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Subparts B and C
Compliance Recertification
Application
for the
Waste Isolation Pilot Plant

Appendix BARRIERS

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Field Office
Carlsbad, New Mexico

Appendix BARRIERS

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1   **ACRONYMS AND ABBREVIATIONS**

2	AISC	American Institute of Steel Construction
3	AISinR	a synthetic brine representative of fluids sampled from the Culebra Member of
4		the Rustler Formation in the WIPP Air Intake Shaft
5	alumina	Al_2O_3
6	aq	aqueous
7	ASTM	American Society for Testing Materials
8	atm	atmosphere(s)
9	BLM	Bureau of Land Management
10	BRAGFLO	Brine and Gas Flow
11	brucite	$Mg(OH_2)$
12	ºC	degrees Celsius
13	calcite	$CaCO_3$
14	CCA	(WIPP) Compliance Certification Application
15	CPR	cellulosic, plastic, and rubber (materials)
16	CRA	(WIPP) Compliance Recertification Application
17	DI	deionized (water)
18	DOE	(U.S.) Department of Energy
19	DRZ	Disturbed Rock Zone
20	EPA	(U.S.) Environmental Protection Agency
21	EQ3/6	a geochemical software package for speciation and solubility calculations
22		(EQ3NR) and reaction-path calculations (EQ6)
23	ERDA-6	Energy Research and Development Administration (WIPP Well) 6, a synthetic
24		brine representative of fluids in Castile-Formation brine reservoirs
25	f_{CO_2}	fugacity (similar to the partial pressure) of CO_2
26	FMT	Fracture-Matrix Transport, a geochemical speciation and solubility code
27	forsterite	Mg_2SiO_4
28	ft	foot (feet)
29	g	gaseous or gram(s)
30	G Seep	a naturally occurring brine collected from G Drift in the WIPP underground
31	gal	gallon(s)
32	GWB	Generic Weep Brine, a synthetic brine representative of intergranular Salado-
33		Formation brines
34	H-17	a synthetic brine representative of brine from the Culebra at the
35		WIPP H-17 Hydropad
36	halite	NaCl
37	hydromagnesite	$Mg_4(CO_3)_3(OH)_2 \cdot 3H_2O$ or $Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$
38	in.	inch(es)
39	K_d	distribution coefficient
40	kg	kilogram(s)
41	km	kilometer(s)
42	L	liter(s)
43	lb	pound(s)
44	lime	CaO
45	m	meter(s)

1	M	molar
2	magnesite	$MgCO_3$
3	mL	milliliters
4	mm	millimeter
5	μm	micrometer(s)
6	mol	mole(s)
7	monticellite	$CaMgSiO_4$
8	MSHA	Mine Safety and Health Administration
9	nesquehonite	$MgCO_3 \cdot 3H_2O$
10	nm	nanometer(s)
11	PA	performance assessment
12	PAVT	(WIPP) Performance Assessment Verification Test
13	periclase	pure, crystalline magnesium oxide, the primary constituent of the WIPP
14		engineered barrier
15	pH	the negative, common logarithm of the activity of hydrogen ion
16	portlandite	$Ca(OH)_2$
17	RCRA	Resource Conservation and Recovery Act
18	RH	relative humidity or remote-handled (TRU waste)
19	s	second(s)
20	silica	SiO_2
21	SMC	Salado Mass Concrete
22	SPC	Salado Primary Constituents, a synthetic brine similar to Brine A
23	spinel	$MgAl_2O_4$
24	SWB	standard waste box
25	TDOP	ten-drum overpack
26	TRU	transuranic (waste)
27	ulvöspinel	$Ti(Fe,Mg)_2O_4$
28	WIPP	(U.S. DOE) Waste Isolation Pilot Plant
29	wt	weight
30	WTS	Westinghouse TRU Solutions
31	VOC	volatile organic compound
32	XRD	X-ray diffraction

1   **BARRIERS-1.0 INTRODUCTION**

2   **BARRIERS-1.1   Purpose and Objectives**

3   Appendix BARRIERS to the Waste Isolation Pilot Plant (WIPP) Compliance Recertification
4   Application (2004) consolidates the information pertaining to engineered and disposal system
5   barriers related to the WIPP repository. In the initial Compliance Certification Application
6   (CCA) (DOE 1996a), this information was contained in Appendices BACK, EBS, PCS, and
7   SEAL.

8   This appendix documents how the WIPP satisfies the Environmental Protection Agency
9   (EPA) assurance requirement to provide different types of barriers to isolate the waste
10   from the accessible environment as required by Title 40 Code of Federal Regulations
11   (CFR) § 191.14(d) (EPA 1993). The EPA's Certification Criteria also required the
12   Department of Energy (DOE) to conduct a benefit and detriment study (40 CFR §
13   194.44) when considering engineered barrier alternatives. The CCA documented this
14   study in Appendix EBS and is included by reference.

15   **BARRIERS-1.2   Background**

16   To address the requirements of 40 CFR 194.44, the DOE performed an Engineered Alternatives
17   Cost/Benefit Study (see CCA Appendix EBS) to examine the benefits and detriments associated
18   with an array of engineered barrier alternatives. Based on the results of these studies and the
19   existing repository design, the DOE proposed four engineered barriers in the CCA: shaft seals,
20   panel closures, magnesium oxide (MgO), and borehole plugs.

21   In Docket A-93-02 Item V-B-2, Compliance Application Review Document No. 44, the EPA
22   states:

23   "EPA reviewed the information contained in the CCA and agreed that the emplacement of MgO in
24   waste panels of the WIPP may be expected to substantially delay the movement of water or
25   radionuclides…For compliance with this requirement, EPA did not evaluate panel seals, shaft
26   seals or borehole plugs. EPA considered these items to be features of the disposal system design
27   and evaluated them in that context."

28   In the final certification decision for WIPP (63 FR 27397) (EPA 1998a) the EPA concluded:

29   "The EPA finds that DOE complies with § 194.44. The EPA found that DOE conducted the
30   requisite analysis of engineered barriers and selected an engineered barrier designed to prevent or
31   substantially delay the movement of water or radionuclides toward the accessible environment.
32   The DOE provided sufficient documentation to show that MgO can effectively reduce actinide
33   solubility in the disposal system. The DOE proposed to emplace a large amount of MgO around
34   waste drums in order to provide additional factor of safety and thus account for uncertainties in the
35   geochemical conditions that would affect CO_2 generation and MgO reactions."

36   The EPA determined that MgO met the regulatory definition of an engineered barrier. The other
37   three systems proposed as engineered barriers by the DOE were viewed by the EPA as part of
38   the disposal system design. For completeness, this appendix describes both the MgO engineered
39   barrier and the other barriers used by the DOE in the repository design which are not considered
40   to meet the regulatory assurance requirement.

1   **BARRIERS-2.0 ENGINEERED BARRIER**

2   **BARRIERS-2.1   Introduction**

3   The DOE is emplacing MgO in the disposal system. The effect of MgO in the disposal system
4   will be to decrease the solubilities of the actinide elements in transuranic (TRU) waste in any
5   brine present in the repository after closure. MgO will decrease actinide solubilities by
6   consuming essentially all carbon dioxide (CO_2) that would be produced by microbial activity-
7   should all cellulosic, plastic, and rubber (CPR) materials in TRU waste and the waste containers
8   be consumed. Although MgO will consume essentially all CO_2, minute quantities (relative to the
9   quantity that would be produced by microbial consumption of all CPR materials) will persist in
10   the aqueous and gaseous phases. The residual quantity will be so small relative to the initial
11   quantity that the adverb "essentially" is omitted hereafter in this appendix. Consumption of CO_2
12   will prevent the acidification of brine or the production of significant quantities of carbonate ion
13   (CO_3^{2-}), which could increase actinide solubilities.

14   The effects of MgO carbonation (consumption of CO_2) were included in the CCA performance
15   assessment (PA) and the recertification PA by assuming there is no CO_2 in the disposal system.
16   This assumption is included in PA by (1) removing CO_2 from the gaseous phase in Brine and
17   Gas Flow (BRAGFLO) calculations, thereby reducing somewhat the predicted pressurization of
18   the repository (see Appendix PA, Section PA-4.2); and (2) using the values of f_{CO_2} and pH
19   established by reactions among MgO, brine, and aqueous or gaseous CO_2 to calculate actinide
20   solubilities (see Appendix PA, Attachment SOTERM).

21   Although the hydration of MgO will remove water (H_2O) from the repository, MgO hydration is
22   not included in PA. Not including MgO hydration in PA is considered a conservative
23   assumption.

24   In this appendix, "MgO" refers to the bulk, granular material being emplaced in the WIPP to
25   serve as the engineered barrier. MgO comprises periclase (pure, crystalline MgO - the main,
26   reactive constituent of the WIPP engineered barrier) and various impurities (see Section 2.5.1 of
27   this appendix). Pure, crystalline MgO is always referred to as periclase in this appendix. The
28   term "periclase" and other mineral names used herein are, strictly speaking, restricted to
29   naturally occurring forms of the materials that meet all other requirements of the definition of a
30   mineral (see, for example, Bates and Jackson 1984). However, mineral names are used for
31   convenience in this appendix.

32   **BARRIERS-2.2   Description of the Waste Isolation Pilot Plant Engineered-Barrier System**

33   The DOE is emplacing MgO in polypropylene "supersacks" on top of the stacks of three seven-
34   packs of 55-gal (208-L) drums, three standard waste boxes (SWBs), or various combinations of
35   these and other waste containers. Other such containers include ten-drum overpacks (TDOPs),
36   four-packs of 85-gal (321-L) drums, and three-packs of 100-gal (379-L) drums (see Appendix
37   DATA, Attachment H). Each supersack contains 4200 ± 50 lb (1905 ± 23 kg) of MgO (WTS
38   2003).

1   Emplacement of MgO in supersacks: (1) facilitates handling and emplacement of MgO; (2)
2   minimizes potential worker exposure to dust; and (3) minimizes the exposure of periclase, the
3   main, reactive constituent of MgO, to atmospheric CO_2 and H_2O during handling and
4   emplacement, and prior to panel closure. WTS (2003) provides detailed specifications for the
5   supersacks. In particular, WTS (2003) specifies that the supersacks "shall provide a barrier to
6   atmospheric moisture and carbon dioxide (CO_2) … equivalent to or better than that provided by a
7   standard commercial cement bag" and "must be able to retain [their] contents for a period of two
8   years after emplacement without rupturing from [their] own weight." The specifications also
9   require a certificate of compliance with all requirements of WTS (2003) for every shipment of
10   MgO (see next paragraph), and a certified chemical analysis of each new lot of MgO. The
11   supersacks are subject to random receipt inspection at the WIPP to ensure compliance with the
12   dimensions and labeling specified by WTS (2003), and to identify any shipping damage.

13   The supersacks contain dry, granular MgO, of which less than 0.5 percent can exceed 3/8 in. (9.5
14   mm) in diameter (WTS 2003). Emplacement of granular MgO instead of powder (1) results in a
15   bulk density high enough that sufficient MgO can be emplaced without causing major
16   operational difficulties, (2) reduces the likelihood of formation and release of dust in the event of
17   premature rupture of a supersack, and (3) ensures that the permeability of the material is high
18   enough to promote complete reaction with aqueous or gaseous CO_2.

19   Creep closure of WIPP disposal rooms will rupture the supersacks and disperse the MgO among
20   and within the ruptured waste containers. This will in turn expose the MgO to the room
21   atmosphere, to any CO_2 produced by microbial consumption of CPR materials, and to H_2O vapor
22   and any brine present.

23   *BARRIERS-2.2.1 Changes in MgO Emplacement since the CCA*

24   Two changes have occurred in MgO emplacement since the CCA, a new supplier was needed for
25   the bulk MgO and operational concerns necessitated the elimination of the minisacks.
26
27   National Magnesia Chemicals provided the MgO emplaced in the WIPP from 1999 through
28   2000. After National Magnesia Chemicals stopped producing MgO, Premier Chemicals in
29   Gabbs, Nevada, was selected as the supplier. Premier MgO was selected based on cost and a
30   technical evaluation verifying its suitability as the engineered barrier (Papenguth 1999). The
31   technical evaluation included a reactivity test developed by Krumhansl et al. (1997). Premier
32   Chemicals has supplied MgO since 2000.
33
34   Initially, MgO was emplaced in both supersacks and minisacks. The 25-pound minisacks were
35   emplaced among the waste containers and between the waste containers and the ribs (sides) of
36   the disposal rooms (see CCA Chapter 3). In 2000, however, the DOE requested EPA approval
37   of the elimination of the minisacks (see Triay 2000); the EPA approved this request in 2001
38   (EPA 2001a).

39   **BARRIERS-2.3   Backfill Conceptual Model**

40   The function of backfill is included in the chemical conditions conceptual model. MgO will
41   create conditions in the repository that decrease actinide solubilities. These lower solubilities are

1 a result of the consumption of CO_2 produced by microbial consumption of CPR materials and by
2 buffering f_{CO_2} and pH in the disposal system. In the model, MgO will initially hydrate by
3 reacting with any brine present in the repository to form brucite:
4
5 $$MgO + H_2O(aq\ or\ g) \rightleftharpoons Mg(OH)_2. \tag{1}$$
6
7 Brucite dissolution is expected to buffer brine by:
8
9 $$Mg(OH)_2 \rightleftharpoons Mg^{2+} + 2OH^-, \tag{2}$$
10
11 CO_2 in the system will initially react with brucite to form metastable phases including
12 hydrogagnesite:
13
14 $$5Mg(OH)_2 + 4CO_2(aq\ or\ g) \rightleftharpoons Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O, \tag{3}$$
15 or:
16
17 $$4Mg(OH)_2 + 3CO_2(aq\ or\ g) \rightleftharpoons Mg_4(CO_3)_3(OH)_2 \cdot 3H_2O, \tag{4}$$
18
19 and nesquehonite:
20
21 $$Mg(OH) + 2H_2O + CO_2(aq\ or\ g) \rightleftharpoons MgCO_3\ 3H_2O, \tag{5}$$
22
23 The DOE believes that hydromagnesite, the most likely metastable phase, and nesquehonite,
24 another possible metastable phase, will dehydrate to form magnesite ($MgCO3$), the stable
25 carbonate, in the event of microbial activity:
26
27 $$Mg_5(CO_3)_4(OH)_2\ 4H_2O + CO_2(aq\ or\ g) \rightleftharpoons 5MgCO_3 + 5H_2O, \tag{6}$$
28
29 EPA summarized the chemical conditions conceptual model in their TSD for 194.24 (Docket A-
30 93-02, V-B-17; EPA 1998d):
31
32 "Based on the above discussion, the sequence of events resulting from brine infiltration
33 and reaction with the MgO backfill in the repository may be conceptualized by the
34 following reactions, in order:
35   1.   Rapid reaction (hours to days) between the brine and MgO to produce
36   brucite.
37   2.   Rapid carbonation (hours to days) of the brucite to produce nesquehonite
38   and possibly hydromagnesite.
39   3.   Rapid conversion (days to weeks) of the nesquehonite to hydromagnesite.
40   4.   Slow conversion (hundreds to thousands of years) of the hydromagnesite
41   to magnesite.
42
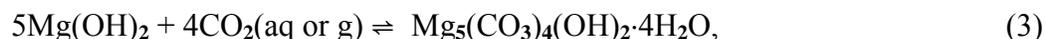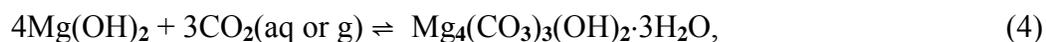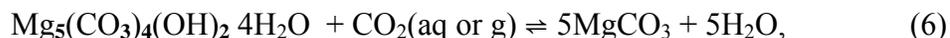
1 The available rate data indicate that some portion, perhaps all, of the hydromagnesite will
2 be converted to magnesite over the 10,000-year period for repository performance. The
3 exact time required for complete conversion has not been established for all chemical
4 conditions. However, the available laboratory and field data clearly indicate that
5 magnesite formation takes from few hundred to, perhaps, a few thousand years. Thus,
6 the early repository conditions can be best represented by the equilibrium between brucite
7 and hydromagnesite. These conditions will eventually evolve to equilibrium between
8 brucite and magnesite."
9
10 For the 2004 Compliance Recertification Application (CRA-2004), DOE has adopted the
11 approach EPA used in the 1997 Performance Assessment Verification Test (PAVT). The DOE
12 assumes for its actinide-solubility calculations that the metastable brucite-hydromagnesite
13 ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) carbonation reaction will buffer f_{CO_2}. However, in the long-term, the
14 brucite-magnesite carbonation reaction will buffer f_{CO_2}.
15
16 **BARRIERS-2.4   Predictions of the Effects of Magnesium Oxide**
17 The following sections discuss the effects of MgO on the disposal system. The predicted effects
18 used in the CCA and the effects now included in the CRA are discussed.
19
20 *BARRIERS-2.4.1   Previous Predictions of the Effects of Magnesium Oxide*
21 Novak et al. (1996) and CCA Appendix BACK concluded that magnesite will be the dominant
22 Mg carbonate in the repository during the 10,000-year regulatory period, and that the brucite-
23 magnesite carbonation reaction,
24
25 $$Mg(OH)_2 + CO_2(aq\ or\ g) \rightleftharpoons MgCO_3 + H_2O(aq\ or\ g), \qquad (7)$$
26
27 will buffer f_{CO_2} in the WIPP whether or not significant microbial CO_2 production occurs. Novak
28 et al. (1996) calculated actinide solubilities for the CCA PA. They did not report f_{CO_2}, but the
29 EPA (1998d, Tables 4-6 and 4-7) reported a value of $10^{-6.89}$ atm for both Salado Primary
30 Constituents (SPC[1]) and Energy Research and Development Administration (WIPP Well) 6
31 (ERDA-6[2]) brines in equilibrium with brucite and magnesite. This value of f_{CO_2} was used for the
32 actinide-speciation and -solubility calculations for all CCA PA vectors (both with and without
33 microbial activity). (Other minerals, such as halite and anhydrite, were also present.) Novak et
34 al. (1996) used the brucite dissolution reaction (see Reaction (2), above) to buffer the pH in their
35 actinide-solubility calculations, but did not report their results. The EPA (EPA 1998d, Tables 4-
36 6 and 4-7) reported pH values of 8.69 and 9.24 for SPC and ERDA-6, respectively, in
37 equilibrium with the mineral assemblages provided above. These values of pH were used for the
38 solubility calculations for all CCA PA vectors.
39

1 SPC is similar to Brine A, another synthetic fluid that has been used to represent intergranular Salado brines (molecke 1983).
2 ERDA-6 is a synthetic brine representative of fluids in brine reservoirs in the Castile Formation (Popielak et al. 1983)

1 For the 1997 PAVT, the EPA specified that the brucite-hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$)
2 carbonation reaction (see Reaction (3), above) will buffer f_{CO_2} in the WIPP whether or not
3 significant microbial CO_2 production occurs. The EPA (1998b, Tables 4.10-3 and 4.10-4;
4 1998d, Tables 4-8 and 4-9) reported a value of $10^{-5.50}$ atm for both SPC and ERDA-6 in
5 equilibrium with brucite and hydromagnesite. This value of f_{CO_2} was used for the actinide-
6 solubility calculations for all 1997 PAVT vectors (both with and without microbial activity;
7 other minerals, such as halite and anhydrite, were also present). The EPA (1998b, Tables 4.10-3
8 and 4.10-4; 1998d, Tables 4-8 and 4-9) reported pH values of 8.69 and 9.24 for SPC and ERDA-
9 6, respectively, in equilibrium with the mineral assemblages provided above. These pH values
10 were used for the solubility calculations for all 1997 PAVT vectors.
11
12 ***BARRIERS-2.4.2   Current Predictions of the Effects of Magnesium Oxid*e**

13 The following sections describe the implementation of the chemical conditions conceptual model
14 in the CRA-2004 PA. Specifically, the effects of MgO hydration and carbonation are discussed
15 along with discussions of MgO's buffering ability and potential impacts on other significant
16 chemical processes included in the CRA-2004 PA.
17
18 BARRIERS-2.4.2.1   Effects of Magnesium Oxide Hydration and Carbonation

19 The most important effect of MgO modeled in PA is its ability to sequester **CO_2** and buffer f_{CO_2}.
20 The PA includes the impacts of MgO on two elements relating to gas generation and actinide
21 solubilities. With respect to gas generation, PA assumes there is no **CO_2** in the disposal system
22 for vectors with microbial activity. For MgO's effect on actinide solubilities, the CRA-2004 PA,
23 Brush and Xiong (2003b) determined the log f_{CO_2} and pH for use in PA solubility calculations.
24 Table BARRIERS-2 compares the values of log f_{CO_2} and pH calculated for the CRA-2004 PA
25 solubility calculations by Brush and Xiong (2003b) with those calculated for the CCA PA and
26 the 1997 PAVT. Table BARRIERS-2 shows that, despite modest differences in the predicted
27 values of log f_{CO_2} and pH, reactions among brine, CO_2, and MgO will consume essentially all
28 CO_2 that could be produced in the repository, buffer f_{CO_2} within a range of about 10^{-5} to 10^{-6} atm
29 (or about 10^{-7} atm if significant quantities of magnesite form), and buffer the pH at about 9.

30 **Table BARRIERS-1. Comparison of Log f_{CO_2} and pH Calculated for the CRA-2004 PA,**
31 **the 1997 PAVT, and the CCA PA[1,2,3]**

Property and Brine	CRA,[1] Microbial Vectors	CRA,[1] Nonmicrobial Vectors	1997 PAVT,[3] All Vectors	CCA,[2] All Vectors
Log f_{CO_2}, Salado Brine	-5.50	-5.48	-5.50	-6.9
Log f_{CO_2}, Castile Brine	-5.50	-6.15	-5.50	-6.9
pH, Salado Brine	8.69	8.69	8.69	8.69
pH, Castile Brine	9.02	8.99	9.24	9.24

[1] From Brush and Xiong (2003b). See text for details.
[2] From Novak et al. (1996) and EPA (1998c). See text for details.
[3] From EPA (1998b, 1998c). See text for details.

1 These values of f_{CO_2} are significantly lower than those anticipated in the absence of MgO (see

2 CCA Appendix SOTERM, Figures SOTERM-1 and SOTERM-2).

3 BARRIERS-2.4.2.2   Effects of Magnesium Oxide in the Event of Significant Microbial
4   Activity

5 The DOE is emplacing significantly more MgO than would be required to sequester the CO_2 that
6 could be produced by microbial consumption of all CPR materials in the WIPP (see Section 2.6
7 of this appendix). Therefore, both brucite and hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$), or
8 brucite, a Mg-Cl-OH-H_2O phase, and hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$), will be present
9 in the repository even if all CPR materials are consumed; and these solids will buffer f_{CO_2} (see
10 Reaction (2), above). In this and other reactions used for thermodynamic calculations, it has
11 been assumed that the effects of possible substitution of Fe(II) for Mg in Mg-bearing solids such
12 as brucite and hydromagnesite are insignificant. Brush and Xiong (2003a, 2003b) used
13 equilibria among Generic Weep Brine (GWB[3]), brucite, $Mg_2Cl(OH)_3 \cdot 4H_2O$, and hydromagnesite
14 ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$), or among ERDA-6, brucite, and hydromagnesite
15 ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$), to buffer f_{CO_2} for the actinide-speciation and -solubility calculations
16 for the CRA-2004 PA vectors with microbial activity. Brush and Xiong (2003b, Table 6)
17 reported a value of $10^{-5.50}$ atm for f_{CO_2} for both GWB and ERDA-6 and the mineral assemblages
18 provided above. Other minerals, such as halite (NaCl) and anhydrite ($CaSO_4$), were also present
19 in these mineral assemblages, but are not reactants or products of the carbonation reaction(s) that
20 buffer f_{CO_2}.

21 The brucite dissolution reaction (see Reaction (2) above), will buffer pH in the WIPP in the
22 event of significant microbial activity. Brush and Xiong (2003b, Table 6) reported a pH value of
23 8.69 for GWB and 9.02 for ERDA-6.

24 These values of f_{CO_2} and pH were used for the actinide-speciation and -solubility calculations for
25 the CRA-2004 PA vectors with significant microbial activity (see Appendix PA, Attachment
26 SOTERM, Section SOTERM-3.0).

27 BARRIERS-2.4.2.3   Effects of Magnesium Oxide in the Absence of Significant Microbial
28   Activity

29 Brush and Xiong (2003a) redefined the reaction that will buffer f_{CO_2} for those PA vectors without
30 microbial activity. Brush and Xiong (2003b) evaluated the effects of this change on f_{CO_2} and pH,
31 and on the speciation and solubilities of thorium (Th), uranium (U), neptunium (Np), plutonium
32 (Pu), and americium (Am). Brush and Xiong (2003b) demonstrated that redefining the reaction
33 that will buffer f_{CO_2} does not change f_{CO_2}, pH, or actinide solubilities significantly. However,

3 GWB is a synthetic brine typical of intergranular (grain-boundary) fluids from the Salado Formation at or near the
stratigraphic horizon of the repository (Snider 2003b)

1 implementation of this change in the CRA-2004 PA has made the actinide solubilities used in
2 these calculations consistent with the conceptual model for microbial activity in the WIPP (see
3 above).

4 Calcite (CaCO$_3$) is more stable under expected WIPP conditions than magnesite, hydromagnesite
5 (Mg$_5$(CO$_3$)$_4$(OH)$_2$·4H$_2$O or Mg$_4$(CO$_3$)$_3$(OH)$_2$·4H$_2$O) or nesquehonite. Furthermore, calcite
6 precipitates readily under the low-temperature conditions expected in the WIPP. Formation of
7 calcite from the carbonation of lime (CaO) and/or portlandite (Ca(OH)$_2$)(has been observed in as
8 little as 16 days in GWB, and by 50 days in ERDA-6, in the carbonation experiments described
9 above. Therefore, Brush and Xiong (2003a, 2003b) suppressed (prevented the formation of)
10 calcite (and magnesite) by "disabling" it in their input files, thereby allowing the formation of
11 hydromagnesite (Mg$_5$(CO$_3$)$_4$(OH)$_2$·4H$_2$O), the third-most-stable carbonate mineral under
12 expected WIPP conditions. This was appropriate for the vectors with microbial activity because
13 the large quantities of CO$_2$ produced in these vectors would overwhelm the capacity of dissolved
14 calcium (Ca^{2+}) to precipitate CO$_2$ as calcite, thus leaving most of the microbial CO$_2$ to react with
15 periclase, brucite, or Mg$_2$Cl(OH)$_3$·4H$_2$O and produce hydromagnesite or (initially) nesquehonite.
16 However, in the absence of microbial CO$_2$ production, the quantity of Ca^{2+} present would be
17 sufficient to precipitate any CO$_2$ present as calcite without formation of metastable Mg
18 carbonates. Therefore, for the vectors without microbial activity, Brush and Xiong (2003a,
19 2003b) allowed calcite to precipitate. The reaction that will buffer f$_{CO_2}$ in the absence of
20 microbial activity is:

21 $$Mg(OH)_2 + Ca^{2+} + CO_2(aq\ or\ g) \rightleftharpoons CaCO_3 + Mg^{2+} + H_2O(aq\ or\ g).\qquad(8)$$
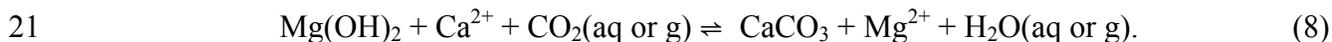
22 Unlike the brucite-hydromagnesite (Mg$_5$(CO$_3$)$_4$(OH)$_2$·4H$_2$O) carbonation reaction (see Reaction
23 (2), above), which buffers f$_{CO_2}$ at a unique value of 10$^{-5.50}$ atm, the value of f$_{CO_2}$ maintained by
24 the brucite-calcite carbonation reaction (Reaction (4)) depends on the ratio of the activities of
25 Mg^{2+} and Ca^{2+}, which in turn depends on the composition of the brine after equilibration with
26 MgO. Brush and Xiong (2003b, Table 6) reported a value of 10$^{-5.48}$ atm for GWB, brucite, and
27 calcite, and 10$^{-6.15}$ atm for ERDA-6, brucite, and calcite. (Other minerals, such as halite and
28 anhydrite, were also present.)

29 The brucite dissolution reaction (see Reaction (3), above) would also buffer pH in the WIPP in
30 the absence of significant microbial activity. Brush and Xiong (2003b, Table 6) reported pH
31 values of 8.69 for GWB and 8.99 for ERDA-6.

32 These values of f$_{CO_2}$ and pH were used for the actinide-speciation and -solubility calculations for
33 the CRA-2004 PA vectors without microbial activity (see Appendix PA, Attachment SOTERM,
34 Section SOTERM-3.0).

35 BARRIERS-2.4.2.4   Effects of Magnesium Oxide on Colloidal Actinide Concentrations

36 Colloids could affect the long-term performance of the WIPP because of their potential ability to
37 bind cationic metals such as the actinide elements in TRU waste and because of their potential
38 mobility under expected repository conditions (Choppin 1988). Colloids are typically defined as
39 phases intermediate in size between dissolved ionic or molecular species and suspended particles

1 large enough to settle by gravity. The size range of colloids is typically on the order of 1 nm to
2 1 μm.

3 Humic substances, microbes, and mineral fragments could bind actinides in the WIPP. Under
4 some conditions, actinides could also form intrinsic colloids without binding to humics,
5 microbes, or minerals. Even if one or more of these four types of colloids form(s) in the WIPP,
6 they would not transport actinides out of the repository unless they remain suspended in brine. If
7 coagulation occurs, any actinides bound to these colloids would be immobile, at least with
8 respect to direct brine releases or injection of brine into the Culebra Member of the Rustler
9 Formation.

10 Chemical conditions in the repository will affect the colloidal actinide source term. For example,
11 the pH of any brine present will affect the concentration(s) of intrinsic colloids. Studies carried
12 out to quantify the colloidal source term included experiments under conditions that will be
13 established by MgO (see Appendix PA, Attachment SOTERM, Section SOTERM-6.0).

14 **BARRIERS 2.5**   Experimental Activities and Modeling Investigations Since the CCA

15 The Scientific Advisor (SA) has investigated MgO efficacy through various experiments to test
16 key functions. Specifically the SA has characterized MgO samples from suppliers and
17 performed hydration and carbonation experiments. The following sections discuss the
18 experiments and implications on the chemical conditions conceptual models.
19
20 *BARRIERS-2.5.1   Characterization of Premier Magnesium Oxide*

21 As stated in Section 2.2.1, Premier Chemicals manufactures the MgO currently being
22 emplaced in the WIPP by mining ore from a sedimentary magnesite deposit and calcining
23 it to expel all CO_2 from magnesite, thereby producing periclase. Calcination of accessory
24 calcite produces small quantities of lime. Calcination of other accessory minerals in the
25 ore creates minor quantities of oxide and silicate minerals such as spinel ($MgAl_2O_4$),
26 ulvöspinel ($Ti(Fe,Mg)_2O_4$), forsterite (Mg_2SiO_4), and monticellite ($CaMgSiO_4$).
27 Calcination also drives off all H_2O in the ore.

28 Bryan and Snider (2001a) reported that a typical chemical analysis of Premier MgO
29 yields about 91 wt percent MgO, 1 wt percent alumina (Al_2O_3), 3 wt percent silica (SiO_2),
30 4 wt percent calcium oxide (CaO), and 1 wt percent iron(III) (Fe(III)) oxide (Fe_2O_3).
31 Most of the MgO and some of the CaO occur as periclase and lime, respectively, in
32 Premier MgO. However, some of the MgO and CaO, and most – if not all – Al_2O_3, SiO_2,
33 and Fe(III) oxide are present in the accessory oxide and silicate minerals described above.

34 Snider (2003a) used inductively coupled plasma-optical emission spectroscopy,
35 gravimetric analysis, and XRD analysis to quantify the mineralogical composition of one
36 of the lots of Premier MgO used for the experiments described below. Based on the
37 assumption that the silicate in this MgO is forsterite, this lot of MgO contains 86.86 wt
38 percent periclase, 2.386 wt percent lime, 2.071 wt percent spinel, and 5.02 wt percent
39 forsterite. If the silicate is monticellite, this lot contains 88.73 wt percent periclase, 1.273
40 wt percent lime, 2.071 wt percent spinel, and 5.756 wt percent monticellite. Given the

1   uncertainties inherent in quantifying the mineralogical composition of materials such as
2   Premier MgO, it is reasonable to conclude that this material contains about 90 wt percent
3   reactive phases (periclase + lime) and 10 wt percent nonreactive phases (oxides and
4   silicates).

5   After the WIPP is filled and sealed, periclase will react with H_2O in the gaseous phase to
6   form brucite ($Mg(OH_2)$), or with H_2O in brine to form brucite or amorphous or crystalline
7   Mg-Cl-OH-H_2O-bearing solids such as $Mg_3Cl(OH)_5 \cdot 4H_2O$ or $Mg_2Cl(OH)_3 \cdot 4H_2O$.
8   Periclase, brucite, and the Mg-Cl-OH-H_2O phases will react with aqueous or gaseous
9   CO_2 to form solids such as hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$ or perhaps
10   $Mg_4(CO_3)_3(OH)_2 \cdot 3H_2O$), nesquehonite ($MgCO_3 \cdot 3H_2O$), and perhaps magnesite. Lime
11   will react with aqueous or gaseous H_2O to form portlandite, and lime and portlandite will
12   react with aqueous or gaseous CO_2 to form calcite. Oxides other than periclase and lime,
13   and silicates will not react with H_2O and CO_2 to a significant extent during the 10,000-
14   year regulatory period. Therefore, oxides other than periclase and lime, and silicates are
15   not included in the calculation of the CO_2 consumption capacity used to calculate the
16   MgO safety factor (see Section 2.6 of this appendix). Furthermore, these oxides and
17   silicates will not affect chemical conditions in the repository significantly.

18   Bryan and Snider (2001a) carried out particle-size analysis of two of the batches of MgO
19   used for their experiments. Table BARRIERS-1 provides the results of this analysis.

20   **Table BARRIERS-2. Particle-Size Distribution of Two Batches of Premier MgO**

21   (Bryan and Snider 2001a)

Size Range (mm)	Batch 1	Batch 2
< 0.15	30.95%	9.89%
0.15 to 0.30	8.36%	29.37%
0.30 to 0.50	4.59%	29.72%
0.50 to 0.71	3.50%	14.98%
0.71 to 2.00	14.16%	14.51%
> 2.00	37.41%	1.53%

22

23   *BARRIERS-2.5.2   Hydration of Magnesium Oxide*

24   The SA investigated MgO hydration, including experiments under conditions similar to those
25   expected in the repository. Bryan and Snider (2001a, 2001b) and Snider (2002, 2003a) studied
26   the hydration of Premier MgO, the material currently being emplaced in the WIPP, under humid
27   and inundated conditions. Humid experiments have been carried out with 3 g of uncrushed
28   Premier MgO at a relative humidity (RH) of 35, 50, 75, or 95 percent and temperatures of 25, 40,

1 60, or 80 ºC for up to 460 days (Snider 2003a); inundated experiments have been conducted with
2 5 g of uncrushed Premier MgO in 100 mL of deionized (DI) H_2O, 4.00-M sodium chloride
3 (NaCl), ERDA-6, or GWB at temperatures of 25, 50, 70, and 90 °C for up to 360 days (Snider
4 2003a).

5 Reaction (1)(see above) is the only hydration reaction observed to date in the humid
6 experiments. Reaction (1) is also the only hydration reaction observed so far in the inundated
7 runs with ERDA-6 (Snider 2003a). In inundated experiments with GWB, hydration has
8 produced both brucite and an amorphous or crystalline Mg-Cl-OH-H_2O phase (Snider 2003a). In
9 most of the runs with GWB, the Mg-Cl-OH-H_2O phase is amorphous and its exact composition
10 has not been determined. In a few experiments at 25 ºC, however, a crystalline phase with the
11 composition $Mg_3Cl(OH)_5 \cdot 4H_2O$ has been identified by X-ray diffraction (XRD) analysis. The
12 thermodynamic speciation and solubility code Fracture-Matrix Transport (FMT) (Babb and
13 Novak 1997 and addenda, Wang 1998) also predicts that both brucite and $Mg_2Cl(OH)_3 \cdot 4H_2O$ are
14 stable in GWB. However, long-term experiments with GWB suggest that brucite may be
15 replacing the amorphous Mg-Cl-OH-H_2O phase.

16 *BARRIERS-2.5.3 Carbonation of Magnesium Oxide*

17 The SA investigated MgO carbonation and intermediate hydrous phases. Bryan and Snider
18 (2001a, 2001b), Snider (2002), Snider and Xiong (2002), and Xiong and Snider (2003) have
19 studied the carbonation of Premier MgO, the material currently being emplaced in the WIPP, and
20 reagent-grade materials under inundated conditions. Inundated experiments have been carried
21 out with 5 g of uncrushed Premier MgO in 100 mL of DI H_2O, 4.00-M NaCl, ERDA-6, or GWB
22 under an atmosphere consisting of compressed, ambient, laboratory air at room temperature for
23 up to 327 days (Snider and Xiong 2002); inundated experiments have also been conducted with
24 uncrushed Premier MgO; crushed, prehydrated Premier MgO; Fisher reagent-grade periclase; or
25 prehydrated Fisher periclase in 100 mL of ERDA-6 or GWB under an atmosphere containing 5
26 percent CO_2 for periods up to 91 days (Snider and Xiong, 2002). Humid experiments have been
27 performed with 2.5 g of prehydrated Fisher periclase in an atmosphere consisting of compressed,
28 ambient, laboratory air at an RH of 33, 58, 75, or 95 percent at room temperature and 40 ºC.

29 In experiments with ERDA-6 and atmospheric CO_2, Snider and Xiong (2002) have detected
30 hydromagnesite with the composition $Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$ by XRD analysis. No other Mg
31 carbonates have been detected in runs with ERDA-6 and atmospheric CO_2. Snider and Xiong
32 (2002) have detected both hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) and nesquehonite by XRD
33 analysis in the experiments with ERDA-6 and 5 percent CO_2, but hydromagnesite is clearly
34 replacing nesquehonite as these experiments proceed. In experiments with GWB,
35 hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) is the only Mg carbonate that has been detected by
36 XRD analysis (Snider and Xiong 2002). Therefore, consistent with the chemical conditions
37 conceptual model, there is strong evidence that hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$) will be
38 the dominant Mg carbonate for at least part of the 10,000-year regulatory period. The duration
39 of these experiments supports the conclusion that an intermediate phase will occur early in the
40 disposal system where magnesite formation is not expected for hundreds of years.

41 Additionally, thermodynamic calculations with EQ3/6 (Daveler and Wolery 1992, Wolery
42 1992a, 1992b, Wolery and Daveler 1992) and FMT imply the magnesite is stable with respect to

1 both hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$ or $Mg_4(CO_3)_3(OH)_2 \cdot 3H_2O$) and nesquehonite
2 under expected WIPP conditions (see Brush and Xiong 2003a). Furthermore, magnesite is
3 commonly observed in the Salado (Lang 1939; Adams 1944; Lowenstein 1983, 1988; Stein
4 1985) and in other formations in the Delaware Basin (Garber et al. 1990). Lowenstein (1988,
5 p. 598) describes the siliciclastic-carbonate mudstone, in which magnesite is most abundant, as a
6 "non-evaporitic sediment" and attributes its origin to subaqueous "settling of fine-grained,
7 suspended material in the center of the Salado basin where the energy of inflow waters had
8 largely dissipated." Therefore, the magnesite observed in the Salado did not necessarily form in
9 situ. However, Garber et al. (1990), who reported that magnesite "occurs pervasively"
10 throughout an 82-m (270-ft) interval of core recovered from a stratigraphic test well located
11 along the subsurface trend of the Capitan Reef 27 km (17 miles) northeast of Carlsbad,
12 concluded that "the most likely origin for the magnesite in the core is the downward movement
13 of dense fluids from the Ochoan Series, Salado Formation into the underlying, and [at the time]
14 shallowly buried Tansil and Yates formations." Clearly, magnesite either formed or persisted for
15 long periods in the Delaware Basin. Therefore, consistent with the chemical conditions
16 conceptual model, the possibility that significant quantities of magnesite could form from
17 carbonation of MgO during the 10,000-year regulatory period cannot be ruled out.

18 ***BARRIERS-2.5.4   Effects of Magnesium Oxide on Gas Generation***

19 The two gas-producing processes included in PA are anoxic corrosion of steels and other Fe-base
20 alloys, which produces H_2, and microbial consumption of CPR materials, which produces mainly
21 CO_2 and methane (CH_4).

22 BARRIERS-2.5.4.1 Potential MgO Impacts on Gas Generation from Anoxic Corrosion of Steels
23   and Other Iron-Base Alloys

24 Telander and Westerman (1993, 1997) studied anoxic corrosion of various metals and
25 concomitant H_2 production under expected WIPP conditions. Wang and Brush (1996a, 1996c)
26 used results from three types of experiments carried out by Telander and Westerman (1993,
27 1997) to establish ranges and probability distributions of H_2-production rates for the CCA PA:
28 (1) experiments with low-carbon (C) steels in or above Brine A under atmospheres consisting of
29 initially pure CO_2, nitrogen (N_2), or hydrogen sulfide (H_2S) in inert (noncorroding), metallic
30 containers at low-to-intermediate pressures (about 1 to 20 atm); (2) experiments with low-C
31 steels in Brine A under H_2, CO_2, or N_2 in autoclaves at high pressures (35 to 127 atm); and
32 (3) runs with low-C steels in ERDA-6 at pH values of 2.8 to 10.6 under N_2. All these
33 experiments were conducted at 30 ± 5 °C. Brine A and ERDA-6 are described above (see
34 Section 2.4.1 of this appendix).

35 Anoxic corrosion of low-C steels in Brine A under initially pure N_2 resulted in a pH of 8.3, 8.3,
36 and 8.4 after 6, 12, and 24 months, respectively (see Telander and Westerman 1993, Table 6-3,
37 Test Containers 10, 17, and 25). Wang and Brush (1996a, 1996c) used the 12-to-24-month data
38 from these experiments to establish a range and probability distribution of inundated, anoxic-
39 corrosion rates of steels and other Fe-base alloys of 0 to 0.5 μm/year for the CCA PA. This is
40 equivalent to a range of 0 to 1.59×10^{-14} m/s. Data on the effects of pH on corrosion rates
41 (Telander and Westerman 1997, Table 6-5) have demonstrated that rates obtained at a pH of 8.3
42 or 8.4 are somewhat higher than those at a pH of 8.69, 8.99, or 9.02, the values expected for the

1 brucite dissolution reaction (see Reaction (3), above). Therefore, the anoxic-corrosion rates
2 established by Brush and Wang (1996a, 1996c) for the CCA incorporated the effects of MgO on
3 pH.

4 For the 1997 PAVT, the EPA specified that the upper limit of the range of the inundated anoxic-
5 corrosion rate be increased from 1.59×10^{-14} m/s to 3.17×10^{-14} m/s (Trovato 1997a, Enclosure
6 2; EPA 1998c, Table ES-4, Section 5.15, and Tables 6.3 and 6.4; Hansen and Leigh 2003). A
7 range of 0 to 3.17×10^{-14} m/s was also used for the CRA-2004 PA (see Appendix PA, Section
8 PA-5.2).

9 BARRIERS-2.5.4.2   Microbial Gas Generation

10 Francis and Gillow (1994, 2000), Francis et al. (1997), and Gillow and Francis (2001a, 2001b,
11 2002a, 2002b) did not include MgO or the effects of pH in their study of microbial gas
12 generation under expected WIPP conditions. Instead, they included bentonite in about half of
13 their experiments because a backfill consisting of 70 wt percent crushed salt and 30 wt percent
14 bentonite had been proposed as an alternative to a backfill consisting entirely of crushed salt, the
15 design-basis backfill in January 1992 when these microbial gas-generation experiments were
16 started. No microbial experiments have been carried out with MgO since the use of this material
17 was proposed in 1996 to consume CO_2 and control f_{CO_2} and pH in the WIPP.

18 The brucite dissolution reaction (see Reaction (3), above) will buffer the pH of any brines
19 present at about 9 whether or not significant microbial activity occurs in the WIPP. This mildly
20 basic value is somewhat higher than the mildly acidic values of pH produced by dissolution of
21 microbial CO_2 in the experiments described by Francis and Gillow (1994, 2000), Francis et al.
22 (1997), and Gillow and Francis (2001a, 2001b, 2002a, 2002b). However, emplacement of MgO
23 in the WIPP and a consequent, mildly basic pH of 9 will not in and of itself preclude significant
24 microbial activity in the repository. This conclusion is based on the common observation of
25 viable alkalohalophilic microbes in alkaline lakes with pH values of 9 to 10. Such alkaline lakes
26 occur frequently in arid and semiarid environments, such as southeastern New Mexico and
27 adjacent areas of west Texas, and could be one of the sources of the halophilic microbes
28 observed in the WIPP.

29 However, several investigators have reported that MgO and compounds derived from MgO
30 possess inhibitory or even biocidal properties (Asghari and Farrah 1993, Chapman et al. 1995;
31 Koper et al. 2002; Sawai 2003; Sawai et al. 1995a, 1995b, 1996, 2000a, 2000b; Stoimenov et al.
32 2002; Yamamoto et al. 1998). Some of the results of these studies may be applicable to the
33 WIPP.

34 First, the inhibitory or biocidal effects of MgO probably result from the presence of brucite, not
35 periclase (Sawai et al. 1995a), because most of the experiments cited above were conducted in
36 aqueous solutions or in growth media that contained H_2O, and most of these experiments were
37 long enough for significant nucleation and growth of brucite on periclase surfaces exposed to
38 these solutions or media.

39 Second, the inhibitory or biocidal effects of MgO do not seem to be caused by the mildly basic
40 pH that results from the presence of brucite in aqueous solutions or growth media. Sawai et al.

1   (1997) reported that the survival of Escherichia coli (E. coli) was unaffected by a MgO-free,
2   alkaline growth medium at pH values of 10, 10.25, and 10.5, but that E. coli survival decreased
3   significantly in the same medium at pH values of 10.75 and 11. This result agrees with the
4   conclusion that a mildly basic pH of about 9 caused by the brucite dissolution reaction (see
5   Reaction (3), above) will not by itself preclude microbial activity in the WIPP.

6   Third, the presence of solid Mg peroxide (MgO_2) (Asghari and Farrah 1993) and/or the anionic
7   dioxygenyl radical ($O_2^{\bullet-}$) (Sawai et al. 1995b) along with periclase may be largely responsible for
8   the inhibitory or biocidal effects of MgO. MgO_2 could be produced by reactions between
9   dissolved hydrogen peroxide (H_2O_2), which will be produced by α radiolysis of H_2O in WIPP
10 brines, and periclase, brucite, or perhaps other Mg-bearing solids. Radiolysis will also produce
11 anionic $O_2^{\bullet-}$.

12 Fourth, inhibition of microbial activity seems to require contact between MgO particles and
13 microbes (Sawai et al. 2000a). This conclusion is based on the observation that increased
14 shaking speed of an MgO-bearing slurry increased the mortality of E. coli in the slurry.

15 Fifth, the inhibitory effect is inversely proportional to the size of the MgO particles (Sawai et al.
16 1996; Koper et al. 2002; Stoimenov et al. 2002) and the temperature at which the MgO was
17 prepared (Sawai et al. 1996).

18 Application of these results to microbial activity in the WIPP is difficult in the absence of long-
19 term experiments under expected repository conditions. Biocides are often used for sterilization
20 of solid materials, but become ineffective as the volume of the material(s) to be sterilized
21 increases. This is because it becomes progressively more difficult to ensure uniform distribution
22 of the biocide throughout these materials, and hence to ensure contact between the biocide and
23 the microbes, as the volume increases. Therefore, sterilization methods such as autoclaving and
24 radiation are used for materials with large volumes. In the case of MgO, Sawai et al. (2000a)
25 reported that inhibition of microbial activity seems to require contact between MgO particles and
26 microbes. Although room closure will rupture the supersacks and disperse the MgO into the
27 interstices among and within the ruptured waste containers, this will not ensure contact between
28 MgO particles and microbes. Furthermore, survival of microbes in samples subjected to
29 treatment with an inhibitory or biocidal agent such as MgO, especially those that have had some
30 contact with particulate MgO, would probably result in the development of increased resistance
31 to MgO.

32 Nevertheless, the results described above suggest that MgO might reduce the rate of microbial
33 gas generation in the WIPP. In the absence of repository-specific experiments, however, it is not
34 possible to reduce the microbial gas-production rates used in PA. Therefore, the rates and
35 probability distributions used for the CRA-2004 PA are identical to those used for the CCA PA
36 and the 1997 PAVT.

37 ### BARRIERS-2.5.5   *Effects of Magnesium Oxide on Room Closure*

38 In the CCA PA, the 1997 PAVT, and the CRA-2004 PA calculations, room closure initially
39 proceeded as if the rooms were open. The free air space was eliminated early in the calculations
40 by unmitigated creep closure. Eventually, the salt contacted the waste and deformed it according

1   to the waste response model. At the same time, corrosion and gas production pressurized the
2   rooms. The coupled processes involved compression owing to the superincumbent rock
3   counterbalanced by gas production, which was obtained from sampled parameters. Thus, room
4   closure was due to salt creep modified by the structural response of the waste and by gas
5   production. MgO had no effect on room closure.

6   *BARRIERS-2.5.6   Effects of Magnesium Oxide on Far-Field Actinide Transport*

7   MgO could affect the matrix distribution coefficients (K_ds) used to predict transport of dissolved
8   Th, U, Pu, and Am through the Culebra (see Brush 1996 or Brush and Storz 1996 for a definition
9   of matrix K_ds). For the CCA PA, data from an empirical sorption study, a mechanistic sorption
10   study, and a column-transport study were used to establish ranges and probability distributions of
11   K_ds for Th, U, Pu, and Am.

12   Most of these K_ds were obtained from six-week, empirical sorption experiments carried out with
13   1 g of dolomite-rich rock crushed to a size range of 75 to 500 μm; 20 mL of Brine A, ERDA-6,
14   AISinR, or H-17 with dissolved Th(IV), U(VI), Np(V), Pu(V), or Am(III); and a controlled
15   atmosphere containing 0.24, 1.4, or 4.1 percent CO_2 to simulate the expected range of f_{CO_2} in the
16   Culebra, about $10^{-3.5}$ to $10^{-1.50}$ atm (see Brush 1996; Brush and Storz 1996). Brine A and ERDA-
17   6 are described above (see Section 2.4.1 of this appendix); AISinR is a synthetic brine
18   representative of fluids sampled from the Culebra in the WIPP Air Intake Shaft; and H-17
19   simulates Culebra brine from the H-17 Hydropad.

20   Brush (1996) and Brush and Storz (1996) extended the empirical K_ds obtained with Brine A and
21   ERDA-6 to a pH of about 9 or 10 with data from a mechanistic sorption study that quantified the
22   effects of f_{CO_2}, pH and ionic strength on the sorption of Th(IV), U(VI), Np(V), Pu(V), and
23   Am(III) from synthetic NaCl solutions by well-characterized, pure dolomite. Therefore, the K_ds
24   for Brine A and ERDA-6 used for the CCA PA included the effects of MgO on pH. The K_ds for
25   the Culebra brines, however, did not include the effects of MgO on pH because it was assumed
26   that, if mixing is sufficient to produce fluids with compositions similar to those of Culebra
27   brines, the pH of these mixtures will also be similar to those of Culebra brines (Brush 1996;
28   Brush and Storz 1996).

29   For the 1997 PAVT, the EPA specified that the probability distributions for the K_ds be changed
30   from uniform to log uniform (Trovato 1997b, Enclosure 2; EPA 1998c, Tables ES-3 and ES-4,
31   Sections 5.34 to 5.38 and Tables 6.3 and 6.4; Hansen and Leigh 2003). However, the EPA did
32   not change any of the K_ds.

33   Brush and Storz (1996) corrected some of the ranges of K_ds established by Brush (1996) for the
34   CCA PA. These corrections were too late for the far-field transport calculations for the CCA
35   PA, and were not included in the far-field transport calculations for the 1997 PAVT. Hansen and
36   Leigh (2003), however, incorporated them in the PA database, and the CRA-2004 PA used the
37   corrected K_ds along with the log-uniform probability distributions specified by the EPA (see
38   Appendix PA, Section PA-5.2). The K_ds for Brine A and ERDA-6 used for the CRA-2004 PA
39   included the effects of MgO on pH (Reaction (8) in Section 2.4.2.3 of this appendix), but the K_ds
40   for the Culebra brines do not (see above).

1 **BARRIERS-2.6 Magnesium Oxide Safety Factor**

2 The MgO safety factor was first established in a request for additional information during the
3 first WIPP certification (DOE 1997, see also Section 2.3). EPA requested information that
4 demonstrated that the excess MgO volume proposed could actually be emplaced in the space
5 above the waste. Documentation developed during the minisack-elimination proposal (Triay
6 2000 and EPA 2001a) detail the method used to determine the amount needed to ensure the
7 chemical conditions assumptions used in PA. Actual waste emplacement information is used to
8 determine emplaced and projected amounts of MgO that will be emplaced. The excess MgO
9 above that needed was termed the safety factor. More specifically, the MgO safety factor is
10 defined as the quantity of MgO to be emplaced in the WIPP divided by the quantity required to
11 consume all CO_2 that would be produced by microbial consumption of all CPR materials in the
12 repository. The amount of CO_2 was conservatively determined by assuming a one-to-one mole
13 conversion of organic C in the waste to CO_2, the highest amount that could possibly be produced.
14 The safety factor was determined to be 1.95 (DOE 1997). However, this value was later reduced
15 to 1.67 as specified by EPA during their acceptance of DOE's request to eliminate the MgO
16 minisacks (EPA 2001a). Therefore, the DOE MgO emplacement scheme maintains the specified
17 1.67 safety factor in each panel.

18 *BARRIERS-2.6.1 Calculation of Magnesium Oxide Safety Factor*

19 As stated above, the MgO safety factor must be maintained at or above 1.67 times the amount
20 necessary to ensure the related assumptions in PA are maintained. The amount needed is that
21 which will sequester the maximum amount of CO_2 that could be produced in the repository.
22 This method conservatively assumes no other reactions that will sequester CO_2 such as reactions
23 with the waste (i.e., reactions with cementitious materials and iron) or the natural environment
24 (i.e., precipitation of calcite by Ca^{2+} from dissolution of SO42—bearing minerals such as
25 anhydrite) occur. The amount of CO_2 produced by microbial consumption of CPR materials
26 assumes a 1:1 molar ratio for the conversion of organic C in the waste to CO_2. Emplaced-waste
27 information and projected waste information are used to determine the amounts of CPR materials
28 in the disposal system. The amount of CPR materials stated in the CCA did not account for CPR
29 materials contained in remote handled (RH) waste or the emplacement materials used to aid the
30 disposal process. The current process includes these materials and therefore is more
31 representative of actual materials in the repository.
32
33 The amount of MgO that would be emplaced in the repository was originally determined in the
34 CCA to be 85,600 tons (later reduced to account for minisack elimination). This was the amount
35 believed to fit in the space above the waste stacks. Current waste-emplacement data are
36 available to better quantify the amount of MgO that has been and will be emplaced. The current
37 safety-factor calculations use the emplacement information and not the amount assumed in the
38 CCA.
39
40 As stated above, the 1.67 safety factor will be maintained by adding additional MgO if necessary
41 to account for locally higher concentrations of CPR materials in the repository. The default
42 MgO emplacement configuration of one supersack per stack of waste will continue to be
43 maintained throughout the disposal rooms. The safety factor calculation used in EPA's approval
44 of the elimination of minisacks (EPA 2001a) in CRA-2004 can be expressed as:

1

$$S_F^{MgO} = \frac{\left(M_{emp}^{MgO}\right)}{M_{req}^{MgO}}$$

2 (9)

3 where

4 M_{emp}^{MgO} = moles MgO emplaced

5
6 M_{req}^{MgO} = moles MgO required to consume CO_2 produced

7
8
9 Each of these terms is discussed below.

10 MOLES MgO EMPLACED

11 The mass of MgO emplaced will be tracked by the DOE as each room is filled. The conversion
12 from mass to moles is as follows:

13

$$M_{emp}^{MgO} = m_{emp}^{MgO}\left(\frac{kg}{2.2046\ lbs}\right)\left(\frac{1000g}{kg}\right)\left(\frac{mole}{40.3g}\right)$$

14 (10)
15
16 Where
17
18 M_{emp}^{MgO} = **moles MgO emplaced**
19
20 m_{emp}^{MgO} = **mass of MgO emplaced in pounds**
21
22
23 MOLES MgO REQUIRED TO CONSUME CO_2 PRODUCED

24 Calculation of the moles of MgO required to consume CO_2 is based on the assumption that one
25 mole of MgO is required to sequester one mole of CO_2 as was done for the safety factor
26 calculation used in the EPA's approval of the elimination of minisacks (EPA 2001a). CO_2 will
27 be produced through the metabolic utilization of CPR materials by microbes in the repository.

28

29 The moles of organic C in the repository are derived from the mass of CPR materials. The total
30 moles of organic C can be expressed as:

31 $$M_T^{OC} = \gamma_{CB}^{OC} \bullet M_{CB}$$ (11)

32 Where

33 M_T^{OC} = total moles of organic carbon

1 γ_{CE}^{OC} = moles of organic carbon per mole of cellulose

2 M_{CE} = moles of cellulose equivalent

3

4 Wang and Brush (1996a) concluded that $\gamma_{CE}^{OC} = 6$

5 The moles of cellulose equivalent are given in Equation 12 (Wang and Brush 1996a). An
6 adjustment is made to account for higher densities of C in plastic materials.

$$M_{CE} = \frac{m_C + m_R + 1.7 \bullet m_P}{MW_{CE}}$$

7 (12)

8 where

M_{CE} = moles of cellulose equivalent

MW_{CE} = molecular weight of cellulose = 162 g/mole

m_C = mass of cellulose

m_R = mass of rubber

m_P = mass of plastic

9
10
11 Equation (9) determines the safety factor. Operational controls track CPR materials emplaced in
12 the repository and the amount of MgO emplaced. As waste is emplaced, the safety factor will be
13 periodically calculated to determine if additional MgO is necessary to maintain the safety factor.
14 BARRIERS.2.6.2   Microbial Investigations since the CCA

15 The SA has continued to investigate microbial gas generation and its impact on long-term
16 repository performance. The MgO engineered barrier will consume CO_2 produced by microbial
17 consumption of CPR materials in the repository. Gas generation from anoxic corrosion of steel
18 and microbial consumption of CPR materials is modeled in PA as described in CRA Chapter 6,
19 Section 6.4.3.3. Microbial consumption of CPR materials is expected to progress via a sequence
20 of processes based on the availability of electron acceptors in the disposal system. The
21 conceptual model of sequential use of electron acceptors is based on the well-known
22 observations that: (1) microbes use the electron acceptor (oxidant) that yields the most free
23 energy per mole of organic C consumed; (2) after depletion of the best available electron
24 acceptor, these microbes – or other microbes – begin to consume the next best electron acceptor;
25 and (3) this process continues until all substrate (CPR materials in the case of the WIPP) is
26 consumed, an essential nutrient is consumed, or some other limiting condition is attained.
27 Sequential use of electron acceptors has been observed in a diverse array of natural
28 environments, such as lacustrine, riverine, estuarine, and oceanic sediments; soils; and in
29 anthropogenic environments, such as landfills. In these environments, the order of use observed
30 is oxygen (O_2) (referred to as aerobic respiration), NO_3^- (denitrification), manganese(IV)
31 (Mn(IV)) oxides and hydroxides (Mn reduction), Fe(III) oxides and hydroxides (Fe reduction),
32 SO_4^{2-} (SO_4^{2-} reduction), and CO_2 (fermentation and methanogenesis) (Froelich et al. 1979;

1   Berner 1980; Criddle et al. 1991; Chapelle 1993; Wang and Van Cappellen 1996; Schlesinger
2   1997; Hunter et al. 1998; Fenchel et al. 2000). (In the following discussion, fermentation and
3   methanogenesis are usually referred to as "methanogenesis" for simplicity.) The sequential
4   reactions used to represent possible denitrification, sulfate (SO_4^{2-}) reduction, and
5   methanogenesis in the WIPP (Wang and Brush 1996a) are:

6

7   $$C_6H_{10}O_5 + 4.8H^+ + 4.8NO_3^- \rightarrow 7.4H_2O + 6CO_2 + 2.4N_2; \quad\quad\quad (13)$$

8   $$C_6H_{10}O_5 + 6H^+ + 3SO_4^{2-} \rightarrow 5H_2O + 6CO_2 + 3H_2S; \quad\quad\quad (14)$$

9   $$C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2. \quad\quad\quad (15)$$
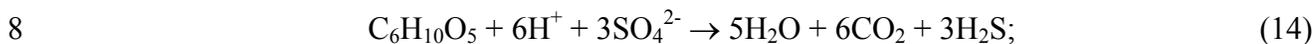
10 For these reactions, the CO_2 yields are 1 mole of CO_2 per mole of organic C consumed from
11 denitrification and SO_4^{2-} reduction, and 0.5 moles of CO_2 per mole of C from methanogenesis.

12 Results of the long-term study of microbial gas generation now confirm that methanogenesis is a
13 likely respiratory pathway in the repository if significant microbial activity occurs. By the time
14 that Wang and Brush (1996a, 1996b) established the model and parameters for microbial gas
15 generation for the CCA PA, Francis and Gillow (1994) and Francis et al. (1997) had observed
16 aerobic respiration and denitrification - but not methanogenesis - in their experiments, which had
17 been carried out for up to 1,228 days (3.36 years). Therefore, there was no experimental
18 evidence at the time of the CCA that methanogenesis would actually occur in the WIPP, that the
19 quantity of CPR materials consumed by methanogenesis in the WIPP would greatly exceed those
20 consumed by denitrification and SO_4^{2-} reduction, or that the overall CO_2 yield in the repository
21 would be close to 0.50 mol per mol of organic C consumed. At the time of the CCA, a possible
22 explanation for the absence of methanogenesis was that no viable fermentative and/or
23 methanogenic microbes were present in these experiments. There were two reasons why viable
24 fermenters and/or methanogens might not have been present: (1) none were present in the
25 materials used to inoculate these experiments (laboratory dust, brine, and mud from the salt lakes
26 in Nash Draw, and G Seep brine collected from G Drift - a drift located in the northern end of the
27 WIPP underground workings and used previously for in-situ experiments); and (2) communities
28 of halophilic, fermentative, and methanogenic microbes capable of metabolizing complex,
29 organic substrates, such as cellulosic materials under expected WIPP conditions, do not exist.

30 Since the CCA PA, however, methanogenesis has been observed in numerous experiments
31 carried out under several combinations of conditions (Francis and Gillow 2000, pp. 2, 3, and 10;
32 Gillow and Francis 2001, pp. 3-4 and 3-5; Gillow and Francis 2002a, pp. 2.1 - 12 to 2.1 – 14; and
33 Gillow and Francis 2002b, pp. 3.1 - 5 to 3.1 - 6). Several definitive conclusions can be drawn
34 from these results.

35 It is now clear that the absence of experimental evidence for methanogenesis at the time of CCA
36 PA was because microbial activity in the initially aerobic experiments had not progressed
37 through aerobic resp/iration, denitrification, and SO_4^{2-} reduction to methanogenesis; and that
38 microbial activity in the initially anaerobic experiments had not progressed through
39 denitrification and SO_4^{2-} reduction to methanogenesis. The requirement that these steps be
40 completed prior to the onset of methanogenesis is a consequence of the conceptual model of

1   sequential use of electron acceptors (see above), according to which methanogenesis does not
2   start until any and all NO_3^- and SO_4^{2-} are depleted, or until some other process renders the
3   environment unsuitable for denitrification and SO_4^{2-} reduction. Although methanogenesis had
4   not been observed by the time of the CCA PA in experiments carried out for up to 1,228 days
5   (3.36 years), it was later observed in inundated experiments after 2,718 days (7.44 years) and in
6   humid experiments after 2,653 days (7.26 years).

7   Therefore, it is also clear now that: (1) there exist communities of halophilic, fermentative, and
8   methanogenic microbes capable of metabolizing complex organic substrates, such as cellulosic
9   materials, under expected WIPP conditions; (2) such microbes are present – and viable – in one
10   or more of the materials used to inoculate these experiments; and (3) these microbes are capable
11   of surviving exposure to O_2. Methanogens are obligate anaerobes and, as such, are extremely
12   sensitive to exposure to O_2. The fact that they produced CH_4 after exposure to O_2 implies that
13   they are capable of producing resistant forms that can survive initially oxic conditions in these
14   experiments.

15   Furthermore, results from the microbial gas-generation study have confirmed that viable
16   halophilic fermenters and methanogens capable of metabolizing cellulosic materials under
17   expected near-field conditions are present in the WIPP underground workings. Francis and
18   Gillow (2000, pp. 2 and 10) detected CH_4 in initially oxic, unamended, and uninoculated
19   experiments, and in initially anoxic, unamended, and uninoculated experiments. The most likely
20   explanation for microbial gas production in these uninoculated experiments is that G Seep, the
21   brine used for these inundated experiments, was collected from the WIPP underground workings.
22   This brine contained a small but viable microflora, including methanogens, and was not
23   sterilized prior to use. The fact that these microbes produced CH_4 after exposure to O_2 in the air
24   used to ventilate G Drift and in initially oxic experiments implies that they are capable of
25   producing resistant forms that can withstand initially oxic conditions in the repository.

26   However, the presence of viable halophilic fermenters and methanogens in the WIPP does not
27   preclude the possibility that similar communities of microbes are also present in the other
28   materials used to inoculate these experiments, especially brine and mud from the salt lakes in
29   Nash Draw. It is quite possible that methanogens in these lakes are also capable of producing
30   resistant forms that can survive the oxic conditions encountered during eolian transport from
31   Nash Draw to the WIPP Air Intake Shaft, and initially oxic conditions in the repository.
32   Therefore, the presence of viable methanogens in the WIPP does not depend on the claim that
33   microbes have survived in the Salado since the Permian Period (Vreeland et al. 2000), a claim
34   that is controversial (see, for example, Hazen and Roedder 2001; Powers et al. 2001).

35   Finally, exclusive use of Reaction (16) (gas-producing methanogenesis) to represent
36   methanogenesis in PA (the current implementation of this respiratory pathway) is probably
37   conservative because Reaction (16) produces an equimolar mixture of CH_4 and CO_2. However,
38   another methanogenic reaction,

39           $$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O, \qquad\qquad (17)$$
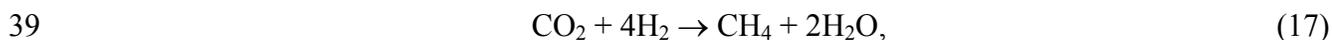
40   which actually consumes CO_2 and H_2, is likely in the WIPP because it is energetically favored
41   with respect to Reaction (16) (see, for example, Madigan et al. 2003, pp. 454-455). Reaction

1 (17) has been simplified somewhat inasmuch as microbes that use this respiratory pathway
2 typically use acetate ($CH_3CO_2^+$) or other organic acids along with H_2 to reduce CO_2 to CH_4.
3 (Reactions (14), (15), and (16) have also been simplified somewhat, as is typically the case when
4 used for geochemical applications such as predicting the CO_2 yield from microbial consumption
5 of CPR materials in the WIPP.) Nevertheless, if CO_2 and H_2 (and acetate) are present, Reaction
6 (17) (gas-consuming methanogenesis, or – strictly speaking – gas-consuming acetotrophic
7 methanogenesis) will probably proceed instead of Reaction (16). Alternatively, Reaction (17)
8 could probably proceed along with Reaction (16). In either case, Reaction (17) could consume
9 significant quantities of CO_2.

10 In the event of significant microbial activity in the WIPP, CO_2 and H_2 (and acetate) will be
11 present because: (1) consumption of CPR via Reaction (14), (15), or (16) will produce CO_2, (2)
12 anoxic corrosion of steels and other Fe-base alloys in waste containers and in the waste will
13 produce H_2 (if brine is present), and (3) acetic acid and sodium acetate are present in the TRU
14 waste to be emplaced in the WIPP (see Appendix DATA, Attachment F) and will dissolve in any
15 brines that enter the repository, possibly reaching a concentration of 3.57×10^{-3} M (Brush and
16 Xiong 2003c).

17 ## BARRIERS-3.0 DISPOSAL SYSTEM BARRIERS

18 ### BARRIERS-3.1   Definition of a Disposal System Barrier

19 Disposal system barriers are included as an integral part of the disposal system design. These
20 disposal system barriers are designed to delay the migration of radionuclides to the accessible
21 environment. Frequently, these disposal system barriers are designed to mitigate impacts to the
22 natural strata and block pathways created in the construction and operational phases of the WIPP
23 facility. As such, they are a necessary part of the overall disposal system design.

24 ### BARRIERS-3.2   Description of Waste Isolation Pilot Plant Disposal System Barriers

25 The DOE incorporated three types of disposal system barriers into the design of the disposal
26 system: panel closures, shaft seals, and borehole plugs.

27 #### *BARRIERS-3.2.1   Panel Closures*

28 In the CCA, the DOE described four possible panel closure designs to be used depending upon
29 ground conditions and potential for gas generation. CCA Appendix PCS was a design report
30 prepared and signed by a professional engineer certified by the state of New Mexico.

31 In the final certification decision for WIPP (63 FR 27405) (EPA 1998a), EPA specified four
32 conditions that apply to the certification. Condition 1 details the panel closure system to be used
33 as Option D with Salado Mass Concrete (SMC)**:**

34   Condition 1: § 194.14(b), Disposal system design, panel closure system. The Department shall
35   implement the panel seal design designated as Option D in Docket A-93-02, Item II-G-1 (October
36   29, 1996, Compliance Certification Application submitted to the Agency). The Option D design
37   shall be implemented as described in [CCA] Appendix PCS of Docket A-93-02, Item II-G-1, with
38   the exception that the Department shall use Salado mass concrete (consistent with that proposed

1   for the shaft seal system, and as described in CCA Appendix SEAL of Docket A-93-02, Item II-g-
2   1) instead of fresh water concrete.

3   Panel closures are included for Resource Conservation and Recovery Act (RCRA) disposal unit
4   closure to prevent potentially unacceptable levels of volatile organic compound (VOC) release
5   during waste management operations, and to protect against the effects of a postulated
6   deflagration in a closed panel. While the panel closures provide a solid structure within the
7   drifts, they were not intended to support long-term repository performance. Of the four options
8   proposed in the CCA, the EPA specified that one of these, Option D, should be used. This
9   Option consists of a concrete barrier emplaced after removing the disturbed rock zone (DRZ),
10 and an explosion wall. EPA also specified that SMC be used for the barrier (EPA 1998a), which
11 was a potential alternative to ordinary portland cement noted in the CCA.

12 Characteristics of the Option D design are incorporated into the PA grid and computational
13 methodologies for the recertification calculations (Appendix PA, Section PA-4.2.8). However,
14 the DOE believes that a redesign of the panel closure system is warranted. In a letter to the EPA
15 dated October 7, 2002 (DOE 2002-0205715), the DOE requested approval of a proposed change
16 to the EPA 40 CFR Part 194 Certification of the Waste Isolation Pilot Plant with regard to the
17 design of the panel closure system. The DOE believes that the redesigned panel closure is a
18 simpler design concept that provides equivalent or improved performance.

19 The EPA responded in a letter dated November 15, 2002 that concluded that the panel closure
20 system design change request would require a rulemaking. Because the rulemaking likely would
21 not be completed before this application would be submitted, the EPA deferred review of the
22 proposal until after the recertification decision. The EPA did agree to construction of the
23 explosion wall and a delay in construction of the Option D concrete monolith after completion of
24 waste emplacement in Panel 1 until a regulatory decision was made on the proposed new panel
25 closure design (Docket A-98-49, II-B-3, Item 44). Until a design change is approved by the EPA
26 and the State of New Mexico, the regulatory baseline includes the modified Option D Panel
27 Closure System.

28 A description of the Option D Panel Closure System, initially provided in CCA Appendix PCS,
29 is discussed in Sections 3.2.1.1 through 3.2.1.5 of this appendix.

30 BARRIERS-3.2.1.1 <u>Overview</u>

31 The panel closure system provides assurance that the RCRA limit for the migration of potential
32 VOCs will be met at the point of compliance, the WIPP site boundary. The panel closure system
33 will be located in the air-intake and air-exhaust drifts to each panel, as shown in Figure
34 BARRIERS-1. The design process commenced with the evaluation of the performance
35 requirements of the panel closure; and the system components have been designed to maintain
36 their intended functional requirements under loads generated from salt creep, internal pressure,
37 and a postulated methane explosion.

1   BARRIERS-3.2.1.2   <u>Design</u>

2   The mandated panel closure system is an enlarged tapered concrete barrier that will be grouted
3   along the interface and an explosion-isolation wall. Figure BARRIERS-2 illustrates this design.
4   The design concept for the enlarged concrete barrier incorporates:

5   • A concrete barrier that is tapered to promote the rapid stress buildup on the host rock.
6   The stiffness was selected to provide rapid buildup of compressive stress and reduction in
7   shear stress in the host rock.

8   • The enlarged barrier requires DRZ removal to keep the tapered shape approximately
9   spherical. DRZ removal limits potential VOC flow through the panel closure system.

10   • The design of the panel closure system includes an explosion-isolation wall designed to
11   provide strength and deformational serviceability during the operational period. The
12   length was selected to assure that uniform compression develops over a substantial
13   portion of the structure and that end-shear loading that might result in fracturing of salt
14   into the back is reduced. While no requirements for barricading waste areas exist under
15   the MSHA, the intent of the regulations is to safely isolate abandoned areas from active
16   workings using barricades of "substantial construction." The CCA examined the
17   potential issue of methane gas generation from TRU waste in closed areas. The principal
18   concern is the postulated occurrence of an explosive mixture of methane and an ignition
19   source, which would result in deflagration. An explosion-isolation wall has been
20   designed of sufficient thickness to resist dynamic loads from such a deflagration and
21   creep loads from closure of the salt around the wall.

22   The CRA-2004 PA calculations implement a conceptual design consistent with Option D, as
23   described above. As noted above, the DOE has reevaluated this panel closure design and believes
24   that a modification is warranted.

25   BARRIERS-3.2.1.3   <u>Design Components</u>

26   The following subsections present system and components design features.
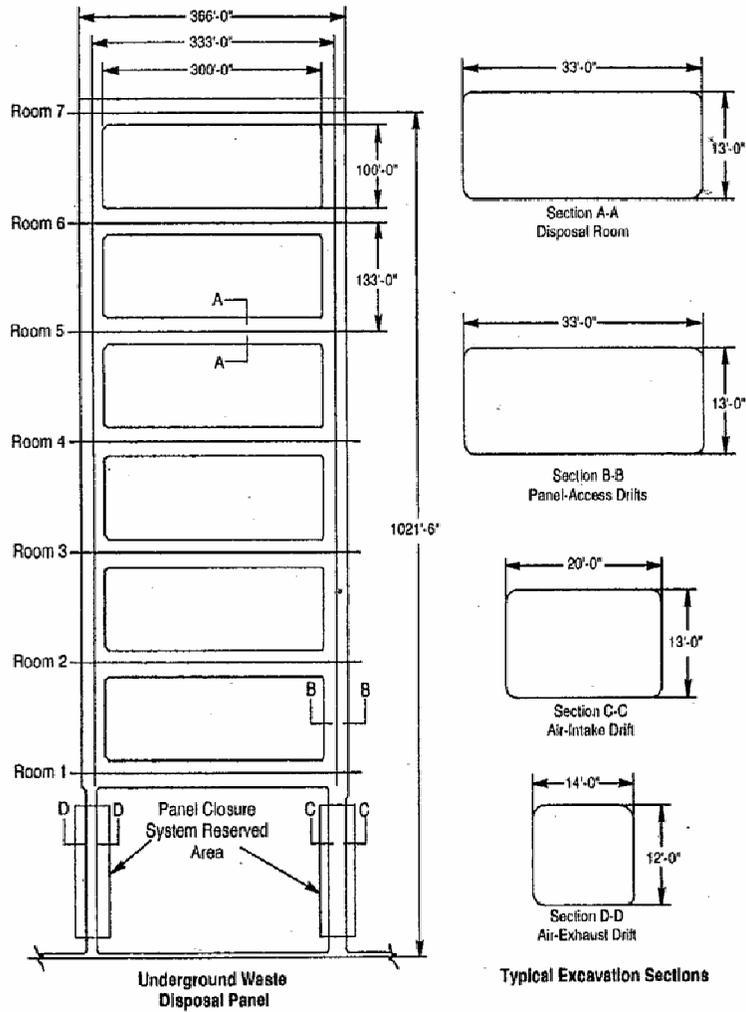
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2   Figure BARRIERS-1. Typical Facilities--Typical Disposal Panel After Westinghouse (1996c)
3   (Note: Figure is not to Scale. All Dimensions Shown are Nominal)
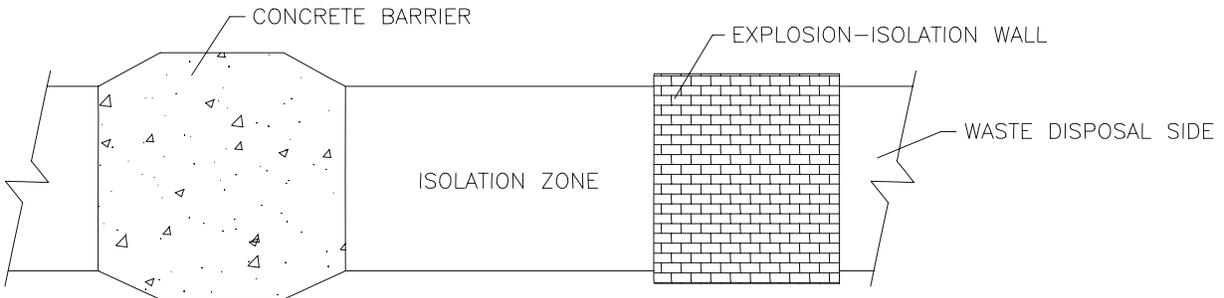
4

5   **Figure BARRIERS-2. Option D. Explosion-Isolation Wall and Concrete Barrier with**
6   **DRZ Removed**

1   BARRIERS-3.2.1.3.1   Concrete Barrier

2   The enlarged concrete barrier consists of SMC, with sufficient unconfined compressive strength
3   and with an approximately circular cross-section excavated into the salt over the central portion
4   of the barrier. The enlarged concrete barrier will be located at the optimum locations in the air-
5   intake and air-exhaust drifts, with the central portion extending just beyond Clay G and MB 139.

6   The enlarged concrete barrier will be placed in four cells, with construction joints perpendicular
7   to the direction of potential air flow. The concrete strength will be selected according to the
8   standards specified by the latest edition of the ACI code for plain concrete. The concrete will be
9   placed through 6-in- (15-cm)-diameter steel pipes and vibrated from outside the formwork. The
10   formwork is designed to withstand the hydrostatic loads during construction, with minimal
11   bracing onto exposed salt surfaces. This will be accomplished by placing a series of steel plates
12   that are stiffened by angle iron, with load reactions carried by spacer rods. The spacer rods will
13   be staggered to reduce potential flow along the rod surfaces through the barrier. Some exterior
14   bracing will be required when the first cell is poured. All structural steel will be American
15   Society for Testing Materials (ASTM) A36, with detailing, fabrication, and erection of structural
16   steel in conformance with the latest edition of the AISC steel manual (AISC 1989). After
17   concrete placement, the formwork will be left in place.

18   BARRIERS-3.2.1.3.2   Explosion Wall

19   An explosion-isolation wall, consisting of concrete blocks, will mitigate the effects of a
20   postulated methane explosion. The concrete block wall design complies with MSHA
21   requirements (MSHA 1987) because it uses incombustible materials of substantial construction.

22   The explosion-isolation wall in the Panel 1 access drift consists of a structure constructed across
23   the entire cross-section of each drift. Each wall is 12 ft (3.65 m) long and is created from solid
24   concrete blocks mortared together and set in a 0.5-ft (0.15-m) deep keyway cut around the full
25   perimeter of the drifts (Figure BARRIERS-3). The explosion-isolation walls were constructed to
26   the specifications the CCA Appendix PCS, except as noted below.

27   The revised design, in which the walls are 30 ft (9.1 m) long, uses identical construction
28   techniques, but specifies materials of higher strengths. In summary, the following changes were
29   specified:

30   • The mortar shall conform to ASTM C 270 type M, using the property specification 3000
31   psi (20.88 MPa) at 28 days, as a minimum requirement. (The wording of the specification
32   was changed slightly, but the compressive strength requirement is unchanged.)
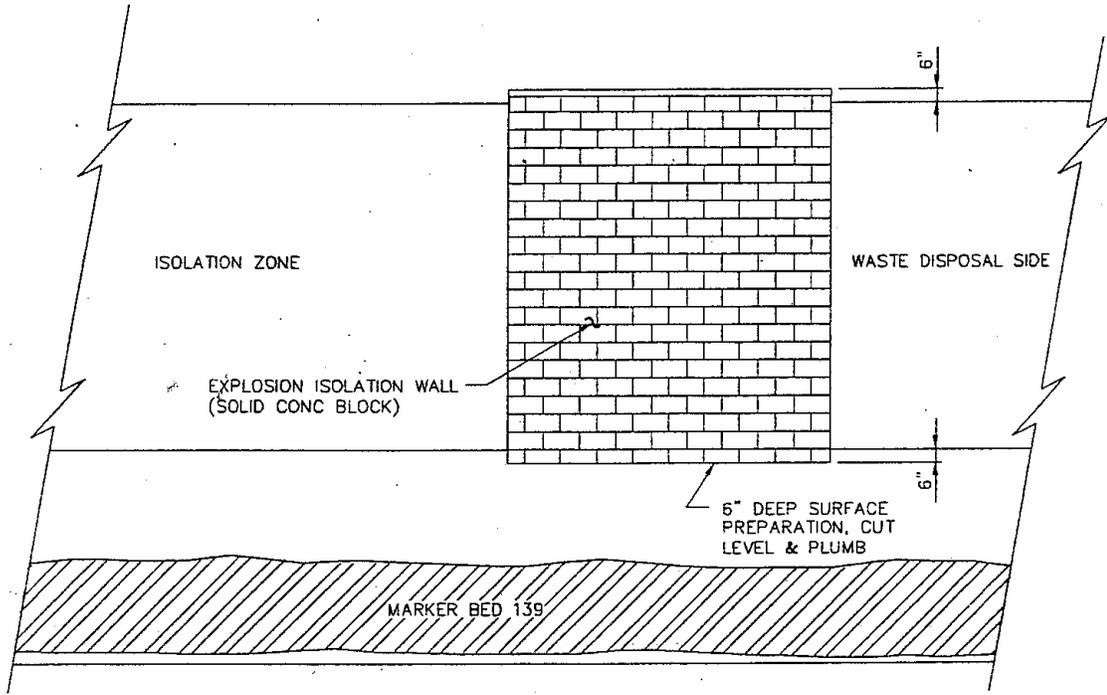
Figure BARRIERS-3. Explosion-Isolation Wall (not to scale)

- The concrete masonry units shall be solid (no cavities or cores), load-bearing, high-strength individual units, having a minimum compressive strength of 5500 psi (37.92 MPa) (average of three units) or 5000 psi (34.47 MPa) for individual unit. (Compressive strength increased from 3500 psi (average of three units) and 3000 psi for individual units.)

- The compressive strength of masonry in each masonry unit shall exceed 5000 psi. (The HWFP specifications do not include this test, which must be performed for each 2000 ft^3 (56.63 m^3) of masonry structure.)

The result of these changes is that materials meeting the specifications of the revised design are consistent with the specification outlined in CCA Appendix PCS. The explosion-isolation wall in Panel 1 was constructed soon after waste emplacement was completed.

BARRIERS-3.2.1.3.3   Interface Grouting

After construction of the main concrete barrier, the interface between the main concrete barrier and the salt will be grouted through a series of grout-supply and air-return lines that will terminate in grout distribution collection boxes. The openings in these boxes will be protected during concrete placement (Figure BARRIERS-4). The grout boxes will be mounted near the top of the barrier. The grout will be injected through one distribution system, with air and return grout flowing through a second distribution system.

1   BARRIERS-3.2.1.4   Panel-Closure System Construction

2   The design uses common construction practices according to existing standards. The proposed
3   construction sequence follows completion of the waste-emplacement activities in each panel: (1)
4   perform subsurface exploration to determine the optimum location for the panel closure system,
5   (2) prepare surfaces for the explosion-isolation walls, (3) install these walls, (4) excavate for the
6   enlarged concrete barrier, (5) install concrete formwork, (6) emplace concrete for the first cell,
7   (7) grout the completed cell, and (8) install subsequent formwork, concrete, and grout until
8   completion of the enlarged concrete barrier.

9   The explosion-isolation walls will be located at some distance from the main concrete barrier.
10   The host rock will be excavated 6 in (15 cm) around the entire perimeter prior to installing the
11   explosion-isolation wall. The surface preparation will produce a level surface for placing the
12   first layer of concrete blocks. Excavation may be performed by either mechanical or manual
13   means.

14   Excavation for the enlarged concrete barrier will be performed using mechanical means, such as
15   a cutting head on a suitable boom. The existing roadheader at the main barrier location in each
16   drift is capable of excavating the back and the portions of the ribs above the floor level. Some
17   manual excavation may be required in this situation as well. If mechanical means are not
18   available, drilling boreholes and an expansive agent can be used to fragment the rock (Fernandez
19   et al. 1989). Excavation will follow the lines and grades established for the design. The
20   tolerances for the enlarged concrete-barrier excavation are +6 to 0 inches (+15 to 0 cm). In
21   addition, loose or spalling rock from the excavation surface will be removed to provide an
22   appropriate surface abutting the enlarged concrete barrier. The excavations will be performed
23   according to approved ground control plans.

24   Following completion of the roof excavation for the enlarged barrier, the floor will be excavated.
25   If mechanical means are not available, drilling boreholes and using an expansive agent to
26   fragment the rock (Fernandez et al. 1989) is a method that can be used. Expansive agents would
27   load the rock salt and anhydrite, producing localized tensile fracturing in a controlled manner to
28   produce a sound surface.

29   A batch plant at the surface or underground will be utilized for batching, mixing, and delivering
30   the concrete to the underground in sufficient quantity to complete placement of the concrete
31   within one form cell.

1
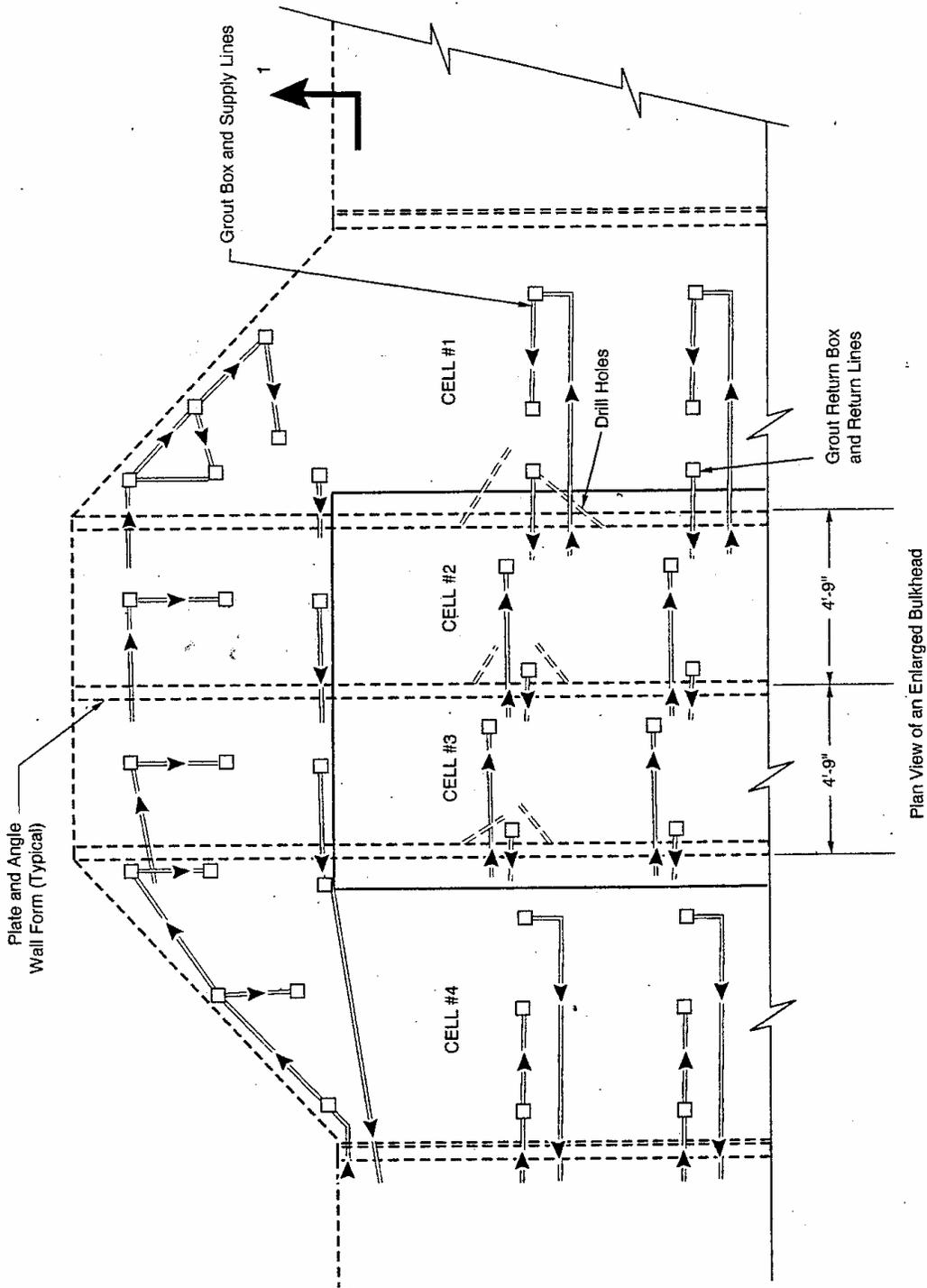
Figure BARRIERS-4. Grouting Details

1   Pumping equipment suitable for placing the concrete into the forms will be provided at the main
2   concrete barrier location. After transporting, and prior to pumping, the concrete will be remixed
3   to compensate for segregation of aggregate during transport. Batch concrete will be checked at
4   the surface at the time of mixing and again at the point of transfer to the pump for slump and
5   temperature. Admixtures may be added at the remix stage in accordance with the batch design.

6   BARRIERS-3.2.1.5   <u>Conclusion</u>

7   A design basis, including the operational requirements, structural and material requirements, and
8   construction requirements, was developed that addresses the governing regulations for the panel
9   closure system. The panel closure system design incorporates mitigative measures to address the
10   treatment in the rock around the openings after fracture and therefore counter the potential
11   migration of VOCs. Several alternatives were evaluated for the treatment of fractures. These
12   included excavation and emplacement of a fully enlarged barrier with removal of the DRZ,
13   excavation of the roof and emplacement of a partially enlarged barrier, and emplacement of a
14   standard barrier with formation grouting. In its final ruling on the CCA, the EPA required, in
15   condition 1, that the Option D design be implemented. This design requires the excavation and
16   emplacement of a fully enlarged barrier. Until resolution is reached on the DOE's proposed
17   design change, the design remains as required by EPA.

18   To investigate several key design issues and to implement the design, design evaluations were
19   performed. These design evaluations can be divided into evaluations satisfying the operational
20   requirements of the system and evaluations satisfying the structural and materials requirements
21   of the system. The conclusions reached from the evaluations addressing the operational
22   requirements are as follows:

23   •   Based on an air-flow model used to predict the mass flow rate of carbon tetrachloride
24   through the panel-closure system for the alternatives, the air-flow analysis suggests that
25   the fully enlarged barrier is protective for restricting potential VOCs during the
26   operational period of 35 years.

27   •   Interface grouting would be performed at the upper boundary of the concrete barrier.

28   •   The results of the transverse plane-strain models show that high stresses could form in
29   nearby brittle marker beds following excavation, but that after installation of the panel
30   closure system, an increase in barrier-confining stress and a reduction in shear stress
31   would result. The concrete barrier would provide substantial uniform confining stresses
32   as the barrier is subjected to secondary salt creep.

33   •   The removal of the fractured salt prior to installation of the main concrete barrier would
34   reduce the potential for flexure.

35   The conclusions reached from the design evaluations addressing the structural and material
36   requirements of the panel closure system are as follows:

37   •   Existing information on the heat of hydration of the concrete supports placing concrete
38   with a low cement content to reduce the temperature rise associated with hydration.

1   Plasticizers might be used to achieve the required slump at the required strength. A
2   thermal analysis, coupled with a salt creep analysis, suggests installation of the enlarged
3   barrier at or below ambient temperatures to adequately control hydration temperatures.

4   • The trace amounts of brine from the salt at the repository horizon will not degrade the
5   main concrete barrier for at least 35 years.

6   • In 20 years, the open passage above the waste stack in the rooms would be reduced in
7   size. Furthermore, rooms with bulkheads at each end would be isolated in the panel. It is
8   unlikely that a long passage with an open geometry would exist; therefore, the dynamic
9   analysis considered a deflagration with a peak explosive pressure of 240 psi (1.7 MPa).

10   • The heat-transfer analysis shows that elevated temperatures would occur within the salt
11   and the explosion-isolation wall; however, the elevated temperatures will be isolated by
12   the panel closure system. Temperature gradients will not significantly affect the stability
13   of the wall.

14   • The fractures in the roof and floor could be affected by expanding gas products reaching
15   pressures on the order of 240 psi (1.7 MPa). Because the peak internal pressure from the
16   deflagration is only one fifth of the pressure, fractures could not propagate beyond the
17   barrier.

18 ***BARRIERS-3.2.2   Shaft Seals***

19 There have been no changes to the shaft seals since the CCA. A description of the shaft seals,
20 initially provided in CCA Appendix SEAL, is discussed in Sections 3.2.2.1 through 3.2.2.4 of
21 this appendix. The representation of the shaft seals in PA has been simplified; see Appendix PA,
22 Section PA-4.2.7 for details.

23 BARRIERS-3.2.2.1   <u>Overview</u>

24 The WIPP underground facilities are accessed by four shafts commonly referred to as the waste,
25 air intake, exhaust, and salt handling shafts. These shafts were constructed between 1981 and
26 1988. Each of the four shafts from the surface to the underground repository must be sealed to
27 limit hazardous material release to the accessible environment and to limit groundwater flow into
28 the repository. Although the seals will be permanent, the regulatory period applicable to the
29 repository system analyses is 10,000 years.

30 BARRIERS-3.2.2.2   <u>Seal Components</u>

31 The shaft sealing system comprises 13 elements that completely fill the shaft with engineered
32 materials possessing high density and low permeability (Figure BARRIERS-5). Salado
33 components provide the primary regulatory barrier by limiting fluid transport along the shaft
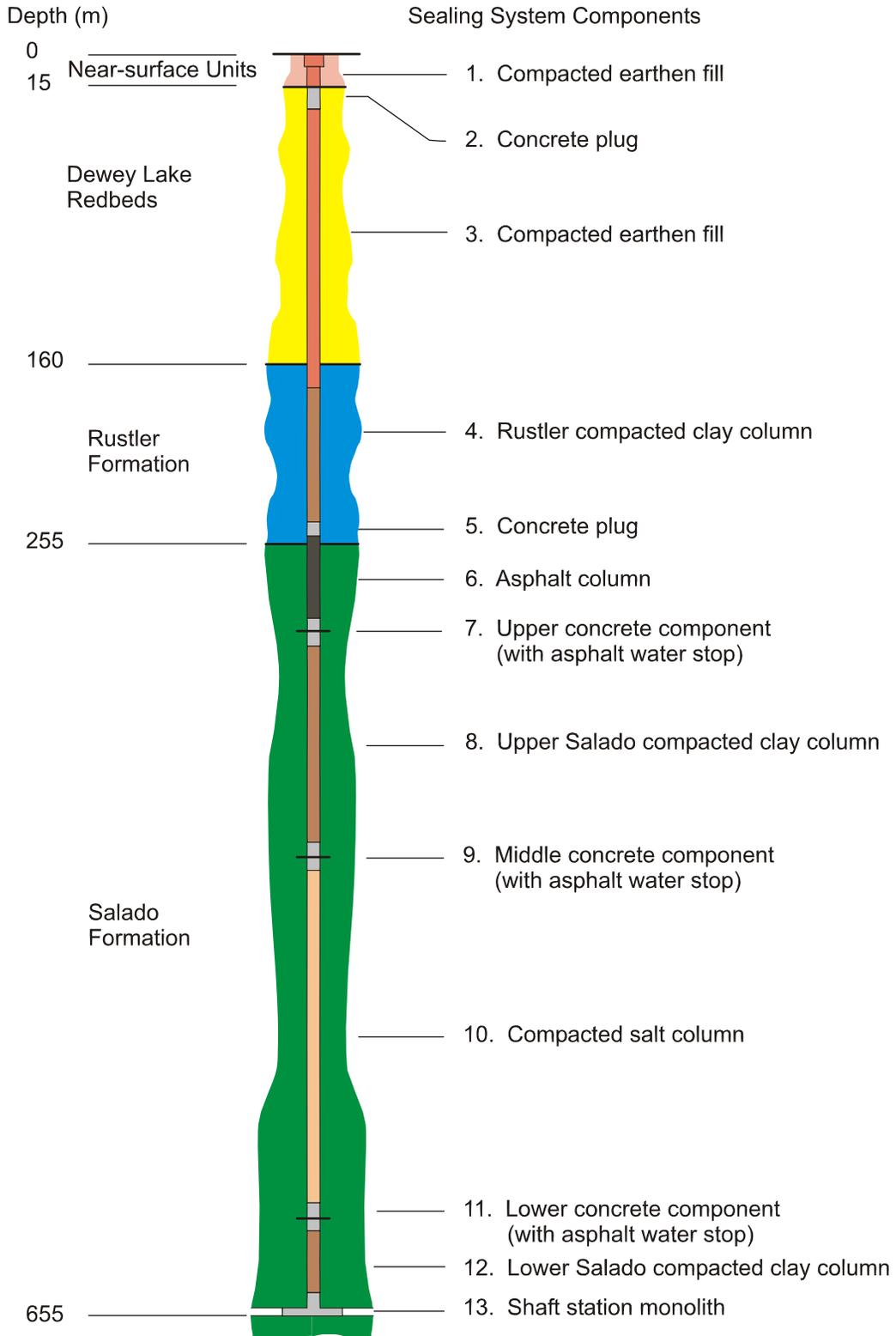
Figure BARRIERS-5. Shaft Sealing System Components

1   during and beyond the 10,000-year regulatory period. Components within the Rustler Formation
2   limit commingling between brine-bearing members, as required by state regulations.
3   Components from the Rustler Formation to the surface fill the shaft with common materials of
4   high density, consistent with good engineering practice. A synopsis of each component is given
5   below.

6   BARRIERS-3.2.2.2.1   Shaft Station Monolith

7   At the bottom of each shaft a salt-saturated concrete monolith supports the local roof. A salt-
8   saturated concrete, called SMC, is specific and is placed using a conventional slickline
9   construction procedure where the concrete is batched at the surface.

10 SMC has been tailored to match site conditions. The salt-handling shaft and the waste-handling
11 shaft have sumps which will also be filled with salt-saturated concrete as part of the monolith.
12 The monoliths function to support the shaft wall and adjacent drift roof, thus preventing damage
13 to the seal system as the access drift closes from natural processes.

14 BARRIERS-3.2.2.2.2   Clay Columns

15 A sodium bentonite is used for three compacted clay components in the Salado and Rustler
16 Formations. Although alternative construction specifications are viable, labor-intensive
17 placement of compressed blocks is specified because of proven performance. Clay columns
18 effectively limit brine movement from the time they are placed to beyond the 10,000-year
19 regulatory period. The upper clay column ranges in length from 102 to 107 m (335 to 351 ft),
20 and the lower clay column ranges in length from 29 to 33 m (94 to 107 ft) in the four shafts. The
21 locations for the upper and lower clay columns were selected based on the need to limit fluid
22 migration into the compacting salt column. The lower clay column stiffness is sufficient to
23 promote healing of fractures in the surrounding rock salt near the bottom of the shafts, thus
24 removing the proximal DRZ as a potential pathway (CCA Appendix SEAL, Appendix D,
25 Section 5.2.1). The Rustler clay column limits brine communication between the Magenta and
26 Culebra Members of the Rustler Formation.

27 A commercial well-sealing-grade sodium bentonite will be used to construct the Rustler
28 compacted clay column, which will effectively limit fluid movement from the time of placement
29 and provide an effective barrier to fluid migration throughout the 10,000-year regulatory period
30 and thereafter. Design length of the Rustler clay column is about 71 m (234 to 235 ft) in the four
31 shafts.

32 BARRIERS-3.2.2.2.3   Concrete-Asphalt Waterstop Components

33 The upper, middle, and lower concrete-asphalt waterstops are identical and are composed of
34 three elements: an upper concrete plug, a central asphalt waterstop, and a lower concrete plug.
35 The concrete specified is SMC. In all cases, the component's overall design length is 15 m
36 (50 ft).

37 The upper and lower concrete plugs of the concrete-asphalt waterstop are identical. They fill the
38 shaft cross-section and have design length of 7 m (23 ft). The plugs are keyed into the shaft wall
39 to provide positive support for the plug and overlying sealing materials. The interface between

1   the concrete plugs and the surrounding formation will be pressure grouted. The upper plug in
2   each component will support dynamic compaction of the overlying sealing material if
3   compaction is specified. Dynamic compaction of the salt column is discussed in CCA Appendix
4   SEAL (Section 6).

5   The asphalt waterstop is located between the upper and lower concrete plugs. In all cases, a kerf
6   extending one shaft radius beyond the shaft wall is cut in the surrounding salt to contain the
7   waterstop. The kerf is 0.3 m (1 ft) high at its edge and 0.6 m (2 ft) high at the shaft wall. The
8   kerf, which cuts through the existing shaft DRZ, will result in the formation of a new DRZ along
9   its perimeter. This new DRZ will heal shortly after construction of the waterstop, and thereafter
10 the waterstop will provide a very low permeability barrier to fluid migration through the DRZ.
11 The formation and healing of the DRZ around the waterstop is discussed in CCA Appendix
12 SEAL (Section 7.6.1). The asphalt fill for the waterstop extends two feet above the top of the
13 kerf to assure complete filling of the kerf. The construction procedure used assures that
14 shrinkage of the asphalt from cooling will not result in the creation of voids within the kerf and
15 will minimize the size of any void below the upper plug.

16 Concrete-asphalt waterstops are placed at the top of the upper clay column, the top of the
17 compacted salt column, and the top of the lower clay column. The concrete-asphalt waterstops
18 provide independent seals of the shaft cross-section and the DRZ. The SMC plugs (and grout)
19 will fill irregularities in the shaft wall, bond to the shaft wall, and seal the interface. Salt creep
20 against the rigid concrete components will place a compressive load on the salt and promote
21 early healing of the salt DRZ surrounding the SMC plugs. The asphalt waterstop will seal the
22 shaft cross-section and the DRZ.

23 The position of the concrete components was first determined by the location of the salt and clay
24 columns. The components were then moved upward or downward from their initial design
25 location to assure the components were located in regions where halite was predominant. This
26 positioning, coupled with variations in stratigraphy, is responsible for the variations in the
27 lengths of the salt and clay columns.

28 BARRIERS-3.2.2.2.4   Compacted Salt Column

29 Each shaft seal includes a column of compacted WIPP salt with 1.5 percent weight water added
30 to the natural material. The compacted salt column will be constructed of crushed salt taken
31 from the Salado. The length of the salt column varies from 170 to 172 m (556 to 567 ft) in the
32 four shafts. The compacted salt column is sized to allow the column and concrete-asphalt
33 waterstops at either end to be placed between the Vaca Triste Unit and MB 136. The salt will be
34 placed and compacted to a density approaching 90 percent of the average density of intact Salado
35 salt. The effects of creep closure will cause this density to increase with time, further reducing
36 permeability. The salt column will offer limited resistance to fluid migration immediately after
37 emplacement, but it will become less permeable as creep closure further compacts the salt. Salt
38 creep increases rapidly with depth; therefore, at any time, creep closure of the shaft will be
39 greater at greater depth. The location and initial compaction density of the compacted salt
40 column were chosen to assure consolidation of the compacted slat column in the 100 years
41 following repository closure. The state of salt consolidation, results of analyses predicting the
42 creep closure of the shaft, consolidation and healing of the compacted salt, and healing of the

1   DRZ surrounding the compacted salt columns can be found in CCA Appendix SEAL (Sections
2   7.5 and 8.4). The location of the compacted salt column near the bottom of the shaft assures the
3   fastest achievable consolidation of the compacted salt column after closure of the repository.
4   Analyses indicate that the salt column becomes an effective long-term barrier in under 100 years.

5   BARRIERS-3.2.2.2.5   Asphalt Column

6   An asphalt-aggregate mixture is specified for the asphalt column. This column is 42 to 44 m
7   (138 to 143 ft) in length in the four shafts. The asphalt column is located above the upper
8   concrete-asphalt waterstop; it extends approximately 5 m (16 ft) above the Rustler/Salado
9   interface. A 6-m (20-ft) long concrete plug (part of the Rustler seals) is located just above the
10   asphalt column.

11   The existing shaft linings will be removed from a point well above the top of the asphalt column
12   to the top of the shaft keys. The concrete shaft keys will be removed to a point just below the
13   lowest chemical seal ring in each key. The asphalt column is located at the top of the Salado and
14   provides an essentially impermeable seal for the shaft cross section and along the shaft wall
15   interface. The length of the asphalt column will decrease slightly as the column cools. The
16   procedure for placing the flowable asphalt-aggregate mixture is described in CCA Appendix
17   SEAL (Section 6).

18   BARRIERS-3.2.2.2.6   Concrete Plugs

19   The Rustler concrete plug is constructed of SMC. The plug is 6 m (20 ft) long and will fill the
20   shaft cross-section. The plug is placed directly on top of the asphalt column of the Salado seals.
21   The plug will be keyed into the surrounding rock and grouted. The plug permits work to begin
22   on the overlying clay column before the asphalt has completely cooled. The option of
23   constructing the overlying clay columns using dynamic compaction (present planning calls for
24   construction using compressed clay blocks) is also maintained by keying the plug into the
25   surrounding rock. Current plans call for an SMC near-surface concrete plug (Component 2,
26   Figure BARRIERS-5). However, freshwater concrete may be used if found to be desirable at a
27   future time. The plug extends 12 m (40 ft) downward from the top of the Dewey Lake Redbeds.
28   It is placed inside the existing shaft lining, and the interface is grouted.

29   BARRIERS-3.2.2.2.7   Earthen Fill

30   The upper shaft is filled with locally available earthen fill. The near-surface upper compacted
31   earthen fill (Component 1 in Figure BARRIERS-5) will be compacted to a density near that of
32   the surrounding material to inhibit the migration of surface waters into the shaft cross-section.
33   The length of this column varies from 17 to 28 m (56 to 92 ft) in the four shafts. In all cases, this
34   portion of the WIPP sealing system may be modified as required to facilitate decommissioning
35   of the WIPP surface facilities. The near-surface lower compacted earthen fill (Component 3 in
36   Figure BARRIERS-5) will be constructed using locally available fill, which will be placed using
37   dynamic compaction (the same method used to construct the salt column). The fill will be
38   compacted to a density equal to or greater than the surrounding materials to inhibit the migration
39   of surface waters into the shaft cross-section. The length of this column varies from 136 to 148
40   m (447 to 486 ft) in the four shafts.

1 BARRIERS-3.2.2.3   <u>Material</u>

2 The four shafts will be entirely filled with dense materials possessing low permeability and other
3 desirable engineering and economic attributes. Seal materials include concrete, clay, asphalt,
4 and compacted salt. Other construction and fill materials include cementitious grout and earthen
5 fill. Concrete, clay, and asphalt are common construction materials used extensively in sealing
6 applications. Their descriptions, drawn from literature and site-specific references, are given in
7 CCA Appendix SEAL (Appendix A). Compaction and natural reconsolidation of crushed salt
8 are uniquely applied here. Therefore, crushed salt specification includes discussion of
9 constitutive behavior and sealing performance, specific to WIPP applications. Cementitious
10 grout is also specified in some detail.

11 Seal system components are materials possessing high durability and compatibility with the host
12 rock. The system contains functional redundancy and uses differing materials to reduce
13 uncertainty in performance. All materials used in the shaft seal system are expected to maintain
14 their integrity for very long periods. Some sealing components reduce fluid flow soon after
15 placement, while other components are designed to function well beyond the regulatory period.

16 A major environmental advantage of the WIPP locale is an overall lack of groundwater to seal
17 against. Even though very little regional water is present in the geologic setting, the seal system
18 reflects great concern for groundwater's potential influence on the shaft seal system. If the
19 hydrologic system sustained considerable fluid flow, brine geochemistry could impact
20 engineered materials. Brine would not chemically change the compacted salt column, but
21 mechanical effects of pore pressure are of concern to reconsolidation. The geochemical setting
22 will have little influence on concrete, asphalt, and clay shaft seal materials. Each material is
23 durable because the potential for degradation or alteration is very low.

24 Materials used to form the shaft seals are the same as those identified in the scientific and
25 engineering literature as appropriate for sealing deep geologic repositories for radioactive wastes.
26 Durability or longevity of seal components is a primary concern for any long-term isolation
27 system. Issues of possible degradation have been studied throughout the international
28 community and within waste isolation programs in the USA. Specific degradation studies are
29 not detailed in this document because longevity is one of the over-riding attributes of the
30 materials selected and degradation is not perceived to be likely. However, it is acknowledged
31 here that microbial degradation, seal material interaction, mineral transformation, such as
32 silicification of bentonite, and effects of a thermal pulse from asphalt or hydrating concrete are
33 areas of continuing investigation.

34 Among longevity concerns, degradation of concrete is the most recognized. At this stage of the
35 design, it is established that only small volumes of brine ever reach the concrete elements (CCA
36 Appendix SEAL, Appendix C, Section C4). Further analysis concerned with borehole plugging
37 using cementitious materials shows that at least 100 pore volumes of brine in an open system
38 would be needed to begin degradation processes. In a closed system, such as the hydrologic
39 setting in the WIPP shafts, phase transformations create a degradation product of increased
40 volume. Net volume increase owing to phase transformation in the absence of mass transport
41 would decrease rather than increase permeability of concrete seal elements.

1 Asphalt has existed for thousands of years as natural seeps. Longevity studies specific to DOE's
2 Hanford site have utilized asphalt artifacts buried in ancient ceremonies to assess long-term
3 stability (Wing and Gee 1994). Asphalt used as a seal component deep in the shaft will inhabit a
4 benign environment, devoid of ultraviolet light or an oxidizing atmosphere. Additional
5 assurance against possible microbial degradation in asphalt elements is provided with addition of
6 characteristics well beyond the regulatory period.

7 Natural bentonite is a stable material that generally will not change significantly over a period of
8 10,000 years. Bentonitic clays have been widely used in field and laboratory experiments
9 concerned with radioactive waste disposal. As noted by Gray (1993), three internal mechanisms,
10 illitization, silicification, and charge change, could affect sealing properties of bentonite.
11 Illitization and silicification are thermally driven processes and, following discussion by Gray
12 (1993), are not possible in the environment or time frame of concern at the WIPP. The naturally
13 occurring Wyoming bentonite, which is the specified material for the WIPP shaft seal, is well
14 over a million years old. It is, therefore, highly unlikely that the metamorphism of bentonite
15 enters as a design concern.

16 BARRIERS-3.2.2.4   Conclusion

17 The principal conclusion is that an effective, implementable shaft seal system has been designed
18 for the WIPP. Design guidance is addressed by limiting any transport of fluids within the shaft,
19 thereby limiting transport of hazardous material to regulatory boundaries. The application or
20 adaptation of existing technologies for placement of seal components combined with the use of
21 available, common materials provide confidence that the design can be constructed. The
22 structural setting for seal elements is compressive, with shear stresses well below the strength of
23 seal materials. Because of the favorable hydrologic regime coupled with the low intrinsic
24 permeability of seal materials, long-term stability of the shaft seal system is expected.
25 Credibility of these conclusions is bolstered by the basic design approach of using multiple
26 components to perform each sealing function and by using extensive lengths within the shafts to
27 effect a sealing system. The shaft seal system adequately meets design requirements and can be
28 constructed.

29 ***BARRIERS-3.2.3   Borehole Plugs***

30 BARRIERS-3.2.3.1   Overview

31 Exploration drilling has been in progress in the vicinity of the WIPP since 1928 (nine township
32 area). This drilling is done primarily for oil, gas, and potash exploration, although several water
33 wells have been drilled. The drilling and abandonment practices for oil and gas wells or potash
34 exploration holes are regulated by either the Bureau of Land Management (BLM) for federal
35 land or the State of New Mexico for State and private land. The WIPP site has no control over
36 the plugging and abandonment (P&A) of oil and gas wells in the vicinity of the site. See Section
37 3.2.3.3 of this appendix for a description of the regulations that apply to these oil and gas wells.

38 The New Mexico State Engineers Office has regulatory authority over the P&A of groundwater
39 production and monitoring wells in the state. The State of New Mexico has several groundwater
40 basins, with each basin having its own district office providing oversight of groundwater issues.

1　The WIPP area is under the jurisdiction of the Roswell, New Mexico branch of the State
2　Engineers Office. The Roswell office will be the principal regulatory body to approve the WIPP
3　plans for well P&A. In all cases, the permit process will be carried out through the appropriate
4　regulatory agency. This will be the State of New Mexico, State Engineers Office for P&A of all
5　water wells (DOE 1999).

6　Sealing and plugging of boreholes and monitoring wells associated with underground waste
7　repositories has been an important issue for many years. To develop the most effective methods
8　to limit the potential for fluids to migrate between formations within a sealed borehole, the DOE
9　has conducted extensive research on plugging and sealing materials and emplacement
10　technologies. In some cases, previous P&A research and regulatory compliance documents have
11　recommended or committed to plugging test wells and boreholes following specific guidelines
12　and techniques. In the CCA, the DOE committed to plugging WIPP's shallow boreholes within
13　the controlled area in accordance with applicable state or federal regulations. The WIPP's deep
14　boreholes within the controlled area will be plugged in accordance with OCD, Order R-111P
15　(NM 1988). The WIPP Final Environmental Impact Statement (DOE 1980) states that all
16　boreholes will be plugged with materials that are physically and chemically compatible with the
17　surrounding rock, resistant to groundwater attack, and will securely bond to surrounding
18　geologic materials.

19　BARRIERS-3.2.3.2　Monitoring Wells

20　As of the date of this compliance application, the DOE has 92 operational monitoring wells
21　within the vicinity of WIPP. Of these, 17 have been drilled and put into use since submittal of the
22　CCA (see Appendix DATA, Attachment G for a description of the groundwater monitoring wells
23　applicable to this compliance application). Also since the CCA, 10 monitoring wells have been
24　plugged to the surface with cement. Two new shallow wells (54 ft. and 19 ft.) were drilled and
25　plugged with drill cuttings and bentonite gel (Appendix DATA, Attachment G).

26　Existing boreholes within the controlled area are identified in Figure BARRIERS-6. Of these
27　boreholes, four exceed the depth of the repository and the rest are shallow boreholes that do not
28　reach the repository horizon.

29　When no longer needed, the four deep wells, DOE 1, ERDA 9, WIPP 12, and WIPP 13 will be
30　plugged according to the State of New Mexico, Oil and Conservation Division, Order R-111-P.
31　See Figures BARRIERS-6 and BARRIERS-7.

32　The key provisions of Order No. R-111-P are as follows:

33　　• 　A salt protection string of casing must be installed at least 100 feet (30 meters) below and
34　　　　not more than 600 ft (183 m) below the base of the salt section. Cementing requirements
35　　　　for both shallow wells (above 5,000 ft [1,524 m]) and deep wells (below 5,000 ft [1,524
36　　　　m]) above or below the Delaware Mountain Group are specified.

37　　• 　All oil and gas wells drilled within the potash area must provide a solid cement plug
38　　　　through the salt section and any water bearing horizon and prevent liquids or gases from
39　　　　entering the hole above or below the salt section.

1
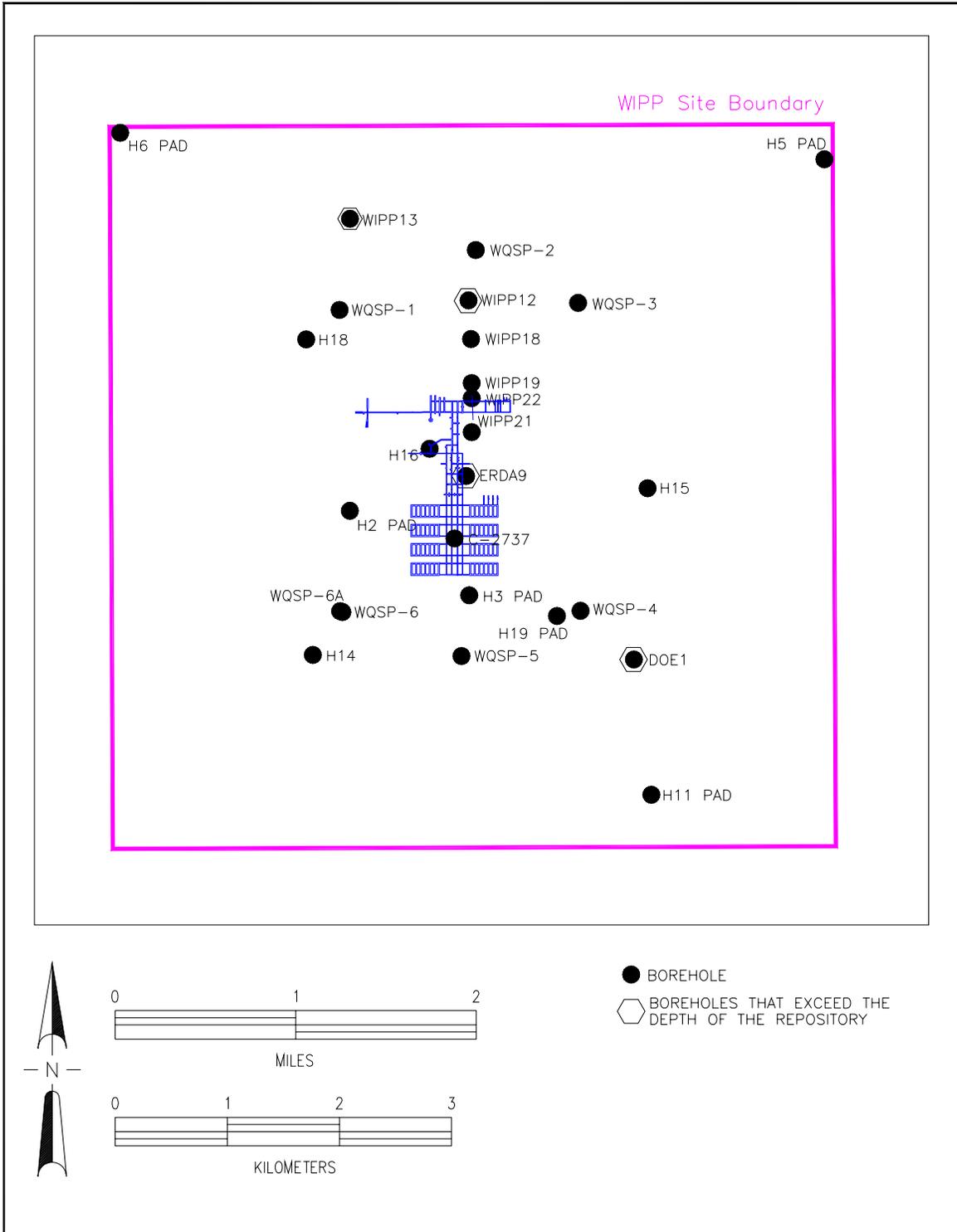
Figure BARRIERS-6. Approximate Locations of Unplugged Boreholes
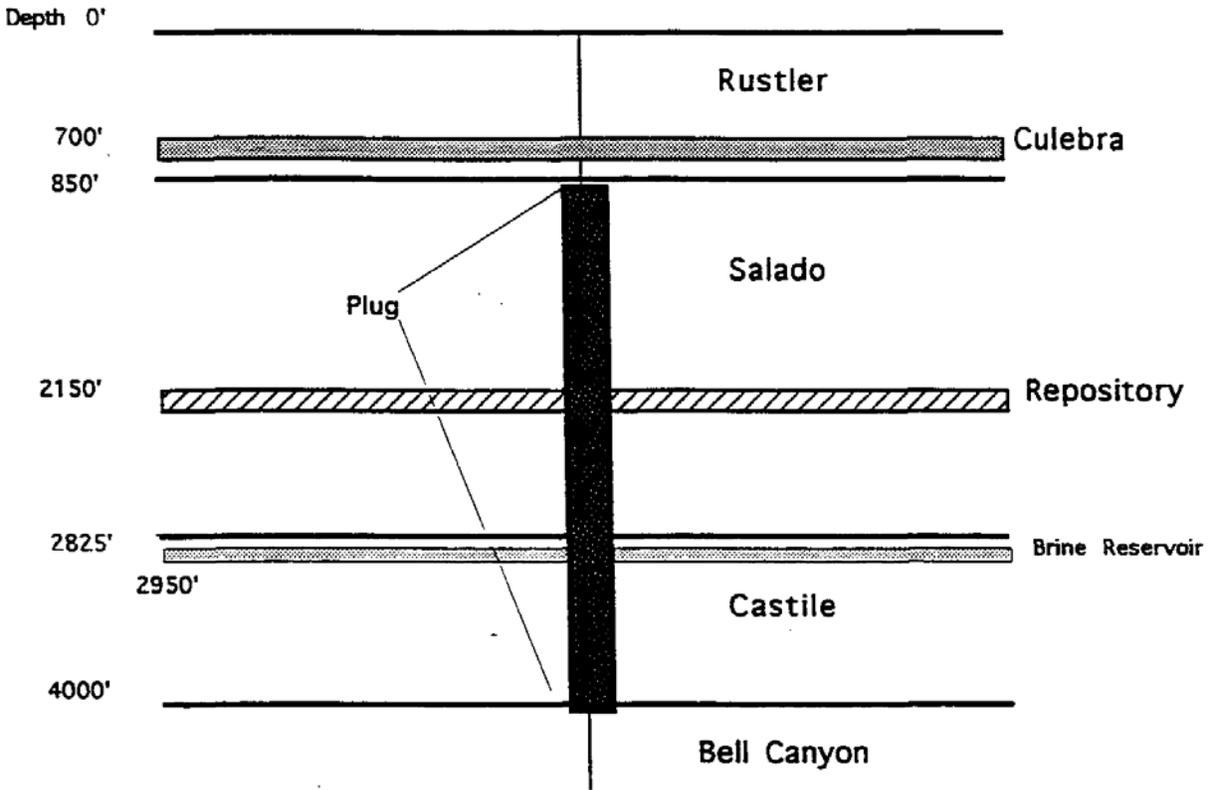
Figure BARRIERS-7. Schematic Diagram for a Continuous Plug

- The fluid used to mix the (plugging) cement must be saturated with salts common to the salt section penetrated but not more than three percent of calcium chloride by weight of cement wherever possible.

As mentioned above, WIPP has been plugging monitoring wells with cement plugs from the bottom to the top of the borehole.

The boreholes not being used for monitoring will be plugged at decommissioning. These boreholes will be plugged to limit the volume of water that could be introduced to the repository from the overlying water-bearing zones and the volume of contaminated brine that could be released from the repository to the accessible environment.

BARRIERS-3.2.3.3   Well Plugging and Abandonment Practices

A description of the plugging and abandonment practices in the area around the WIPP, initially provided in CCA Appendix DEL, is discussed in Sections 3.2.3.3.5 through 3.2.3.4 of this appendix. The representation of borehole plugs in PA is presented in Chapter 6.0, Section 6.4.7.2.

1   BARRIERS-3.2.3.3.1   BLM Oil and Gas Plugging and Abandonment

2   The BLM regulations on oil and gas plugging and abandonment in 43 CFR § 3162.3-4 and Oil
3   and Gas Order No. 2 are discussed in detail in CCA Appendix DEL, Section DEL.4.1.2.2. This
4   section serves as a summary of that discussion.

5   BARRIERS-3.2.3.3.1.1   Oil and Gas Well Plugging Sequence

6   The first step in plugging and abandoning a well is the submission of the Sundry Notice (Form
7   3160-5, Attachment 2) that informs the BLM of the operator's intent to abandon the well. This
8   form must include a plan by the operator detailing how the well will be plugged. BLM
9   inspectors will review and approve the plan as presented or make modifications that the operator
10   must follow.

11   The operator must provide a 24-hour notice to the BLM before beginning abandonment
12   operations in order to allow BLM personnel an opportunity to witness the operation. BLM does
13   not consider the plugging and abandonment procedure completed until a surface cap has been
14   welded on the opening to the casing, a 4-in (10 cm)-diameter pipe, 10 ft (3 m) long, has been
15   embedded in cement and extended 4 feet (1 m) above ground level, and the cellars have been
16   filled to the surface. When all phases of the abandonment are complete and have been inspected,
17   the well plugging bond may be released (see CCA Appendix DEL, Section DEL.6.1.5).

18   Plugging operations are typically carried out using a pulling unit (a truck with a large mounted
19   derrick). The pulling unit sets up over the wellbore and is used to complete the plug and
20   abandonment operation. The first step in the plugging process is to set the required cast iron
21   bridge plug at the depth shown in the plugging plan approved by the BLM. The point of
22   placement for the bridge plug is just above the uppermost production perforations in the casing.
23   Once the bridge plug is in place, the pulling unit operator will tag the bridge plug (touch the top
24   of the plug with the tubing) to make certain that it is set at the correct depth as specified on the
25   plugging plan contained in Form 3160-5 (Attachment 2).

26   When the proper depth is confirmed, a minimum of 25 ft (8 m) of cement is placed on top of the
27   bridge plug. The operator will then fill the borehole with at least nine-lb mud or brine water,
28   filling the borehole to the site of the next plug location. The viscosity of the mud allows the
29   operator to then pump a type C or H cement through the tubing to its correct depth on top of the
30   mud. The mud column will support the weight of the cement until it sets up. The operator, if
31   required by the BLM, will again tag the top of the cement to verify both the position and length
32   of the plug.

33   While the NMOCD has inspection personnel on site in every instance to verify this process, the
34   BLM elects to witness only selected plugging operations. The process of setting plugs will
35   continue in the same manner until each of the plugs identified on the plugging plan has been
36   properly placed. At this point, plugging operations are complete. The only remaining
37   requirement to complete the plug and abandonment operation is that of returning the drill pad to
38   a near-original state. This process may be completed in only a few days or possibly up to several
39   months after plugging has been completed.

1   BARRIERS-3.2.3.3.1.2 Plugging of Temporarily Abandoned Wells

2   Wells may be temporarily abandoned for up to five one-year periods with BLM approval (see
3   CCA Appendix DEL, Section DEL.6.1.2.3). A Sundry Notice must be submitted requesting
4   temporary abandonment (Form 3160-5, Attachment 2). The notice must include a description of
5   the abandonment procedure, a complete wellbore diagram, and the anticipated date the
6   operations will occur. As with plugging and abandonment, this plan must be reviewed and
7   approved by BLM inspectors. Once approved, a 48-hour notice must be given to BLM to allow
8   an opportunity for the plugging inspection. Operators must install a bridge plug or a cement plug
9   50 to 100 ft (15 to 30 m) above the perforations. If a cement plug is chosen, it must be tagged to
10   make certain it is at the proper depth. Bridge plugs are set using a wireline with the proper depth
11   being verified before the plug is set.

12   The integrity of the casing must be also be verified. If testing indicates problems with the
13   casing, repairs must be made before the well may be temporarily abandoned.

14   BARRIERS-3.2.3.3.1.3 Plugging in the Potash Resource Area

15   BLM requirements for plugging and abandonment in the potash areas are the same as in non-
16   potash areas. Although the BLM has not overseen the plugging of any oil or gas wells in the
17   potash area in a number of years, the requirements of the New Mexico Oil Conservation
18   Commission (NMOCC) Order R-111-P (see CCA Appendix DEL, Section DEL.6.2.4) will be
19   considered at the appropriate time (Personal Communication 1996a). According to the Secretary
20   of the Interior Order of October 28, 1986 (51 FR 39425) on oil, gas, and potash leasing, the BLM
21   will cooperate with the NMOCD in implementing state rules and regulations although the BLM
22   will make the final decision.

23   BARRIERS-3.2.3.3.1.4 Most Common Technical Violations for Oil and Gas Well Plugging

24   Large national oil companies and large independent companies normally comply strictly with the
25   oil and gas well plugging requirements. Large businesses, which have the necessary resources to
26   properly plug and abandon their wells, typically contract with other large businesses to perform
27   their plugging operations. It has been BLM's experience that these companies follow sound
28   business practices and wish to remain in good standing with the BLM. Smaller, independent
29   operators are more likely to lack resources to respond as quickly to the BLM and may not plug a
30   well with the same expertise that a larger established company might have. The BLM is aware
31   of situations that pose a potential for improper plugging. If the agency has a concern regarding a
32   contractor's methods, BLM personnel are present during the entire plugging operation (Personal
33   Communication 1996b).

34   Plugging bonds are required to ensure that wells are plugged and abandoned properly and within
35   a reasonable time frame (see CCA Appendix DEL, Sections DEL.6.1.5 and DEL.6.2.1). Both
36   NMOCD and BLM have experienced higher rates recently of what they refer to as "orphan
37   wells." These are wells that should be plugged and abandoned, but the owners of these wells
38   cannot be located. When this occurs, plugging of these wells becomes the responsibility of the
39   agency upon whose land they are located. Both agencies have orphan-well-plugging funds that
40   are funded partially through plugging bonds that have not been returned and money from their

1 operating budgets. These orphan wells are a matter of concern to both agencies, and they are
2 working to conserve financial resources for plugging.

3 BARRIERS-3.2.3.3.2   State of New Mexico Oil and Gas Plugging and Abandonment

4 The NMOCD regulations on well plugging and abandonment are discussed in CCA Appendix
5 DEL, Sections DEL.6.2.2 and DEL.6.2.3. They are similar in many respects to the BLM
6 requirements.

7 *BARRIERS-3.2.3.3.2.1   Plugging Outside the Potash Resource Area*

8 The major distinction between NMOCD and BLM practices is that NMOCD witnesses every
9 well plugging and abandonment operation on state and private land, whereas the BLM is only
10 able to witness approximately 50 percent of the plugging operations on federal leases. Both
11 agencies require sundry notices to be filed with an abandonment plan and both agencies review
12 and approve or modify those plans.

13 *BARRIERS-3.2.3.3.2.2   Plugging Within the Potash Resource Area (R-111-P)*

14 Operators must follow the same procedures within the potash enclave as they do in other areas,
15 with the exception that the NMOCD requires the operator to run a solid cement plug through the
16 entire salt section and water bearing zones in addition to installing a bridge plug above the
17 perforations. Installing a solid cement plug through the salt provides additional assurance that no
18 fluids or gases escape through the casing into potash mining areas or fresh water formations (see
19 CCA Appendix DEL, Section DEL.6.2.3 on NMOCC Order R-111-P).

20 *BARRIERS-3.2.3.3.2.3   Most Common Technical Violations for State of New Mexico Oil and*
21   *Gas Well Plugging*

22 Because NMOCD inspectors are able to witness 100 percent of the plugging and abandonment
23 operations, technical violations are very rare. NMOCD inspectors are present for each step in
24 the plugging operation. Operators are informed that plugging operations are not to begin before
25 NMOCD inspectors are on site. If NMOCD inspectors are not present when plugging operations
26 begin, the operator may be required to remove everything from the well and start over. The
27 NMOCD also requires plugging bonds to be secured by the operator before plugging and
28 abandonment are carried out (see CCA Appendix DEL, Section DEL.6.2.1). The bond is not
29 released until all requirements for plug and abandonment have been properly completed
30 (Personal Communication 1996c).

31 BARRIERS-3.2.3.3.3   Plugging of Oil and Gas Service Wells

32 Oil and gas operators are required to follow NMOCD Rule 705 on commencement,
33 discontinuance, and abandonment of injection operations when plugging an injection well. This
34 rule requires operators to file a Notice of Discontinuance when a decision has been made to
35 cease injection operations. The rule forbids temporary abandonment of service wells. Plugging
36 requirements are the same as when plugging oil and gas wells or dry holes.

1   BARRIERS-3.2.3.3.4   Plugging of Potash Coreholes

2   In June 1975, the land that is now the WIPP land withdrawal area became part of the Carlsbad
3   Underground Water Basin. This placed potash coreholes under the jurisdiction of the State
4   Engineer. A review of the records maintained by BLM on commercial potash coreholes
5   indicates that, since 1975, 155 coreholes have been drilled and plugged in the New Mexico
6   portion of the Delaware Basin. Of the 155 coreholes, 151 were plugged from bottom to top with
7   solid cement while four were plugged with a mixture of mud and cement. As indicated by this
8   review, the current plugging practice is to fill potash coreholes with a cement slurry from the
9   bottom of the hole to the surface.

10   BARRIERS-3.2.3.3.5   Plugging of Water Wells

11   The State Engineer has authority for all water wells. The State Engineer must be notified when a
12   well is to be plugged and then designates how it is to be plugged. The method typically used in
13   the Carlsbad Underground Water Basin is to remove all casing from the hole, clean the hole to
14   the bottom using a sand pump or a cable tool drilling rig with a bailer, and fill the hole with red
15   clay. The red clay is compacted as the hole is filled. Another method of filling the hole is to
16   circulate the hole full of cement. This method is more expensive and is not typically used.

17   BARRIERS-3.2.3.4   Conclusion

18   The WIPP is surrounded by land where oil and gas drilling is taking place. Plugging and
19   abandonment of these oil and gas wells is regulated by either the BLM or the State of New
20   Mexico, depending on the ownership of the land. Water wells also exist in the vicinity of WIPP
21   and are regulated by the State of New Mexico. WIPP has no control over the plugging and
22   abandonment of these wells.

23   WIPP has drilled monitoring wells to sample for constituents. These wells are regulated by the
24   State of Mexico and will be plugged and abandoned according to the regulations when they are
25   no longer needed for monitoring.

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