regulatory period.

Location	^{235}U Mass Available $M^{favor}_{f,e,^{235}U}$ (kg)	Conditional Steady-State Consequence[a] $\Sigma\overline{F}^{CS}_{f,e,^{235}U}$	Computational Scenario Subclass ^{235}U Probability $\overline{\wp}\{\mathcal{A}^{CS}_{f,e,^{235}U}\}$	Probability Weighted ^{235}U Consequence $\Sigma\overline{F}^{CS}_{f,e,^{235}U}$
CRA-26-19P Surplus Pu in CCOs				
Rooms[b]	1 000	8.4×10^{24}	3.2×10^{-12}	2.7×10^{13}
Repository Deposition[c]	7 250	6.1×10^{25}	2.2×10^{-10}	1.35×10^{16}
Culebra Deposition[d]	7.8×10^{-3}	0	0	0
Total		6.9×10^{25}	2.2×10^{-10}	1.35×10^{16}
CRA-26-19PAdded Generic Pu with either B_4C (Option A) or Hydrogenous Limit (Option B/C)				
Rooms[b]	255	2.1×10^{24}	6.5×10^{-6}	1.4×10^{19}
Repository Deposition	2550	2.1×10^{25}	2.2×10^{-10}	4.7×10^{15}
Total (Surplus + Generic)		9.3×10^{25}	6.5×10^{-6}	1.4×10^{19}
CRA-2019				
Rooms[b]	150	1.3×10^{24}	5.3×10^{-12}	6.6×10^{12}
Repository Deposition[c]	1 500	1.3×10^{25}	4.6×10^{-11}	5.8×10^{14}
Culebra Deposition[d]	1 120	9.4×10^{24}	3.2×10^{-10}	3.0×10^{15}
Total		2.3×10^{25}	3.7×10^{-10}	3.6×10^{15}

[a] Cyclic steady-state condition assumes 8.4×10^{20} fissions/y-t-^{235}U with duration of 10^4 y
[b] Probability of criticality computational scenario subclass for CCOs in rooms taken from Table II.
[c] Probability taken from Table V
[d] Probability taken from Table IV

IX.B. Steady-State Fissions in Repository from Mobilized Panel Mass

The cumulative fissions (conditional on criticality occurring) after a cyclic, steady-state criticality elsewhere in underground facility ($\Sigma\overline{F}^{CS}_{rep,H}$), are 6.1×10^{25} fissions and 1.3×10^{25} fissions of ^{235}U, respectively, for CRA-26-19P and CRA-2019 (Table VII), based on the product of (a) average ^{235}U consumption rate of 8.4×10^{20} fissions/y-t ^{235}U, (b) 10^4-y duration, and (c) maximum ^{235}U mass available (7250 kg ^{235}U in CRA-26-19P and 1500 kg in CRA-2019—Fig. 13). The probability-weighted fission cumulative consequences are very small: 1.35×10^{16} fissions and 5.8×10^{14} fissions in CRA-26-19P and CRA-2019, respectively (Table VII).

IX.C. Steady-State Fissions in Culebra Dolomite

The conditional cumulative ^{235}U fissions possible after a cyclic, steady-state criticality in the Culebra dolomite of the geologic barrier ($\Sigma\overline{F}^{CS}_{Culebra,H}$), are 9.4×10^{24} fissions for CRA-2019 (Table IV), based on the product of (a) average ^{235}U rate of consumption of 8.4×10^{20} fissions/y-t-^{235}U, (b) 10^4-y duration, and (c) maximum ^{235}U mass available (1 120 kg ^{235}U in CRA-2019—Fig. 13). The probability-weighted ^{235}U fission cumulative consequences are very small: 3.6×10^{15} fissions for CRA-2019 (Table VII).

IX.D. Inconsequential Fissions

The exclusion of a FEP or scenario class based on a low-consequence rationale, depends upon the significance of estimates of the FEP consequences for criticality $\overline{R}_C$ (or the fission surrogate $\overline{F}_C$ for the criticality example here) relative to total consequences ($\overline{R}_{total}$ or $\overline{F}_{total}$). Thus, any consequence screening rational must to some extent recognize the estimate of $\overline{R}_{total}$ or $\overline{F}_{total}$.[31] For the 1996 CCA,[29;32;133] $\overline{R}_{total}$ was solely from cuttings brought to the surface from an inadvertent intrusion. For CRA-2019 and CRA-2026, the cuttings are still very important. In turn, the cuttings releases depended primarily on the inventory of radionuclides and so the change in inventory caused by a criticality is useful for comparison.

The author uses 10^{24} fissions (1% of the approximate average of 7.0×10^{25} and 1.3×10^{26} estimated fissions represented in RH-TRU waste in CRA-26-19P and CRA-2019, respectively), beyond which fission consequences are considered *de minimus*. The potential probability-weighted fissions in the disposal rooms prior to mobilization estimated in §VIII.B above for CRA-26-

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19P and CRA-2019 are respectively 11 and 12 orders of magnitude less than this *de minims* value.

The fissions represented by the small amount of fission products in RH-TRU waste are estimated as follows. As noted in §VIII.A, a heat power of 5 kW (~4.6%) is from RH-TRU in CRA-2019, of which 1.6 kW is from decay of fission products contained in spent nuclear fuel (SNF) fragments. The 1.6 kW of the RH-TRU roughly represents 1.3×10^{26} total cumulative fissions $\bar{F}_{total}$ if one assumes the initial thermal heat for a typical (in 2008) commercial SNF package to be disposed at the proposed Yucca Mountain repository at the Nevada Nuclear Security Site (i.e., 10.5 kW/pkg[134, Table 1] for a package with 8.4 t-U/pkg,[106, Fig. 7] 38 GW-d/t-U,[135] and 2.765×10^{24} fissions/GW-d).

The RH-TRU waste in CRA-26-19P has a heat power of 2.5 kW, of which 0.83 kW is from fission products. The total cumulative fissions ($\bar{F}_{total}$) represented in 0.83 kW of the RH-TRU is roughly 7.0×10^{25} fissions, assuming characteristics of a typical commercial SNF package to be disposed at the proposed Yucca Mountain repository in 2008.

X. STEADY-STATE HEAT OF CRITICALITY

X.A Decay Heat in Disposal Rooms

The projected activity of TRU waste in WIPP for CRA-2019 is 6.1 MCi (230 PBq) with a thermal power of 109 kW at WIPP closure in 2033 or 93 kW ten years later (Fig. 14).[48] Of the projected 109 kW for CRA-2019,[48] 95.4% is from radioactive decay of CH-TRU actinides, of which 29.6% is from ^{238}Pu (generated at SRS for power generators in space and elsewhere), 25.6% from ^{239}Pu, 9.3% from ^{240}Pu, and 35.4% from ^{241}Am. The remaining 4.6% of the 109 kW is primarily from fission product decay in RH-TRU of ^{90}Y (21.5% and in secular equilibrium with parent of ^{90}Sr) and ^{137m}Ba (18.4% and in secular equilibrium with parent of ^{137}Cs) and the actinides ^{238}Pu (14.5%) and ^{244}Cm (22.7%). The fission products are from contaminated material that results when examining and reprocessing fuel elements for producing ^{239}Pu.

Because ~77% of the RH-TRU thermal power is from short-lived fission products and actinides, the activity drops more than CH-TRU over 10^4 years, but not as much as glass HLW stored at SRS (where only the SRS portion of HLW and N-Reactor portion of SNF managed by DOE is shown to compare with the mass of WIPP TRU waste).

Including 40 t of surplus Pu for CRA-26-19P increases the activity and thermal power.[49] The projected emplaced activity of CH-TRU waste for CRA-26-19P is 9.3 MCi (300 PBq) with a thermal power of 279 kW at WIPP closure in 2083 (Fig. 14). Of the projected 279 kW,[49] 18.7% is from ^{238}Pu (at SRS), 46.5% from ^{239}Pu, 12.3% from ^{240}Pu, and 21.4% from ^{241}Am.

The projected thermal power of RH-TRU waste for CRA-26-19P is 3.0 kW at WIPP closure in 2083 and primarily from fission product decay of ^{90}Y (11.4% and parent of ^{90}Sr) and ^{137m}Ba (10.4% and parent of ^{137}Cs). Other important actinides are ^{238}Pu (29.0%), ^{241}Am (20.0%), and ^{244}Cm (12.1%).

In comparison, the 1996 CCA had a projected activity of 7.88 MCi (290 PBq) and a thermal power of 136 kW, as of December 1995.[18, App. BIR Rev. 2] The projected thermal power at closure in 2033 was ~102 kW (Fig. 14).

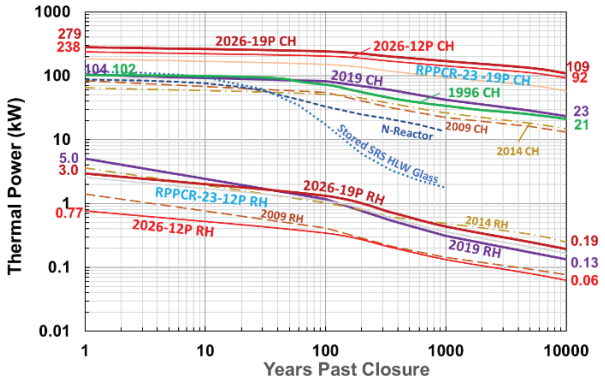


Fig. 14. Inventory thermal power, which derives primarily from Pu isotopes, for disposition of 6-t (CRA-2019), 13.1-t (RPPCR-23-12P), and 40-t surplus Pu (CRA-26-19P) compared to thermal power of past WIPP evaluations.[11;12;18, App. BIR Rev. 2;19;20;48;52;136]

X.B Steady-State Criticality Heat in Disposal Rooms Prior to Mobilization

Based on 8.4×10^{20} fissions/y-t ^{235}U (§VIII.A and Table VII) produced by a cyclic steady state criticality, the corresponding thermal heat is 0.8 kW in CRA-26-19P (using conversion of one fission is 8.679×10^{-18} kW-h). Although the direct consequence of ^{239}Pu criticality is beneficial, the indirect heat consequence is not necessarily beneficial. The ^{239}Pu heat would be ~3.2 kW (4 times greater than ^{235}U because of 4 times greater ^{239}Pu mass). For CRA-2019, the corresponding ^{235}U heat consequence is 0.12 kW and the ^{239}Pu heat consequence is 0.50 kW.

The 0.5 kW is a factor of 200 less than the 104-kW decay heat of the TRU waste at WIPP closure in 2033 for CRA-2019; the 3.2 kW is a factor of 90 less than 279-kW decay heat at WIPP closure in 2083 for CRA-26-19P (Fig. 14). Furthermore, the 0.5 kW for CRA-2019 and 3.2 kW for CRA-26-19P are still less than that of the TRU waste after 10^4 years: <23 kW for CRA-2019 and <109 kW for CRA-26-19P (Fig. 14). This thermal heat is conditional on criticality occurring (not the probability-weighted thermal heat). Hence, the heat

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generated during cyclic, steady-state criticality remains within the envelope of heat generated during normal evolution of the disposal system and has no indirect consequence.

X.C. Steady-State Criticality Heat in Repository from Mobilized Panel Mass

To be consistent with the probability estimate and PA analysis, the mass of fissile material mobilized, transported, and deposited inside the underground facility is reasonably set at the maximum fissile mass in a repository panel disposing of CCOs: maximum of 29 000 kg ^{239}Pu and maximum of 7250 kg ^{235}U in CRA-26-19P and 6000 kg ^{239}Pu and 1500 kg ^{235}U in CRA-2019.

The conditional ^{239}Pu heat consequences from the estimated fissions (Table VII) are 24 kW for CRA-26-19P and 5 kW for CRA-2019, which are a factor of 12 below the initial 279 kW decay heat of CRA-26-19P and factor of 20 below the initial 104 kW decay heat of CRA-2019 (Fig. 14). Both values are of no consequence.

X.D. Steady-State Criticality Heat in Culebra Dolomite

The maximum ^{235}U and ^{239}Pu mass carried to the Culebra dolomite in CRA-2019 is respectively 1120 kg and 2810 kg (Fig. 13). The corresponding conditional heat is respectively 0.93 kW and 2.3 kW.

These conditional heat estimates for the Culebra dolomite are reasonable based on bounding estimates using critical asymptote concentrations and the estimated power density of the Oklo natural reactors. Specifically, the volume occupied by 2 810 kg of ^{239}Pu is <760 m^3 in CRA-2019, based on a critical concentration of 3.7 kg/m^3 for PuO_2 in Culebra dolomite with Culebra brine (Fig. 7). The partially pressurized natural uranium reactors at Oklo were estimated to have reached 650 K at a power density of ~0.1 kW/m^3.[38;95;122;137] The power produced by a similar critical assembly in the Culebra dolomite would amount to 76 kW for ^{239}Pu in CRA-2019, which bound the estimates of 1.1 W and 2.3 kW above.

XI. TRANSIENT CONSEQUENCES OF CRITICALITY AFTER HUMAN INTRUSION

Presumably, the theoretical energy release of a transient event would thoroughly disrupt the configuration such that it would only occur once during the regulatory period. As discussed below, the cumulative fissions produced from the transient event are unimportant in comparison to fissions potentially produced by cyclic steady-state fission of sufficient duration. Furthermore, any indirect consequences that might occur at WIPP are also small.

XI.A. Transient Fission Consequences

The anthropogenic, aqueous-type accidents in nuclear fuel processing plants (i.e., ^{235}U and ^{239}Pu aqueous solutions) and criticality experiments mentioned in §IV.F, were used as an analogue for estimating energy release from a transient critical event after fissile material is mobilized, elsewhere in underground facility, and Culebra dolomite.[78;131] The observed energy releases from aqueous accidents have a mean of 5.8×10^{18} fissions/event (§IV.F).[78, Tables II and III;81;138]

For CRA-26-19P and CRA-2019, the probability-weighted direct transient consequences from ^{235}U criticality are imperceptible relative to the steady-state direct consequences (e.g., 1.9×10^{7} fissions and 1.3×10^{9} fissions for the disposal room and elsewhere in underground facility in, based on probabilities in CCOs for CRA-26-19P—Table VII).

XI.B. Disruption of Salado Salt in Underground Facility

By analogy to criticality accidents, the potential damage to the salt from a transient criticality is negligible. Specifically, the small amount of rapidly produced energy, from an average 3.2×10^{19} total fissions (~1 GJ or 240 kg TNT explosive),[78, Tables II and III;81;138] would be unlikely to cause any significant damage to the immediate rock located 658 m below the surface at the repository horizon.

In rock of any type, the potential void created would have a small radius as shown by using an empirical equation developed for designing buildings that may experience explosive mishaps.[139] The radius of a potential spherical camouflet (cavity void plus the debris) formed beneath the surface from an explosion is roughly[37;78;139ee]

$$r_{cav} = 0.483 m_{exp}^{0.252} d_{depth}^{0.135} \quad (35)$$

where r_{cav} is void radius (m), m_{exp} is mass of explosive (kg), and d_{depth} is depth below surface (m). The explosive mass rather than the energy from the explosive is used in the empirical expression because the exponent is so small (~1/4); the type of rock is not used for rough estimates because it has a secondary effect.

A potential cavity of ~4.6 m radius would occur in the underground facility 658 m below the surface (Fig. 2), a diameter slightly more than twice the original 4-m height of the disposal rooms. Furthermore, the potential cavity radius is much less (1.4 m) if only prompt 6×10^{17}

[ee] Originally expressed as $r_{cav} = 1.053 w_{exp}^{0.252} f_{depth}^{0.135}$ where r_{cav} and f_{depth} are in feet, and w is pounds of explosive.

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fissions are used, as originally argued in the rationale for excluding criticality in the 1996 CCA.[37, §6.4] Hence, there are no measurable indirect transient consequences.

In comparison to 1961 Project Gnome, DOE detonated a 3.1-kilotonne nuclear explosive 361 m below the surface in the Salado Formation at a site ~13 km south of the WIPP waste disposal area (Fig. 1).[140] The explosion created an approximately spherical cavity with a total void volume of ~27 200 m^3 with equivalent radius of 18.7 m (Fig. 15).

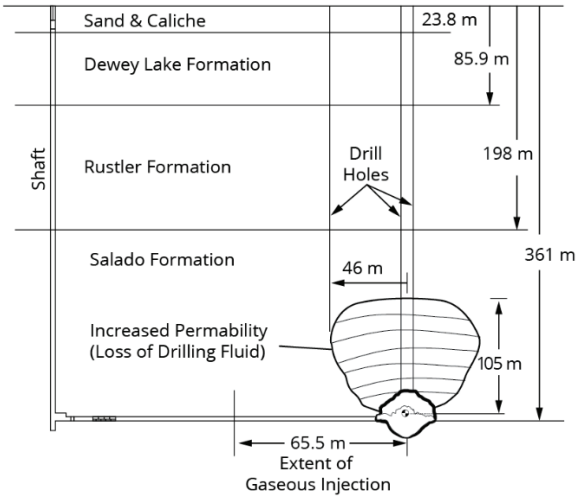


Fig. 15. Stratigraphic layers and cross section of 27 200-m^3 Gnome cavity void produced by 3.1-kt nuclear explosive 361 m below the surface in the Salado Formation ~13 km south of WIPP.[140, Fig. 2.2]

The hemispherical cavity above the rubble and salt melt had a volume of ~24 180 m^3 (with equivalent radius of 22.6 m).[140, App. D] Rock melt injected in fractures was observed 40 m laterally, 38 m above, and 25 m below the explosion center.[140, p. 44] Evidence of gaseous injection in bedding planes was observed out to 65.5 m. Increased permeability was observed (from loss of fluid when drilling postshot boreholes) in a cone that extended >46 m laterally and 105 m above the explosion center. The empirical relationship in Eq. (36) estimates a camouflet radius of 46 m.

XI.C. Disruption of Culebra Dolomite

The potential damage to the dolomite from a transient criticality of the site is minor, as estimated by analogy to surface criticality accidents and experiments with an average of 5.8×10^{18} fissions per incident. The potential camouflet radius is similar at the shallower depth of 216 m for the Culebra as calculated in the Salado salt for the underground facility (4.0 m versus 4.6 m radius).

The energy release from the hypothesized configuration in volcanic tuff with positive feedback, as described in §IV.I.2 provides a useful bound on physical damage consequences in the Culebra,[ff] because the strength of the vuggy Culebra is less (e.g., intact core cannot be retrieved from Unit 3[46, Fig. 3]). Bowman and Venneri estimated an energy release of 630 GJ for 108 kg ^{239}Pu).[31;78;106] Kastenberg et al.[90] bound the energy release at 1.3 TJ (0.31 kilotonne TNT) from the homogenization of 254 kg of ^{239}Pu.[90;100] About 0.31 kt would produce a camouflet radius of 4.2 m.

These energy releases would not likely vent to the surface, because the Culebra is 216 m below the surface. As cited by Kastenberg et al.,[90] the rule of thumb at the Nevada National Security Site is that venting is unlikely (i.e., an nuclear explosion was contained) provided the depth exceeds 120·(energy in kilotonne)$^{1/3}$ (i.e., 120·(0.31 kt)$^{1/3}$= 81 m < 216 m).[141]

XII. RISK OF CRITICALITY

Risk is generally used to express some measure that combines the gravity of harm to something valued that is caused by FEPs (or scenarios formed from these FEPs) and the probability of the FEPs or scenarios.[64] As shown in Eq. (1), EPA selected the cumulative release of radioisotopes over 10^4 years as the indicator of the gravity of harm (i.e., consequences) and the mean complementary cumulative distribution function (CCDF) of the cumulative release as its measure, which includes the product with the FEP probability. Regardless of the degree of computational sophistication used, a CCDF is a convenient approach for showing the interplay between $\bar{R}_m^{CS}$ and $\bar{\wp}\{\mathcal{A}_m^{CS}\}$ in Eq. (9), based on the discretization of the criticality event into m computational scenarios: The CCDF of $\bar{R}_C$ is

$$\wp\{\bar{R}_C > R\} = 1 - \mathcal{G}(\bar{\mathcal{R}}_m^{CS}) \tag{36}$$

$$= \sum_{m=1}^{n_{CS}} \mathcal{E}^A\{\mathcal{H}\{\bar{\mathcal{R}}_m^{CS}\,\bar{\wp}\{\mathcal{A}_m^{CS}\} - R\} \tag{37}$$

where R is number ≥ 0; $\mathcal{G}(x)$ is cumulative distribution of x; and $\mathcal{H}\{x\}$ is Heaviside indicator function with $\mathcal{H}\{x\} = 0$ if $x \leq 0$ and $\mathcal{H}\{x\} = 1$ if $x > 0$. The expression in Eq. (37) can be implemented by ordering $\bar{\mathcal{R}}_m^{CS}$ from least to greatest, and then pairing with the estimated cumulative probability $\sum_{n=m}^{n_{CS}} \bar{\wp}\{\mathcal{A}_n^{CS}\}$.

[ff] In using this analogy to an explosive force, the author does not mean to imply the nuclear positive feedback hypothesis dismissed in §IV.I.2 (Fig. 3). Rather, the analogy in which the fission energy is all converted to kinetic energy (such as through the buildup of steam pressure in a container) allows one to bound the potential damage consequences. The release of kinetic energy from rapid thermal heating would be slower than either a chemical (or nuclear explosion), and so the conversion to TNT represents an upper bound.

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Herein, *m* computational criticality scenarios in Eq. (37) are expressed by the location and container type features and disruptive event ($\mathcal{A}^{CS}_{f,e}$) (for example, $\mathcal{A}^{CS}_{rm-CCO,U}$ for undisturbed conditions inside the disposal room for the CCOs) and the conditional cumulative fissions ($\Sigma\mathcal{F}^{CS}_{f,e}$) are used as a surrogate for the conditional cumulative releases ($\bar{\mathcal{R}}^{CS}_{m}$). Only one CCDF for each criticality computational scenario is generated here because of the use of mean values over the epistemic uncertainty (i.e., $\bar{\wp}\{\mathcal{A}^{CS}_{rm-CCO,U}\}$ and $\Sigma\bar{F}^{CS}_{rm-CCO,U}$)).

The total CCDF, formed from the sum of the individual CCDFs of criticality in the disposal room, underground facility and the Culebra ($\mathcal{A}^{CS}_{rm-CCO,U}$, $\mathcal{A}^{CS}_{rep,H}$, and $\mathcal{A}^{CS}_{Culebra,H}$), show the estimated probabilities and consequences are small (Fig. 16). Specifically, the total criticality probability for CRA-2019 $\bar{\wp}\{\mathrm{A}_C^{CRA-2019}\}$ is 2.35×10^{-7} and 2.6 orders of magnitude below the regulatory limit (Fig. 16). The total probability $\bar{\wp}\{\mathrm{A}_C^{CRA-2019}\}$ includes the probability of criticality in uranium and plutonium, but the consequences of ^{239}Pu criticality are only indirect and difficult to estimate. The probability-weighted consequence of ^{235}U criticality is ~5 orders of magnitude below a reasonable *de minimus* of 10^{24} fissions (i.e., $\bar{\wp}\{\mathrm{A}_C^{CRA-2019}\}\bullet\Sigma\mathcal{F}^{CRA-2019}_{f,e}=5.5\times10^{18} < 10^{24}$). The bounding CCDF assuming the maximum screening probability of 10^{-4} over 10^4 years is still small (i.e., $10^{-4}\Sigma\mathcal{F}^{CRA-2019}_{f,e}=2.3\times10^{21}$).

The total criticality probability for CRA-26-19P $\bar{\wp}\{\mathrm{A}_C^{CRA-2026}\}$ of 2×10^{-7} is 2.7 orders of magnitude below the regulatory limit of 10^{-4} over 10^4 years. The bounding CCDF of the estimated total probability and summed consequence is small (i.e., $\bar{\wp}\{\mathrm{A}_C\}\bullet\Sigma\mathcal{F}^{CRA-2026}_{f,e}$ $=1.4\times10^{19}$), as represented by the dashed CCDF of Fig. 16.

When including the possibility for some miscellaneous fissile material to be disposed in CCOs,[42;43] the probability of ^{235}U criticality in CCOs ($\bar{\wp}\{\mathcal{A}^{CRA-2026}_{rm-CCO,U,^{235}U}\}$) increases to 6.5×10^{-6} and the number of probability-weighted ^{235}U fissions in a room possibly increases to 1.4×10^{19} (Fig. 16). The bounding CCDF for ^{239}Pu criticality ($\bar{\wp}\{\mathcal{A}^{CRA-2026}_{rm-CCO,U,^{239}Pu}\}$) has probability 10^{-5} and probability-weighted ^{235}U fissions of 9.3×10^{20} (Fig. 16).

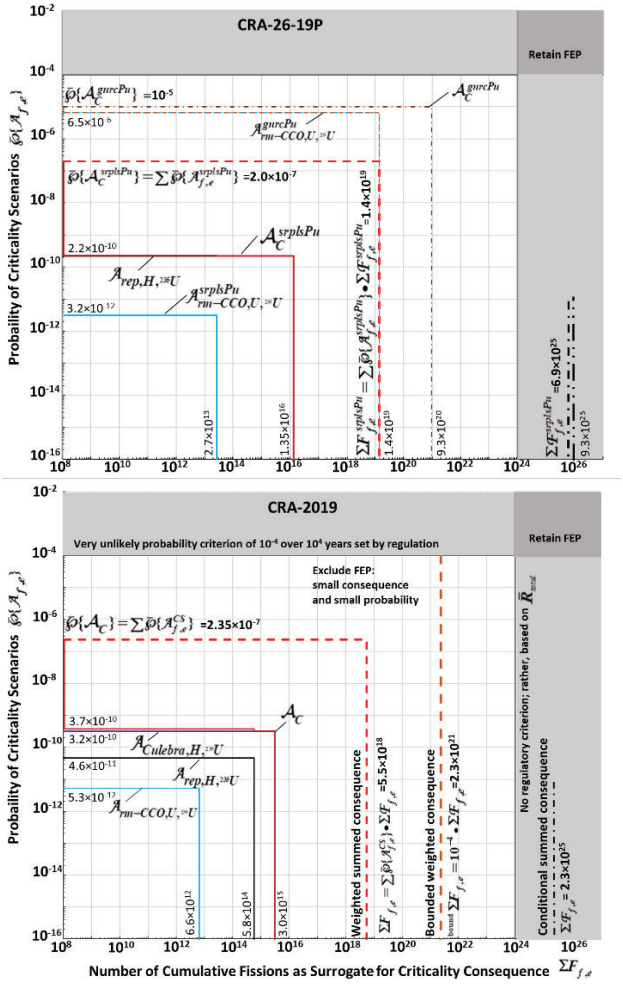


Fig. 16. CCDFs of total criticality scenario class A_C and individual computational scenarios $\mathcal{A}^{CS}_{rm-CCO,U}$, $\mathcal{A}^{CS}_{rep,H}$, and $\mathcal{A}^{CS}_{Culebra,H}$ for CCOs with surplus Pu in CRA-2019 and CRA-26-19P (Tables II, IV, V, VII).

XIII. SUMMARY

The criticality scenario class is not included when assessing the performance of WIPP in relation to EPA post-closure standards because of its low probability and low consequence. The low probability and low consequence rationale presented here consider inventory of 6-t and 40-t surplus plutonium waste and modeling changes related to the 2019 and 2026 Compliance Re-certification Applications (CRA-2019 and CRA-26-19P). The evaluation will also indirectly support updates to environmental impact statements for (1) expanding the disposal area of the underground facility (but not increasing the legislated maximum TRU waste volume),

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and (2) accepting 34-t for surplus plutonium disposition as CH-TRU waste.[15;16]

The qualitative reasoning that criticality will not occur, as presented in three companion reports, was summarized in §IV. In addition, this article presents quantitative reasoning that criticality has low risk at WIPP, particularly CCOs with surplus Pu contents, as follows.

XIII.A. Low Probability of Criticality at WIPP

The probability of criticality at WIPP is quantitatively approximated as the sum of (1) probability of criticality in CCOs in the disposal room prior to an inadvertent human intrusion, (2) probability of criticality elsewhere in repository after human intrusion, and (3) probability of criticality in the Culebra dolomite after human intrusion. That is,

$$\overline{\wp}\{\mathcal{A}_C\} \approx \overline{\wp}\{\mathcal{A}^{CS}_{rm-CCO}\}(1-\overline{\wp}\{E'_H\}) + (\overline{\wp}\{\mathcal{A}^{CS}_{rep,H}\} + \overline{\wp}\{\mathcal{A}^{CS}_{Culebra,H}\})\overline{\wp}\{E_H\} \quad (38)$$

As summarized in the next sections, the quantitatively estimated probability of ^{239}Pu criticality is 2.0×10^{-7} and ^{235}U criticality is 2.2×10^{-10} in CRA-26-19P (Fig. 16). The quantitatively estimated probability of ^{239}Pu criticality is 2.0×10^{-7} and ^{235}U criticality is 3.7×10^{-10} in CRA-2019.

XIII.A.1. Low Probability of Undisturbed Scenario

At WIPP, the probability of undisturbed scenario is based on the Poisson discrete distribution function. For CRA-26-19P, the probability of no intrusion over 10^4 years is 4.7×10^{-10}. For CRA-2019, the probability of no intrusion into the disposal rooms over 10^4 years is 1.6×10^{-5}. Hence, in both CRA-2019 and CRA-26-19P, the probability of no intrusion is negligible. However, most CCO compaction occurs in the first 1000 years and the probability of no intrusion is greater during this period. The probability over 1000 years (i.e., $1-\overline{\wp}\{E'_H\}$ in Eq. (38)) is 0.030 and 0.33 for CRA-26-19P and CRA-2019, respectively.

XIII.A.2. Low Probability of Criticality in Disposal Room

The probability of criticality in a disposal room ($\overline{\wp}\{\mathcal{A}^{CS}_{rm-CCO}\}$) was quantitatively estimated as the product of probability of favorable compaction conditions ($p\{\mathcal{A}^{CS}_{rm-CCO,U}\,|\,E^{missB_4C\cap missH}_{CCO}\}$); probability of mistakenly omitting B_4C neutron poison in a CCO ($p\{E^{missB_4C}_{CCO}\}$); probability of mistakenly estimating the amount of hydrogenous material in a CCO ($p\{E^{missH}_{CCO}\}$); and the number of CCOs (N^{WP}_{CCO}). That is,

$$\overline{\wp}\{\mathcal{A}^{CS}_{rm-CCO,U}\} \approx p\{\mathcal{A}^{CS}_{rm-CCO,U}\,|\,E^{missB_4C\cap highH}_{CCO}\} \bullet p\{E^{missB_4C}_{CCO}\}p\{E^{highH}_{CCO}\}N^{WP}_{CCO} \quad (39)$$

The number of CCOs (N^{WP}_{CCO}) for CRA-26-19P is 105 300 and for CRA-2019, 15 800 (Table II). The criticality evaluation established that the system reactivity of the irregular, non-uniformly compacted array of CCOs was due to reactivity in small, local areas, rather than global behavior of the entire system. Thus, the probability of criticality given favorable conditions (i.e., $p\{\mathcal{A}^{CS}_{rm-CCO,U}\,|\,E^{missB_4C\cap highH}_{CCO}\}$ in Eq. (37)) was set at 0.10.

For the diluted surplus Pu manufactured at SRS, the probability in mistakenly omitting 10-g boron carbon in a CCO (i.e., $p\{E^{missB_4C}_{CCO}\}$) is taken as 1.25×10^{-7} per container, which was based on a human factor analysis of the probability of humans selecting the wrong material during manufacture of the procured handling container. Any mistake in estimating hydrogenous material in CCOs from SRS (i.e., $p\{E^{highH}_{CCO}\}$) would also require a procurement error, which would have a probability of 1.25×10^{-7} per container (like B_4C).

Consequently, the quantitative estimate of the probability of ^{239}Pu criticality in CCOs in the disposal rooms is 4.9×10^{-12} in CRA-26-19P and 8.2×10^{-12} in CRA-2019. The probability of ^{235}U criticality in CCOs in the disposal rooms is somewhat smaller at 3.2×10^{-12} in CRA-26-19P and 5.3×10^{-12} in CRA-2019 (Fig. 16 and Table II).

XIII.A.3. Low Probability of Criticality Elsewhere in Underground Facility after Fissile Mobilization

The probability of criticality elsewhere in the underground facility was quantitatively estimated as the product of the probability of criticality given favorable conditions in a repository panel, the probability of favorable criticality conditions in the underground facility, and the probability of inadvertent human intrusion into the underground facility:

$$\overline{\wp}\{A^{CS}_{rep,H}\}\overline{\wp}\{E_H\} = \overline{\wp}\{A^{CS}_{rep,H}\,|\,E^{hydro\cap chem}_{rep,H}\}\,\overline{\wp}\{E^{hydro\cap chem}_{rep,H}\}\overline{\wp}\{E_H\} \quad (40)$$

The probability of ^{239}Pu criticality given favorable conditions in a repository panel ($\overline{\wp}\{A^{CS}_{rep,H}\,|\,E^{hydro\cap chem}_{rep,H}\}$) is estimated as 2.0×10^{-1} for CRA-26-19P based on the analogy to Oklo natural reactors and the maximum mass of 2.9×10^4 kg of ^{239}Pu in a panel. The probability of ^{235}U criticality given favorable conditions is 2.2×10^{-4}. The probability of errors in finding favorable conditions in the repository ($\overline{\wp}\{E^{hydro\cap chem}_{rep,H}\}$) is estimated as 10^{-6}. The probability of an inadvertent human intrusion into the

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underground facility ($\overline{\wp}\{E_H\}$) is set at unity. Hence, the probability of criticality in the underground facility after mobilizing fissile material in a repository panel filled with CCOs is 2.0×10^{-7} for ^{239}Pu criticality and 2.2×10^{-10} for ^{235}U criticality in CRA-26-19P (Fig. 16 and Table V). The presence of less ^{239}Pu and ^{235}U mass in a waste panel, results in an estimated probability of ^{239}Pu criticality of 4.1×10^{-8} and ^{235}U criticality of 4.6×10^{-12} in CRA-2019.

XIII.A.4. Low Probability of Criticality in Culebra Dolomite of Geologic Barrier

The probability of criticality in the Culebra dolomite of the geologic barrier was quantitatively estimated as the product of the probability of criticality given favorable conditions in the Culebra the probability of favorable criticality conditions in the Culebra, and the probability of inadvertent human intrusion into the underground facility:

$$\overline{\wp}\{A^{CS}_{Culebra,H}\}\overline{\wp}\{E_H\}$$
$$= \overline{\wp}\{A^{CS}_{Culebra,H}\,|\,E^{hydro\cap chem}_{Culebra,H}\}\,\overline{\wp}\{E^{hydro\cap chem}_{Culebra,H}\}\overline{\wp}\{E_H\} \qquad (41)$$

For CRA-2019, the probability of criticality given favorable conditions is 1.5×10^{-7} based on the analogy to Oklo natural reactors and the maximum release of 2810 kg of ^{239}Pu up the intrusion borehole. The probability of 5% enriched ^{235}U criticality given favorable conditions is smaller at 3.2×10^{-10}, based on the maximum release of 1120 kg. The probability of errors in finding favorable conditions in the Culebra ($\overline{\wp}\{E^{hydro\cap chem}_{Culebra,H}\}$) is estimated as 10^{-5}. The probability of an inadvertent human intrusion into the underground facility ($\overline{\wp}\{E_H\}$) is set at unity (Fig. 16 and Table IV).

XIII.B. Low Consequences of Criticality

Consequences from a critical event at WIPP might include (a) directly increasing actinides and fission products produced by the event and ultimately the increased hazard from radionuclide release at the disposal system boundary, and/or (b) indirectly compromising the isolating and stabilizing functions of the disposal system such as damaging the engineered or geologic barriers through the release of kinetic energy or through additional of heat energy.

Two potential extremes of criticality are (1) a transient critical event (also called rapid transient[38]), or (2) numerous critical events in cyclic steady-state (also called quasi steady state[38]). A transient critical event did not produce notable direct or indirect fission consequences; only steady-state consequences were large enough to consider and even they were far below the fissions represented by the fission products in the RH-TRU waste.

XIII.B.1. Low Steady-State Heat Consequences

Indirect steady-state consequences are localized and would be imperceptible at WIPP. The heat produced is less than already caused by normal decay of actinides and fission products in TRU waste. A hypothetical release of kinetic energy through a steam explosion has only localized effect at Culebra dolomite depth and does not vent to the surface. Also, disruption of the repository is localized. Disruption of a few TRU waste containers is inconsequential in WIPP the post-closure period. The function of TRU waste containers at WIPP is to allow safe transportation, handling, and possible retrieval of the waste during operations. None of the containers used at WIPP act as an engineered barrier to radionuclide release after closure of the repository.

XIII.B.2. Low Steady-State Fission Consequences

The direct consequences are very low because a hypothetical post-closure criticality is isolated from humans, and the amount of fission products produced is much less than already disposed at WIPP. Furthermore, criticality in ^{239}Pu is mostly beneficial; the health hazard is reduced because the fission products from ^{239}Pu criticality have less health hazard than ^{239}Pu. The probability-weighted consequences in a disposal room, the WIPP underground facility, or the Culebra dolomite strata are far below a reasonable criterion of 10^{24} fissions, which is 1% of the ~10^{26} fissions represented in fission products in the RH-TRU waste.

To elaborate, after salt creep closes a disposal room in CRA-2019 and CRA-26-19P, criticality in ^{235}U (decayed from ^{239}Pu in CCOs) might produce a total of 8.4×10^{24} fissions in CRA-26-19P and 1.3×10^{24} fissions in CRA-2019. the probability-weighted consequence in CRA-26-19P is 1.2×10^{13} fissions and in CRA-2019, 7.0×10^{11} fissions (Table VII).

After brine flow from a hypothetical inadvertent intrusion mobilizes ^{235}U mass in a repository panel and deposits it elsewhere in the underground facility criticality might produce a total of 6.1×10^{25} fissions or a probability-weighted consequence of 1.35×10^{16} fissions for conditions in CRA-26-19P (Table VII). About 1.3×10^{25} fissions or a probability-weighted consequence of 5.8×10^{14} fissions might be produced for repository conditions in CRA-2019.

Criticality in a Culebra-dolomite deposit might produce a total of 9.4×10^{24} fissions or a probability weighted consequence of 3.0×10^{15} fissions for conditions in CRA-2019 (Fig. 16 and Table VII), provided a degraded borehole plug hundreds of years after a hypothetical inadvertent drilling intrusion into the underground facility allows brine flow from an underlying pressurized brine pocket to mobilize, transport, and deposit a maximum of 1120 kg of ^{235}U in the overlying Culebra dolomite strata.

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