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Sandia Review of High Bridge Associates Report:

Comparison of Plutonium Disposition Alternatives: WIPP Diluted Plutonium Storage and MOX Fuel Irradiation

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The subject report from High Bridge Associates (HBA) was issued on March 2, 2016, in reaction to a U.S. Department of Energy (DOE) program decision to pursue down-blending of surplus Pu and geologic disposal at the Waste Isolation Pilot Plant (WIPP). Sandia National Laboratories was requested by the DOE to review the technical arguments presented in the HBA report. Specifically, this review is organized around three technical topics: criticality safety, radiological release limits, and thermal impacts. Questions raised by the report pertaining to legal and regulatory requirements, safeguards and security, international agreements, and costing of alternatives, are beyond the scope of this review.

Examples of Overstatement

An initial observation is that the HBA report has indulged in overstatement in a way that tends to undermine the report's credibility. Examples of the practice include:

- "… creating a high likelihood of an uncontrolled criticality" (p. 1) could be viewed as intentionally provocative, and is supported by analysis that is incomplete and focused to reach a desired conclusion.
- The 29.2 kg/m^3 concentration of Pu-239 is based on the inner volume of the CCCs and not the CCOs, for which the average concentration is 1.73 kg/m^3 (p. 1, last bullet). Comparing this value to a single-parameter limit of 7.3 kg/m^3 (p. 1; p. 6, last para.; p. 31, 3rd para.) is valid only for the stated conditions in the standard ("uniform aqueous nitrate solution that is maintained at concentrations that do not exceed those of the saturated solutions," ANSI/ANS-8.1-2014 Section 5.1). Such conditions will not exist in the repository.
- Comparing the *maximum* concentration of down-blended Pu (29.2 kg/m^3 in CCCs) with the *average* concentration of Pu in TRU waste currently at WIPP (0.12 kg/m^3) (p. 2, 4th para.; p. 10, 3rd bullet; and p. 37, 4th bullet) ignores the overall volume of disposal panels for surplus Pu, and the heterogeneity of TRU waste.
- "...violation of the current NEPA FEIS permit" (p. 5) is inappropriate because no such permit actually exists, rather, NEPA documents are prepared to explain alternatives and support project decisions.
- "...it is not permitted to store large quantities of concentrated weapons grade Pu at WIPP..." (p. 17) is not accurate because down-blended surplus Pu would not be "concentrated," and because storage of such material is not specifically disallowed.
- "...extremely large quantities..." (p. 42) is an exaggeration; there are larger quantities of similar nuclear materials in the U.S. inventory for which a disposal pathway may also be sought someday.

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Note also that the HBA report refers to salt domes (p. 28, 1st para.; p. 35, 1st para.) whereas the geologic setting for WIPP is bedded salt. As discussed below, the report does not accurately represent conditions in the WIPP repository, nor does it reflect understanding of the technical basis for WIPP certification.

Post-closure Criticality

Scenarios involving disposal of CCOs containing more than 34 MT of surplus weapons-grade Pu have not been analyzed previously because parties responsible for the WIPP performance analysis had not yet been directed to consider this new mission (p. 1, 4th para.). NEPA analyses related to this inventory and its fate in a repository environment will be conducted, and normal and credible abnormal conditions will be evaluated for impacts. These analyses will include factors and processes such as mass, moderation, reflection, and neutron absorption. Repository consolidation that potentially crushes containers also will be considered in these analyses.

As stated by the HBA report, the new disposal mission should, and will, be analyzed including the response of CCOs in the disposal environment. As support for this statement, Studsvik analyzed a finite array configuration of CCOs that had the initial spacing (pitch) between CCCs reduced to 30% to simulate salt creep laterally crushing the 7-packs (Configuration 3). The k-eff was around 1. However, these calculations do not support the statement "High Bridge concludes that such a design would not be acceptable" without diluting the Pu concentration in the CCOs (p. 43, last para.) because the Studsvik analysis is not definitive.

Several additional factors will be considered for screening of features, events and process (FEPs) related to criticality. There will only be chloride brine (and not fresh water) in the repository for undisturbed conditions or after human intrusion (an example of such a calculation is presented in the Appendix A of this review). Consolidation of the disposal drifts due to salt creep, will be analyzed realistically using the extensive knowledge of WIPP salt geomechanics developed over more than three decades. Also, a more realistic source term for the Pu in CCCs will be used. For the Studsvik analysis, Pu-239 was assumed to be dispersed in a uniform mixture of 74% water, 25% polyethylene, and 1% beryllium, as assumed when modifying the U.S. Nuclear Regulatory Commission (NRC) certificate of compliance for TRUPACT-II shipping containers transporting CCOs. Instead, the actual or a reasonable approximation of Pu adulterant composition in the CCCs will be considered, which may lower the potential for criticality. Finally, the possible addition of other neutron poisons (in addition to natural chlorine) such as boron in various forms will be analyzed.

The Studsvik appendix (Appendix F) in the HBA report developed highly conservative estimates for Pu-239 concentration as a uniform mixture, to argue that the overall concentration would be too high (i.e., starting with 29 kg/m^3 in the CCCs and then deriving a uniform concentration of 25 kg/m^3 in the disposal rooms after crushing). The estimate is unrealistic because other material in the disposal rooms has been omitted (containers, MgO backfill, salt debris, etc.). The Studsvik appendix went on to use the unrealistic estimate as rationale for simulating CCOs in finite arrays.

The claim that the process of moderation "has been completely ignored in the analyses for WIPP criticality" (p. 30, 3rd para.) is incorrect given the 1999 Sandia calculations which took into account the presence of host rock and brine (Rechard et al. 1999). The Studsvik analysis may indeed be the first criticality analysis of WIPP disposal conditions to incorporate MgO backfill explicitly, but the amount of MgO used for disposal of CCOs is likely to be less than they assumed (especially their Case 3 on p. F-14). Also, under current WIPP procedures there is some flexibility to tailor the amount of MgO used in disposal rooms to the carbon content of the waste (CCOs contain less carbon than general TRU waste). Importantly, the analysis of surplus Pu in WIPP disposal rooms should include realistic representation of whatever material impinges on the CCOs during consolidation, including salt debris as well as MgO, and its geometry.

The HBA report incorrectly asserts that increasing the amount of surplus Pu will increase the dissolved concentration of Pu (p. 27, 3rd para.). In the WIPP Performance Assessment (PA) calculations, dissolved Pu concentrations predicted by the WIPP thermodynamic model are solubility-limited, not inventory-limited, i.e., independent from inventory. The HBA report states in the same paragraph that “the fissile concentration of actinides leached out of the surplus Pu inventory will be approximately 100%” which is not relevant. Analysis of the potential for criticality downstream from the repository will consider the specific inventory likely to be present, as has been done in the past (Rechard et al. 1999).

Earlier work by Sandia on screening criticality Features, Events, and Processes (FEPs) for WIPP performance assessment used single-parameter limits, but the findings were actually constrained by neutronic simulations using relevant site-specific data. That work considered the most important disturbed scenario for a salt repository (inadvertent human intrusion) and the conclusions were validated in the WIPP certification process. As the disposal mission evolves, the methodology can and will be revisited. There is no requirement as implied in the HBA report (p. 22; p. 33) to use the analysis methodology developed previously, for a new mission with Pu-239 uniformly distributed throughout repository disposal rooms (e.g., to apply a Pu-239 concentration limit of 3 kg/m^3).

The HBA report (p. 31, 3rd para.) repeats the Studsvik claim that the 3 kg/m^3 Pu concentration limit used in the earlier Sandia work has “no basis.” This reflects an incomplete reading of the report (Rechard et al. 1999), particularly Figure 16(a) which shows that 3 kg/m^3 is a reasonable lower bound for criticality behavior of Pu-239 in spherical bodies at in situ porosity, with Culebra brine (which is less saline than Salado or Castile brine). Furthermore, the HBA report makes selective use of the 1999 Sandia calculations (Rechard et al. 1999). In particular, use of the Culebra dolomite example, with Culebra brine, ignores the more likely halite example, with Salado or Castile brine. The Culebra is located above the host salt in the stratigraphic column, and waste radionuclides could only migrate there as groundwater species after a borehole intercepts the repository. A more appropriate example would be halite, with Salado brine, which is described in the same paragraph: “...the critical concentration for a ^{239}Pu/halite/brine mixture is 53 kg/m^3 and the minimum critical mass is 72 kg, because of the effects from the chlorine in the salt.”

The HBA report incorrectly asserts that “The impacts of the results of a sustained criticality in the WIPP repository are unpredictable and have not been considered in any DOE/NNSA Performance Assessment for WIPP.” The reason criticality has not been included in a performance assessment is because it was screened out on low probability. Nonetheless, the consequences of a criticality event have been considered as a FEP by Rechard et al. (1999) and Rechard (2015). Fission product and actinide inventories from hypothetical criticality events after repository closure have been evaluated (Rechard et al. 1995; OCRWM 2003; NDA 2010). For the types of events that are considered most plausible, the consequences have been characterized and shown not to be significant to repository waste isolation performance (p. 1, 3rd para.; p. 42, 2nd para.).

Finally, the HBA report makes an obvious point that nuclear criticality safety calculations are necessary for disposal of surplus Pu at WIPP. However, the Studsvik calculations presented in

Appendix F of the HBA report were unrealistic and used extremely conservative assumptions. As discussed in Appendix A to this review, the Pu down-blending mixture assumed by Studsvik in the HBA report tends to maximize k-eff in CCO/CCC configurations. Preliminary criticality calculations performed by SNL (Appendix A) show the value of more realistic models that include chloride brine, illustrating the important effect of natural Cl-35 and B-10 in a salt repository, on the potential for criticality. Further investigations are planned to realistically represent the down-blending mixture, and to develop realistic representations of the repository environment including compaction processes and brine.

Radiological Release Limits

The HBA report throughout Section 5 makes an important mistake in not recognizing that the post-closure performance standard for WIPP is effectively a *release* standard (40CFR191) and not a *dose* standard. For example, pg. 41, bottom paragraph, incorrectly states that the additional Pu "will have a significant, unanalyzed impact on the long-term dose rates at WIPP." The WIPP total-system performance measure is calculated from estimated releases for certain radionuclides, divided by their inventories in the repository. Thus, addition of Pu-239 inventory does not change the performance measure as long as the estimated releases are proportional. In other words, decreased performance can only occur if the amount of Pu in cuttings + spallings released in an inadvertent human intrusion scenario, is disproportionately larger than the new inventory, because of different chemical/physical processes. Individual protection requirements (40CFR191.15) do include committed dose limits that apply to WIPP, but these are restricted to undisturbed performance without human intrusion, for which dose is effectively nil (DOE 2014b).

The HBA report goes on to claim that the attractiveness of surplus Pu after disposal (and after closure of WIPP) will lead to "additional unanalyzed intrusion scenarios" that would be intentional and overt diversions "for national or nefarious purposes" (p. 42). The notion that the waste form determines the manner and likelihood of future intrusion scenarios is contrary to established rationale for repository regulation. Disposing of weapons grade material does not make it more or less likely that future societies will intrude on the repository. The National Research Council stated in 1995 about human intrusion, that "...it makes no sense—indeed it is presumptuous—to try to protect against the risks arising from the conscious activities of future human societies..." (National Resource Council 1995) This rubric carries into the U.S. EPA and U.S. NRC regulations for repositories, including WIPP, which limit credit that can be taken for institutional controls in the future, but also limit intrusion scenarios to *inadvertent*. And inadvertent human intrusion does not include theft or sabotage. One could fabricate reasons why any repository, such as a repository with thousands of tons of commercial spent fuel, could be intruded by future humans, so the principle applies to all nuclear waste geologic disposal concepts and not just surplus Pu disposal.

The EPA rule 40CFR191 in Appendix C provides guidance on the frequency of human intrusion that needs to be taken into consideration. Without promulgated regulations and their rationales, no productive discussion of nuclear safety can occur, including for the safety of MOX fuel production and irradiation.

The report then speculates about joint consequences from a post-closure criticality event and intentional human intrusion, which would "substantially alter the source term used in the pathways analyses and would have a significant impact on the performance assessment for WIPP" (p. 42, 2nd para.). In response to such speculation, the likelihood of intentional human intrusion cannot be reasonably quantified as discussed above. Furthermore, using the regulatory compliance approach that is applicable for WIPP certification, a post-closure criticality event would be highly unlikely, such that it could be excluded from performance assessment *independently* from human intrusion. Following 40 CFR Part 194, Section 194.32 (d), events are screened out for low probability if their likelihood of occurrence is less than one in 10,000 over 10,000 years.

The HBA report reflects basic misunderstanding about the regulatory safety basis for geologic disposal in general, and for WIPP certification in particular. It claims importance for criticality FEPs that are outside the scope of repository regulations that were developed and reviewed by national safety experts, and have been in place for decades. It also attempts to combine consequences from low probability events without considering joint likelihood or regulatory context.

Thermal Impacts

Each CCO containing an upper limit of 380 g of Pu-239 would emit 0.91 W of decay heat (the HBA report gives a similar figure). Thermal loading within a disposal room (91 m long, 10 m wide) is estimated using an average CCO footprint area (0.26 m^2), with CCOs stacked three high, to be approximately 9.6 kW, or 10.6 W/m^2. This is the areal heating rate within disposal rooms and does not account for lateral heat dissipation into the pillars between rooms. Dividing instead by an area that takes the 30-m pillars into account (91 m long, 40 m wide) gives an average thermal load of 2.6 W/m^2. Heating by CCOs in WIPP would be less than this because each CCO would actually contain less than 380 g Pu-239 to accommodate measurement uncertainty. For example, using a value of 300 g Pu-239 per CCO, the average heat output decreases to 2.1 W/m^2.

Decay heat limits for contact-handled (CH) waste at WIPP are given by the Waste Acceptance Criteria (WAC; DOE 2013, Section 4.0) which states that the design basis is 10 kW per acre, or 2.5 W/m^2 (using the overall plan outline of the WIPP disposal area; see DOE 2014a, Section 6.2.1.2.3). This is design basis information, not a “regulatory limit” as stated by the HBA report (Section 6, 5^{th} para.).

A thermal study evaluating the feasibility of disposing of heat-generating high-level waste (HLW) in a salt repository was conducted in 2009 (Clayton and Gable 2009). The study assumed a layout of waste packages similar to the current panel and room layout of the WIPP, with average thermal load of 39 W/m^2. A maximum average salt temperature of approximately 150°C was calculated, for a temperature rise of 123°C. Note that salt has the greatest thermal conductivity of all prospective repository host geologic media by a factor of 2, and temperature tolerance of at least 200°C. Concepts for disposal of HLW and spent nuclear fuel in salt have been developed for thermal loading of 10 kW/package and greater (Hardin et al. 2012).

Scaling down the HLW study result to the average areal heating rate for CCOs (maximum of 2.6 W/m^2 calculated above) a maximum average salt temperature of approximately 35°C could be expected. A similar result is obtained by scaling up the WIPP average thermal load of 0.7 W/m^2 and temperature rise of 1.6°C for CH waste (DOE 2014a, Section 6.2.1.2.3). The WIPP repository and the surplus Pu waste form can tolerate higher temperatures, so there is considerable margin available for thermal management. Slightly higher temperatures could be present near the middle of the waste cross section, and near remote-handled (RH) waste packages, so CH waste loading could be adjusted to keep the peak temperature within any prescribed temperature limit for waste form stability. Temperatures could also be slightly higher if k-eff is greater than approximately 0.8 because of subcritical neutron multiplication. The disposal scheme to be used for surplus Pu will be modeled in detail for coupled thermal and geomechanical responses, and subcritical multiplication, and the associated WIPP FEP documentation (DOE 2014a) will be revisited to determine if temperature conditions are consistent with previous screening.

The HBA report errs with respect to the basis and authority for WIPP thermal limits; it overestimates the average areal thermal loading associated with surplus Pu disposal in CCOs; and it misses the fact that salt repositories are capable of greater thermal loading. The idea of "overheating" is not defined and very unlikely for drifts in salt, loaded with Pu-bearing CCOs.

Other Comments

The fact that current waste storage and handling operations at WIPP are based on modified ("terminated") safeguards requirements, does not preclude the construction and operation of facilities that meet additional safeguards requirements (p. 25, 3rd para.). The current design of WIPP facilities is not the only one possible, and WIPP (or some part of it) can be effectively operated to other requirements as determined in the future.

Nuclear material safeguards after permanent disposal will take into account the difficulty of undetected underground access to waste in a closed repository panel, and the low likelihood that such access would not be interdicted. Special methods are not necessary to prevent human intrusion for 10,000 years (p. 2, 1st para.). Regardless of the waste inventory, geologic repositories cannot be designed to prevent *intentional* intrusion in the far future (see quote from the National Research Council above).

Summary

The HBA report relies on overstatement to criticize a strawman disposal concept, and fails to make a cogent case against disposal of surplus Pu in any of the topical areas reviewed: post-closure criticality, radionuclide release limits, and thermal impacts.

The analysis of post-closure criticality (after permanent disposal) for disposal of surplus Pu in CCOs at WIPP appears to be limited to a few examples that are unrealistic and use extremely conservative assumptions (such as the composition of down-blended Pu), while not including available and credible thermal neutron absorbers (such as chloride brine). The analysis is incomplete, and appears focused to reach a pre-determined conclusion.

The HBA report makes an important error in characterizing the post-closure performance standard for WIPP as a dose standard, when it is effectively a release standard. Thus, disposal of additional Pu at WIPP would increase the compliance measure only if Pu releases from the increased inventory were disproportionately greater. Further, it proposes *intentional* future human intrusion as a release pathway, which has been rejected by the national safety experts who developed and reviewed the geologic disposal regulations.

Finally, the report errs with respect to WIPP thermal limits, it overestimates the thermal loading associated with surplus Pu disposal, and it misses the fact that salt repositories are capable of greater thermal loading.

Disposal of surplus Pu at WIPP has not been analyzed previously because parties responsible for WIPP performance analysis had not yet been directed to consider it. Obviously such analysis has not yet been included in NEPA or WIPP certification documents. This review has suggested how new information would be used in analysis of surplus Pu disposal at WIPP. The HBA report appears to have been intended to make the case that disposing of down-blended Pu at WIPP is not a viable option; our review suggests that, given the report's overstatements and errors, it fails to make its intended case.

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Acronyms

2-D 2-Dimensional

ANS	American Nuclear Society
ANSI	American National Standards Institute
CCC	Criticality Control Container
CCO	Criticality Control Overpack
CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
ENDF	Evaluated Nuclear Data File
EPA	U.S. Environmental Protection Agency
ERDA	Energy Research and Development Agency
FEIS	Final Environmental Impact Statement
FEP	Feature, Event or Process
GWB	Generic Weep Brine
HAC	Hypothetical Accident Case
HBA	High Bridge Associates
HLW	High-Level Waste
k-eff	Reactivity coefficient k-effective
MOX	Metal Oxide (nuclear fuel)
MT	Metric Tons
NEPA	National Environmental Protection Act
NCT	Normal Condition Transport
NRC	U.S. Nuclear Regulatory Commission
PA	Performance Assessment
SNL	Sandia National Laboratories
TRU	Transuranic
USL	Upper Subcritical Limit
WAC	Waste Acceptance Criteria
WIPP	Waste Isolation Pilot Plant

Appendix A

Criticality Assessment Calculations in Support of High Bridge Associates Report Review

Introduction

The High Bridge Associates (HBA) report includes a criticality assessment performed by Studsvik Scandpower (Aupperle et al. 2016) to support the possibility of exceeding an upper subcritical limit (USL). In this appendix, models from the HBA report are replicated; then, the effects from adding brine with realistic composition are illustrated.

Programs and Nuclear Data

Simulations described in this appendix were performed by Sandia National Laboratories (SNL) using the MCNP 6 code (Monte Carlo N-Particle Transport Code), a stochastic simulation code for nuclear processes developed by Los Alamos National Laboratory. The simulations use the continuous energy ENDF/B-VII.R0 cross-section library, which is the same library used by KENOVI, a new version of the KENO Monte Carlo criticality code developed by Oak Ridge National Laboratory, as cited by the HBA report. HELIOS, a deterministic neutron and gamma transport code, also uses 177-group neutron library ENDF/B-VII.R0. In addition, MCNP applies S (alpha-beta) treatment for more accurate behavior of moderated neutrons in light water.

Inputs

The material compositions, dimensions, and a temperature described in the HBA report were used to replicate their results. For material compositions, the elemental compositions were specified but the isotopic compositions were not, so natural isotopic abundances were assumed for all elements except where specified (e.g., Pu-239). The geometry of criticality control containers (CCCs) and criticality control overpacks (CCOs) was estimated using figures from the HBA report. In multiple-CCO configurations, the material between CCOs was assumed to be air unless otherwise specified.

Single CCO Case

The MCNP case is an exact replica of that described in the HBA report, with reflective boundary conditions all around. The normal condition transport (NCT) k-eff of an infinite 2-D array of single CCOs is:

HELIOS:	0.81248	
KENOVI:	0.8147	± 0.00100
MCNP:	0.80795	± 0.00026

The hypothetical accident case (HAC) k-eff for an infinite 2-D array of single CCOs is:

HELIOS:	1.58328	
KENOVI:	1.58538	± 0.00052
MCNP:	1.58964	± 0.00006

The MCNP results appear to agree well with those from the Studsvik analysis in the HBA report given the same geometry, material compositions, and temperature (at 20°C, for comparison).

7x3 Stack of CCOs

Figure 1 is a replicated model of a 7x3 stack of CCOs in HAC configuration (as stacked in the repository). MCNP used white boundary condition in the x- and y-directions, and black boundary condition in the z-direction, similar to the HBA models. HBA does not report whether their model includes air or vacuum between drums, so for the MCNP models air was assumed between the CCOs and to the boundaries. The replicated model has a difference of about 8% in k-eff:

KENOVI: 0.8595 ± 0.0011
MCNP: 0.79113 ± 0.00026

The geometry of this model is not an exact replica of Studsvik's model as the report lacked information about how stacked drums were modeled, and what materials were assumed in the vicinity. Although the results obtained using MCNP are in general agreement with results from Studsvik using KENOVI, the differences may be attributable to these factors.

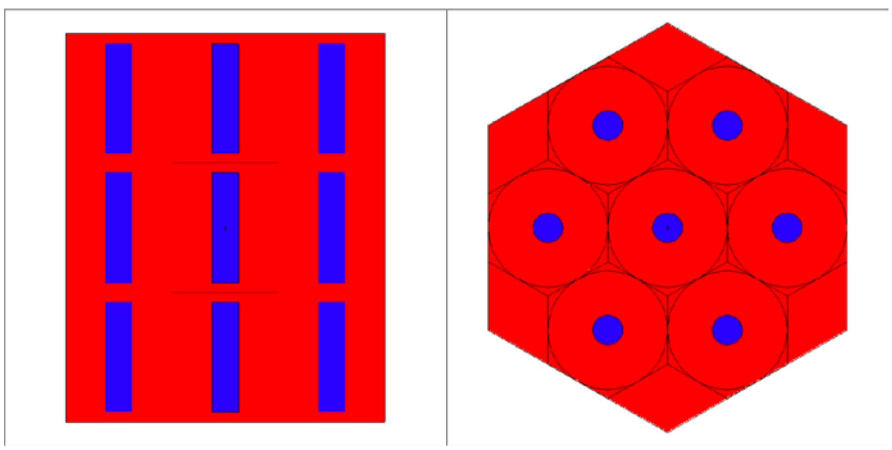

Figure 1. A vertical cross section and a horizontal cross section of a 7x3 stack of CCOs in HAC configuration. Blue represents CCCs containing water, polyethylene, beryllium, and Pu. Red represents air. Other materials such as steel and plywood were ignored as reported for the Studsvik models.

Two Compacted 7x3 Stacks of CCOs

In the HBA report, the only compaction factor mentioned is decreasing pitch for CCOs from 61 cm to 20 cm to simulate compaction. The difference in k-eff is 4% for this case:

KENOVI: 0.9911 ± 0.0011
MCNP: 0.95259 ± 0.00027

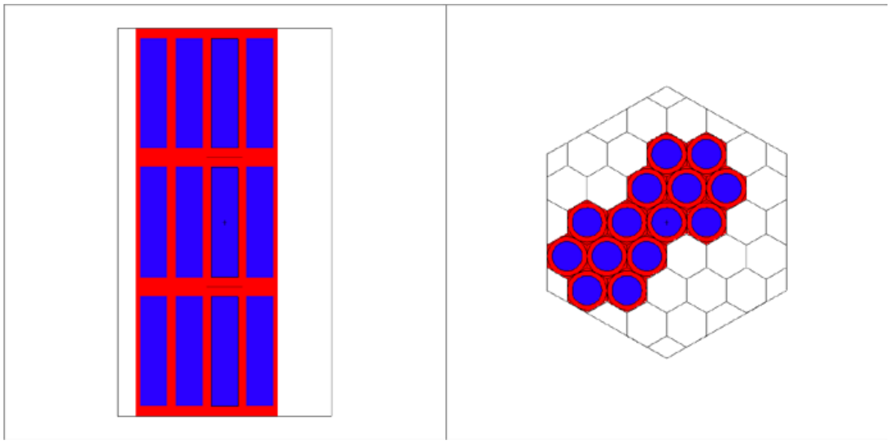

Figure 2. The CCOs are radially compressed to a third of original volume, and the pitch between CCCs is decreased to 21 cm, but the CCCs are not compressed. The white area inside the boundary represents vacuum (no interaction with neutrons) and an all-black boundary condition is applied.

MgO Effect on Reflective Properties

Case 0 in the HBA report (p. F-14) has three uncompressed 7x3 stacks of CCOs without MgO, for which the k-eff is:

KENOVI: 0.6397 ± 0.0012
MCNP: 0.61275 ± 0.00024

Case 1 has supersacks of MgO placed on top of each 7x3 stack of CCOs (Figure 3), for which k-eff is:

KENOVI: 0.6650 ± 0.0011
MCNP: 0.63459 ± 0.00024

Case 2 has supersacks on top of each 7x3 stack, and MgO completely filling spaces between CCOs (Figure 3). The resulting k-eff is:

KENOVI: 0.8294 ± 0.0013
MCNP: 0.75304 ± 0.00023

Case 3 has the supersacks on top of each 7x3 stack, in between CCOs, and all around the outside of the three 7x3 stacks (Figure 3). The resulting k-eff is:

KENOVI: 0.9829 ± 0.0015
MCNP: 0.96224 ± 0.00023

MgO supersacks are designed to break open so that the MgO can migrate in between the drums; therefore, it is unrealistic to assume case 2 or 3 because MgO has to be either on top or in between the drum stacks. Case 3 includes a volume of MgO much greater than could be available in three 50 cm-thick supersacks.

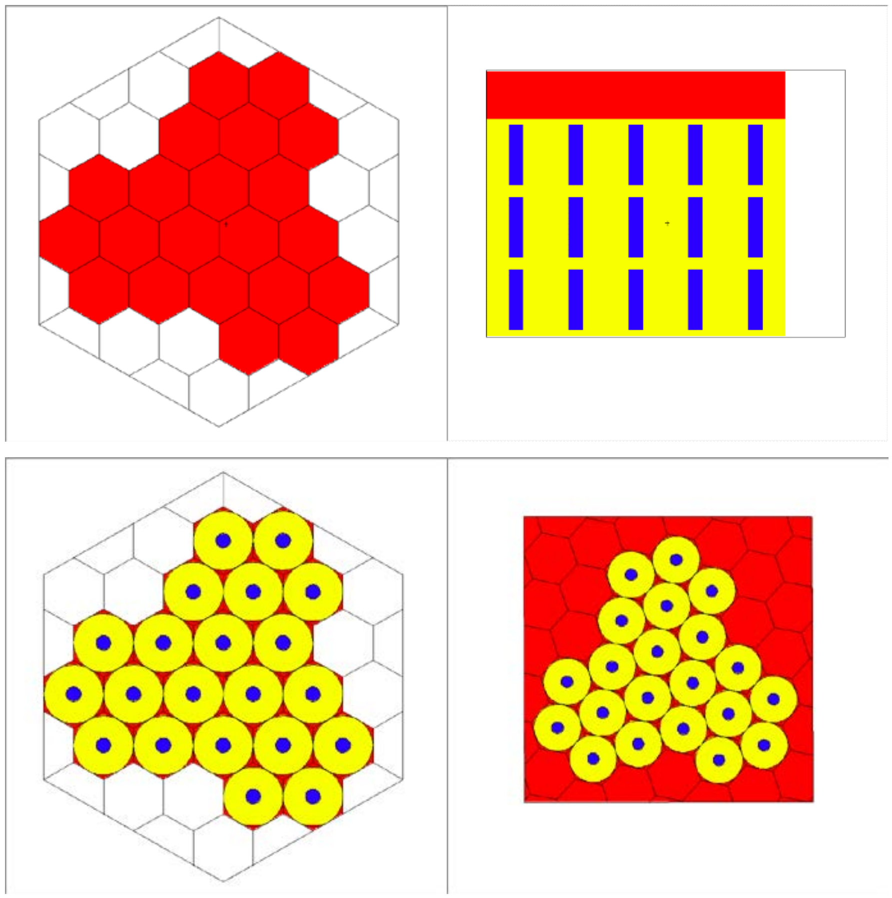

Figure 3. Top figures are the replicates for Case 1 from the HBA report (p. F-14), and the bottom figures are the replicates for Case 2 (left) and Case 3 (right). Red represents MgO, yellow is air, and blue represents CCCs.

Comparison of Replicated Cases

All replicated models but one had k-eff values lower than reported in HBA. Such discrepancies can occur from lack of isotopic information, specific geometric configuration, differences in the neutron library used, differences in KENOVI and MCNP codes, etc. All of the replicated cases with MCNP 6 are within 10% of the results with KENOVI as reported by HBA.

Having replicated Studsvik calculations in the HBA report, the next section shows the effects from introducing Salado brine.

1. Salado Brine Intrusion Between CCC and CCO Drum

To evaluate the effects of Salado brine on criticality, brine with the "GWB" composition shown in Figure 4 (generic weep brine; another brine from the ERDA-6 borehole is also shown) was introduced between CCCs and CCOs in the infinite 2-D array described above for the Single CCO case.

Recipes for Synthetic Salado and Castile Brines Equilibrated with Halite, Anhydrite, Brucite and Hydromagnesite (5424) on Molality Scale

Salt	GWB	ERDA-6
	Grams for 922.44 g H_2O^A	Grams for 983.31 g H_2O^A
$Na_2B_4O_7{\cdot}10H_2O$	18.06	6.77
NaBr	3.27	1.28
LiCl	0.21	None
NaCl	259.28	328.70
KCl	41.71	8.15
$MgCl_2{\cdot}6H_2O$	129.00	24.50
$CaCl_2{\cdot}2H_2O$	1.82	1.89
Na_2SO_4	29.69	27.11
Na_2CO_3	0.0426	0.0567

^{A} Crystalline H_2O in salts is added into solvent of water to make a total of 1,000 g.

Figure 4. Brine recipes from WIPP activity/project specific procedure (Xiong 2008).

As an additional sensitivity case, Salado brine without boron was represented by completely replacing $Na_2B_4O_7(H_2O)_{10}$ with $Na_2O_7(H_2O)_{10}$. Also, the last case tabulated below included crushed Salado salt (NaCl) with porosity of 25% in between the CCC and the CCO drum without any water mixed in. In all cases, the down-blended Pu in CCCs consisted of Pu-239 with water, beryllium, and polyethylene, as assumed in the Studsvik models.

Material Between CCC and CCO Drum	k-eff (MCNP 2-D)	Error (±)
Air	1.58964	0.00006
Water	0.80513	0.00023
GWB Salado brine, per recipe in Figure 4	0.68747	0.00023
GWB Salado brine without boron	0.70410	0.00023
Salado halite 25% porosity	0.95904	0.00022

These infinite-array calculations illustrate that capturing moderated neutrons, by both fresh water and Salado brine, can effectively decrease k-eff values.

2. Salado Brine Intrusion Into CCOs

The model in Figure 5 has the same boundary conditions as the model in Figure 1. The only difference between the two is the thin layers of the brine between the CCOs. The difference in k-eff between the two cases tabulated below is about 0.12, which shows the significant negative effect of chloride (and boron) containing brine on k-eff.

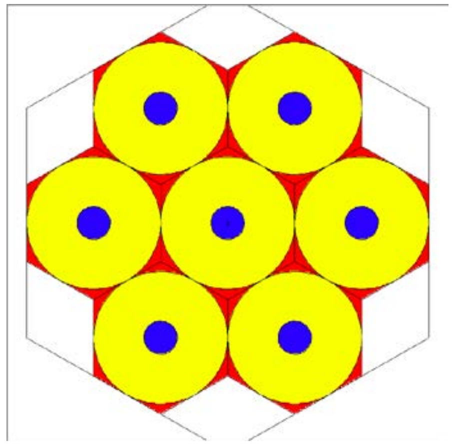

Figure 5. Blue represents the homogeneous mixture with Pu, yellow represents air and red is Salado brine positioned in between drums, but not on top or bottom.

7x3 Stack in HAC Configuration with Surrounding Medium (Figures 1 and 5)	k-eff (MCNP 2-D)	Error (±)
Air	0.79113	0.00026
Brine	0.67443	0.00023

As an additional example, Salado brine was introduced into the model shown in Figure 2. The boundary condition is black all around, the same as the previous simulation. Brine was introduced between CCOs and between the CCC and drum for each CCO, but it was not placed on the top or bottom of the stacks.

Two Compacted 7x3 Stacks with Black Boundary (Figure 2)	k-eff (MCNP 2-D)	Error (±)
Only air surrounding the HAC stacks (replicating Studsvik model)	0.95259	0.00027
Brine between CCOs and inside CCOs	0.79065	0.00029

Conclusion

Additional nuclear criticality safety calculations are necessary to evaluate surplus Pu disposal in WIPP. However, the Studsvik calculations presented in the HBA report are unrealistic and used extremely conservative assumptions. The Pu down-blending mixture assumed by Studsvik in the HBA report tends to maximize k-eff in CCO/CCC configurations, because neutrons generated by

Pu-239 are moderated in fresh water, polyethylene, and beryllium. Moreover, beryllium is a neutron multiplier if it absorbs high-energy neutrons (such as those produced by Pu fission), producing two neutrons and two alpha particles. Each of the two alpha particles can liberate one additional neutron from another beryllium upon collision. Even in this optimized situation, introducing fresh water around the CCOs decreases k-eff significantly, and the negative effect is even stronger with Salado brine. Simulations with Salado brine illustrate the important effect of natural Cl-35 in a salt repository, on the potential for criticality.

Further studies are planned to realistically represent the down-blending mixture, and to develop realistic representations of the repository environment including compaction processes and brine. Possible enhancements include additional tests and engineering analysis to evaluate consolidation in the repository, and the use of non-soluble neutron poisons such as boron carbide to offset the moderation effects of a flooded WIPP room. Finally, bulk volumetric abundance calculations will be reevaluated with discrete geometry and appropriate upper safety limits.

References for Appendix A

Aupperle, K., H. Garson, M. High, C. Hess, A. Kadak, S. Maehr and T. Simeonov 2016. *Comparison of Plutonium Disposition Alternatives: WIPP Diluted Plutonium Storage and MOX Fuel*. High Bridge Associates. Mar 2, 2016. pp. F-1 through F-16.

Xiong, Y. 2008. *Preparing Synthetic Brines For Geochemical Experiments Revision 2*. WIPP Activity/Project Specific Procedure SP 20-4. pp. 1-14

Sandia National Laboratories

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date: August 1, 2016

to: Sachiko McAlhany, Senior Technical Advisor
Office of Material Management and Minimization (NA-23)

Paul E. Shoemaker

from: Paul E. Shoemaker, Senior Manager
Sandia National Laboratories, Carlsbad

subject: Commentary on Report by High Bridge Associates, Inc. dated March 2, 2016

On March 2, 2016, High Bridge Associates, Inc. published a report entitled, "Comparison of Plutonium Disposition Alternatives: WIPP Diluted Plutonium Storage and MOX Fuel Irradiation." The report was prepared for the MOX Services Board of Governors. Transmitted by this memo is a review by Sandia National Laboratories of assertions made in that report, particularly with respect to criticality safety, radiological releases and limits thereto, and thermal impacts.

Those reading the paper transmitted by this memo should keep in mind that, in its review of the High Bridge Associates report, Sandia has not attempted to perform its own Nuclear Criticality Safety evaluation, but merely to shed light on some assumptions in the High Bridge report, and to provide a more realistic scenario not addressed by that report. A full Nuclear Criticality Safety analysis would have to document that all normal and credible abnormal conditions are subcritical through evaluation of those conditions and their impact on various Nuclear Criticality Safety related parameters as well as how they impact the system multiplication factor. This is the type of work that will be undertaken as part of the assessment of impact on WIPP's long-term performance disposing of diluted weapons grade plutonium may have, an assessment that NNSA has asked Sandia to undertake.

Those reading the paper transmitted by this memo should also keep in mind that the inventory of plutonium we believe High Bridge Associates is using in its report is primarily weapons grade plutonium that was a candidate for treatment at the MOX Fuel Fabrication Facility and other weapons grade plutonium declared excess to U.S. needs. Sandia did not see in the High Bridge report anything specific to the 6 MT of non-pit plutonium coming to WIPP as a result of a recently signed Record of Decision associated with the Surplus Plutonium Disposition Supplemental Environmental Impact Statement, nor has Sandia made any comments specific to that inventory in our review of the High Bridge report.

We welcomed the opportunity to review the High Bridge Associates report for the NNSA. We will be pleased to respond to any inquiries you may have about the enclosed review.