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***Title 40 CFR Part 191  
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***

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## *Appendix BARRIERS*

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**ACRONYMS AND ABBREVIATIONS**

1		
2	<b>AISC</b>	<i>American Institute of Steel Construction</i>
3	<b>AISinR</b>	<i>a synthetic brine representative of fluids sampled from the Culebra Member</i>
4		<i>of the Rustler Formation in the WIPP Air Intake Shaft</i>
5	<b>alumina</b>	<i>Al<sub>2</sub>O<sub>3</sub></i>
6	<b>anhydrite</b>	<i>CaSO<sub>4</sub></i>
7	<b>aq</b>	<i>aqueous</i>
8	<b>ASTM</b>	<i>American Society for Testing Materials</i>
9	<b>atm</b>	<i>atmosphere(s)</i>
10	<b>BLM</b>	<i>Bureau of Land Management</i>
11	<b>BRAGFLO</b>	<i>Brine and Gas Flow</i>
12	<b>brucite</b>	<i>Mg(OH)<sub>2</sub></i>
13	<b>°C</b>	<i>degrees Celsius</i>
14	<b>calcite</b>	<i>CaCO<sub>3</sub></i>
15	<b>CCA</b>	<i>(WIPP) Compliance Certification Application</i>
16	<b>CH</b>	<i>contact-handled (TRU waste)</i>
17	<b>CPR</b>	<i>cellulosic, plastic, and rubber (materials)</i>
18	<b>CRA</b>	<i>(WIPP) Compliance Recertification Application</i>
19	<b>DI</b>	<i>deionized (water)</i>
20	<b>DOE</b>	<i>(U.S.) Department of Energy</i>
21	<b>DRZ</b>	<i>Disturbed Rock Zone</i>
22	<b>EPA</b>	<i>(U.S.) Environmental Protection Agency</i>
23	<b>EQ3/6</b>	<i>a geochemical software package for speciation and solubility calculations</i>
24		<i>(EQ3NR) and reaction-path calculations (EQ6)</i>
25	<b>ERDA-6</b>	<i>Energy Research and Development Administration (WIPP Well) 6, a</i>
26		<i>synthetic brine representative of fluids in Castile-Formation brine reservoirs</i>
27	<b>f<sub>CO<sub>2</sub></sub></b>	<i>fugacity (similar to the partial pressure) of CO<sub>2</sub></i>
28	<b>FMT</b>	<i>Fracture-Matrix Transport, a geochemical speciation and solubility code</i>
29	<b>forsterite</b>	<i>Mg<sub>2</sub>SiO<sub>4</sub></i>
30	<b>ft</b>	<i>foot (feet)</i>
31	<b>g</b>	<i>gaseous or gram(s)</i>
32	<b>G Seep</b>	<i>a naturally occurring brine collected from G Drift in the WIPP</i>
33		<i>underground</i>
34	<b>gal</b>	<i>gallon(s)</i>
35	<b>GWB</b>	<i>Generic Weep Brine, a synthetic brine representative of intergranular</i>
36		<i>Salado-Formation brines</i>
37	<b>H-17</b>	<i>a synthetic brine representative of brine from the Culebra at the</i>
38		<i>WIPP H-17 Hydropad</i>
39	<b>halite</b>	<i>NaCl</i>
40	<b>hydromagnesite</b>	<i>Mg<sub>4</sub>(CO<sub>3</sub>)<sub>3</sub>(OH)<sub>2</sub>·3H<sub>2</sub>O or Mg<sub>5</sub>(CO<sub>3</sub>)<sub>4</sub>(OH)<sub>2</sub>·4H<sub>2</sub>O</i>
41	<b>in.</b>	<i>inch(es)</i>
42	<b>K<sub>d</sub></b>	<i>distribution coefficient</i>
43	<b>kg</b>	<i>kilogram(s)</i>
44	<b>km</b>	<i>kilometer(s)</i>
45	<b>L</b>	<i>liter(s)</i>

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

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 requirements to provide different types*  
9 *of barriers to isolate the waste from the accessible environment as required by Title 40 Code of*  
10 *Federal Regulations (CFR) § 191.14(d) (EPA 1993):*

11 *“Disposal systems shall use different types of barriers to isolate the wastes from the accessible*  
12 *environment. Both engineered and natural barriers shall be included.”*

13 *In addition, Title 40 Code of Federal Regulations (CFR) § 194.44 (EPA 1996) provides detail*  
14 *on the selection criteria for engineered barriers:*

15 *(a) Disposal systems shall incorporate engineered barrier(s) designed to prevent or substantially*  
16 *delay the movement of water or radionuclides toward the accessible environment.*

17 *(b) In selecting any engineered barrier(s) for the disposal system, the Department shall evaluate*  
18 *the benefit and detriment of engineered barrier alternatives, including but not limited to:*  
19 *Cementation, shredding, supercompaction, incineration, vitrification, improved waste canisters,*  
20 *grout and bentonite backfill, melting of metals, alternative configurations of waste placements*  
21 *in the disposal system, and alternative disposal system dimensions. The results of this evaluation*  
22 *shall be included in any compliance application and shall be used to justify the selection and*  
23 *rejection of each engineered barrier evaluated.*

24 *(c)(1) In conducting the evaluation of engineered barrier alternatives, the following shall be*  
25 *considered, to the extent practicable:*

26 *(i) The ability of the engineered barrier to prevent or substantially delay the movement*  
27 *of water or waste toward the accessible environment;*

28 *(ii) The impact on worker exposure to radiation both during and after incorporation of*  
29 *engineered barriers;*

30 *(iii) The increased ease or difficulty of removing the waste from the disposal system;*

31 *(iv) The increased or reduced risk of transporting the waste to the disposal system;*

32 *(v) The increased or reduced uncertainty in compliance assessment;*

33 *(vi) Public comments requesting specific engineered barriers;*

34 *(vii) The increased or reduced total system costs;*

35 *(viii) The impact, if any, on other waste disposal programs from the incorporation of*  
36 *engineered barriers (e.g., the extent to which the incorporation of engineered barriers*  
37 *affects the volume of waste);*

1            *(ix) The effects on mitigating the consequences of human intrusion.*

2            *(2) If, after consideration of one or more of the factors in paragraph (c)(1) of this section, the*  
3            *Department concludes that an engineered barrier considered within the scope of the evaluation*  
4            *should be rejected without evaluating the remaining factors in paragraph (c)(1) of this section,*  
5            *then any compliance application shall provide a justification for this rejection explaining why*  
6            *the evaluation of the remaining factors would not alter the conclusion.*

7            *(d) In considering the ability of engineered barriers to prevent or substantially delay*  
8            *the movement of water or radionuclides toward the accessible environment, the benefit*  
9            *and detriment of engineered barriers for existing waste already packaged, existing*  
10           *waste not yet packaged, existing waste in need of re-packaging, and to-be-generated*  
11           *waste shall be considered separately and described.*

12           *(e) The evaluation described in paragraphs (b), (c) and (d) of this section shall consider*  
13           *engineered barriers alone and in combination.*

14 ***BARRIERS-1.2 Background***

15 *For the CCA, the Department of Energy (DOE) performed an Engineered Alternatives*  
16 *Cost/Benefit Study (see CCA Appendix EBS) to examine the benefits and detriments*  
17 *associated with an array of engineered barrier alternatives. Based on the results of these*  
18 *studies, the DOE proposed four engineered barriers in the CCA: shaft seals, panel closures,*  
19 *magnesium oxide (MgO), and borehole plugs.*

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

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

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

28            *“The EPA finds that DOE complies with § 194.44. The EPA found that DOE conducted the*  
29            *requisite analysis of engineered barriers and selected an engineered barrier designed to prevent*  
30            *or substantially delay the movement of water or radionuclides toward the accessible*  
31            *environment. The DOE provided sufficient documentation to show that MgO can effectively*  
32            *reduce actinide solubility in the disposal system. The DOE proposed to emplace a large amount*  
33            *of MgO around waste drums in order to provide additional factor of safety and thus account for*  
34            *uncertainties in the geochemical conditions that would affect CO<sub>2</sub> generation and MgO*  
35            *reactions.”*

36 *The EPA determined that MgO met the regulatory definition of an engineered barrier. The*  
37 *other three systems proposed as engineered barriers by the DOE were viewed by the EPA as*  
38 *part of the disposal system design.*

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



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

4 *Condition 1: § 194.14(b), Disposal system design, panel closure system. The Department shall*  
5 *implement the panel seal design designated as Option D in Docket A-93-02, Item II-G-1*  
6 *(October 29, 1996, Compliance Certification Application submitted to the Agency). The Option*  
7 *D design shall be implemented as described in [CCA] Appendix PCS of Docket A-93-02, Item*  
8 *II-G-1, with the exception that the Department shall use Salado mass concrete (consistent with*  
9 *that proposed for the shaft seal system, and as described in CCA Appendix SEAL of Docket A-*  
10 *93-02, Item II-g-1) instead of fresh water concrete.*

## 11 **BARRIERS-2.0 ENGINEERED BARRIER**

### 12 **BARRIERS-2.1 Introduction**

13 *The DOE is emplacing MgO in the disposal system to decrease the solubilities of the actinide*  
14 *elements in transuranic (TRU) waste in any brine present in the repository after closure.*  
15 *MgO will decrease actinide solubilities by consuming essentially all carbon dioxide (CO<sub>2</sub>) that*  
16 *would be produced by microbial consumption of all cellulosic, plastic, and rubber (CPR)*  
17 *materials in TRU waste or waste containers in the repository. Although MgO will consume*  
18 *essentially all CO<sub>2</sub>, minute quantities (relative to the quantity that would be produced by*  
19 *microbial consumption of all CPR materials) will persist in the aqueous and gaseous phases.*  
20 *The residual quantity will be so small relative to the initial quantity that the adverb*  
21 *“essentially” is omitted hereafter in this appendix. Consumption of CO<sub>2</sub> will prevent the*  
22 *acidification of brine or the production of significant quantities of carbonate ion (CO<sub>3</sub><sup>2-</sup>),*  
23 *which could increase actinide solubilities.*

24 *The geochemical functions that MgO must perform to decrease actinide solubilities and serve*  
25 *as an effective engineered barrier are to: (1) consume all CO<sub>2</sub> that could be produced in the*  
26 *repository, and (2) buffer (control) the fugacity of CO<sub>2</sub> ( $f_{CO_2}$ ) and pH within ranges favorable*  
27 *from the standpoint of the speciation and solubilities of the actinides. (The fugacity of a*  
28 *gaseous species,  $f_i$ , is similar to the partial pressure of that species,  $p_i$ )*

29 *The effects of MgO carbonation (consumption of CO<sub>2</sub>) have been included in the performance*  
30 *assessment (PA) calculations for the CCA, the first WIPP Compliance Recertification*  
31 *Application (CRA-2004), and various impact assessments by: (1) removing CO<sub>2</sub> from the*  
32 *gaseous phase in Brine and Gas Flow (BRAGFLO) calculations, thereby reducing somewhat*  
33 *the predicted pressurization of the repository (see Appendix PA, Section PA-4.2); and*  
34 *(2) using the values of  $f_{CO_2}$  and pH established by reactions among MgO, brine, and aqueous*  
35 *or gaseous CO<sub>2</sub> to calculate actinide solubilities (see Appendix PA, Attachment SOTERM).*

36 *Another function that MgO will perform in the repository is to consume water (H<sub>2</sub>O) in brine,*  
37 *or H<sub>2</sub>O vapor in the gaseous phase. MgO hydration (H<sub>2</sub>O consumption) could consume H<sub>2</sub>O*  
38 *in quantities that are potentially significant from the standpoint of the long-term repository*  
39 *performance. Subsequent carbonation of hydrated MgO will not necessarily release this H<sub>2</sub>O*  
40 *(see Sections 2.3.2 and 2.3.4 of this appendix). Potentially beneficial effects of MgO hydration*

1 *include reductions in gas production, pressurization caused by gas production, and direct-*  
2 *brine and spillings releases. However, MgO hydration is not included in PA at present.*

3 *In its May 1998 certification rulemaking, the EPA specified MgO as the only engineered*  
4 *barrier in the WIPP disposal system (EPA 1998a).*

5 *In this appendix, “MgO” refers to the bulk, granular material being emplaced in the WIPP to*  
6 *serve as the engineered barrier. MgO comprises periclase (pure, crystalline MgO - the main,*  
7 *reactive constituent of the WIPP engineered barrier) and various impurities (see Section 2.3.1*  
8 *of this appendix). Pure, crystalline MgO is always referred to as periclase in this appendix.*  
9 *The term “periclase” and other mineral names used herein are, strictly speaking, restricted to*  
10 *naturally occurring forms of the materials that meet all other requirements of the definition of*  
11 *a mineral (see, for example, Bates and Jackson 1984). However, mineral names are used for*  
12 *convenience in this appendix.*

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

14 *The DOE is emplacing MgO in polypropylene “supersacks” on top of the stacks of three*  
15 *seven-packs of 55-gal (208-L) drums, three standard waste boxes (SWBs), or various*  
16 *combinations of these and other waste containers. Other such containers include ten-drum*  
17 *overpacks (TDOPs), four-packs of 85-gal (321-L) drums, and three-packs of 100-gal (379-L)*  
18 *drums (see Appendix DATA, Attachment H). Each supersack contains  $4200 \pm 50$  lb*  
19 *( $1905 \pm 23$  kg) of MgO (WTS 2003).*

20 *National Magnesia Chemicals provided the MgO emplaced in the WIPP from 1999 through*  
21 *2000. After National Magnesia Chemicals stopped producing MgO, Premier Chemicals in*  
22 *Gabbs, NV, was selected as the supplier. Premier MgO was selected based on cost and a*  
23 *technical evaluation its suitability as the engineered barrier (Papenguth 1999). The technical*  
24 *evaluation included a reactivity test developed by Krumhansl et al. (1997). Premier Chemicals*  
25 *has supplied MgO since 2000.*

26 *Initially, MgO was emplaced in both supersacks and minisacks. The minisacks were emplaced*  
27 *among the waste containers and between the waste containers and the ribs (sides) of the*  
28 *disposal rooms. In 2000, however, the DOE requested EPA approval of the elimination of the*  
29 *minisacks (see Triay 2000); the EPA approved this request in 2001 (EPA 2001a).*

30 *Emplacement of MgO in supersacks: (1) facilitates handling and emplacement of MgO; (2)*  
31 *minimizes potential worker exposure to dust; and (3) minimizes the exposure of periclase, the*  
32 *main, reactive constituent of MgO, to atmospheric CO<sub>2</sub> and H<sub>2</sub>O during handling and*  
33 *emplacement, and prior to panel closure. WTS (2003) provides detailed specifications for the*  
34 *supersacks. In particular, WTS (2003) specifies that the supersacks “shall provide a barrier to*  
35 *atmospheric moisture and carbon dioxide (CO<sub>2</sub>) ... equivalent to or better than that provided*  
36 *by a standard commercial cement bag” and “must be able to retain [their] contents for a*  
37 *period of two years after emplacement without rupturing from [their] own weight.” The*  
38 *specifications also require a certificate of compliance with all requirements of WTS (2003) for*  
39 *every shipment of MgO (see next paragraph), and a certified chemical analysis of each new lot*  
40 *of MgO. The supersacks are subject to random receipt inspection at the WIPP to ensure*

1 *compliance with the dimensions and labeling specified by WTS (2003), and to identify any*  
2 *shipping damage.*

3 *The supersacks contain dry, granular MgO, of which less than 0.5 percent can exceed 3/8 in.*  
4 *(9.5 mm) in diameter (WTS 2003). Emplacement of granular MgO instead of powder*  
5 *(1) results in a bulk density high enough that sufficient MgO can be emplaced without causing*  
6 *major operational difficulties, (2) reduces the likelihood of formation and release of dust in*  
7 *the event of premature rupture of a supersack, and (3) ensures that the permeability of the*  
8 *material is high enough to promote complete reaction with aqueous or gaseous CO<sub>2</sub>.*

9 *Creep closure of WIPP disposal rooms will rupture the supersacks and disperse the MgO*  
10 *among and within the ruptured waste containers. This will in turn expose the MgO to the*  
11 *room atmosphere, to any CO<sub>2</sub> produced by microbial consumption of CPR materials, and to*  
12 *H<sub>2</sub>O vapor and any brine present.*

### 13 *BARRIERS-2.3 Effects of Magnesium Oxide on Near-Field Processes and Conditions*

14 *The most important effect of MgO in the repository will be to consume all CO<sub>2</sub> that would be*  
15 *produced by microbial consumption of CPR materials, thereby creating conditions that*  
16 *decrease actinide solubilities relative to those expected in the presence of CO<sub>2</sub>. The effects of*  
17 *MgO on other processes in the repository could also be significant (see Sections 2.3.3, 2.3.4,*  
18 *and 2.4 of this appendix).*

#### 19 *BARRIERS-2.3.1 Characteristics of Premier Magnesium Oxide*

20 *Premier Chemicals manufactures the MgO currently being emplaced in the WIPP by mining*  
21 *ore from a sedimentary magnesite (MgCO<sub>3</sub>) deposit and calcining it to expel all CO<sub>2</sub> from*  
22 *magnesite, thereby producing periclase. Calcination of accessory calcite (CaCO<sub>3</sub>) produces*  
23 *small quantities of lime (CaO). Calcination of other accessory minerals in the ore creates*  
24 *minor quantities of oxide and silicate minerals such as spinel (MgAl<sub>2</sub>O<sub>4</sub>), ulvöspinel*  
25 *(Ti(Fe,Mg)<sub>2</sub>O<sub>4</sub>), forsterite (Mg<sub>2</sub>SiO<sub>4</sub>), and monticellite (CaMgSiO<sub>4</sub>). Calcination also drives*  
26 *off all H<sub>2</sub>O in the ore.*

27 *Bryan and Snider (2001a) reported that a typical chemical analysis of Premier MgO yields*  
28 *about 91 wt percent MgO, 1 wt percent alumina (Al<sub>2</sub>O<sub>3</sub>), 3 wt percent silica (SiO<sub>2</sub>), 4 wt*  
29 *percent calcium oxide (CaO), and 1 wt percent iron(III) (Fe(III)) oxide (Fe<sub>2</sub>O<sub>3</sub>). Most of the*  
30 *MgO and some of the CaO occur as periclase and lime, respectively, in Premier MgO.*  
31 *However, some of the MgO and CaO, and most – if not all – Al<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>, and Fe(III) oxide are*  
32 *present in the accessory oxide and silicate minerals described above.*

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

1 *to conclude that this material contains about 90 wt percent reactive phases (periclase + lime)*  
 2 *and 10 wt percent nonreactive phases (oxides and silicates).*

3 *After the WIPP is filled and sealed, periclase will react with H<sub>2</sub>O in the gaseous phase to form*  
 4 *brucite (Mg(OH)<sub>2</sub>), or with H<sub>2</sub>O in brine to form brucite or amorphous or crystalline*  
 5 *Mg-Cl-OH-H<sub>2</sub>O-bearing solids such as Mg<sub>3</sub>Cl(OH)<sub>5</sub>·4H<sub>2</sub>O or Mg<sub>2</sub>Cl(OH)<sub>3</sub>·4H<sub>2</sub>O. Periclase,*  
 6 *brucite, and the Mg-Cl-OH-H<sub>2</sub>O phases will react with aqueous or gaseous CO<sub>2</sub> to form solids*  
 7 *such as hydromagnesite (Mg<sub>5</sub>(CO<sub>3</sub>)<sub>4</sub>(OH)<sub>2</sub>·4H<sub>2</sub>O or perhaps Mg<sub>4</sub>(CO<sub>3</sub>)<sub>3</sub>(OH)<sub>2</sub>·3H<sub>2</sub>O),*  
 8 *nesquehonite (MgCO<sub>3</sub>·3H<sub>2</sub>O), and perhaps magnesite. Lime will react with aqueous or*  
 9 *gaseous H<sub>2</sub>O to form portlandite (Ca(OH)<sub>2</sub>), and lime and portlandite will react with aqueous*  
 10 *or gaseous CO<sub>2</sub> to form calcite (CaCO<sub>3</sub>). Oxides other than periclase and lime, and silicates*  
 11 *will not react with H<sub>2</sub>O and CO<sub>2</sub> to a significant extent during the 10,000-year regulatory*  
 12 *period. Therefore, oxides other than periclase and lime, and silicates are not included in the*  
 13 *calculation of the CO<sub>2</sub> consumption capacity used to calculate the MgO safety factor (see*  
 14 *Section 2.5 of this appendix). Furthermore, these oxides and silicates will not affect chemical*  
 15 *conditions in the repository significantly.*

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

18 *Table BARRIERS-1. Particle-Size Distribution of Two Batches of Premier MgO*  
 19 *(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%

20 **BARRIERS-2.3.2 Hydration and Carbonation of Magnesium Oxide**

21 *Predictions of the effects of MgO on chemical conditions in the WIPP depend somewhat on*  
 22 *whether significant microbial activity occurs in the repository. The effects of MgO hydration*  
 23 *do not depend on whether microbial activity occurs, but the carbonation reactions that would*  
 24 *buffer f<sub>CO<sub>2</sub></sub> in the event of microbial activity are different from those that would buffer f<sub>CO<sub>2</sub></sub> in*  
 25 *the absence of microbial activity. Furthermore, the values of f<sub>CO<sub>2</sub></sub> that would result from these*  
 26 *reactions would be slightly different. This prediction differs from those in the CCA and the*  
 27 *EPA’s 1997 Performance Assessment Verification Test (PAVT); in both of these cases, the*  
 28 *predicted effects of MgO on f<sub>CO<sub>2</sub></sub> were assumed to be identical regardless of whether microbial*  
 29 *activity occurs (see Section 2.3.2.5 of this appendix).*

30 *There are large uncertainties as to whether significant microbial activity will occur during the*  
 31 *10,000-year WIPP regulatory period (Brush 1995). Therefore, it is assumed that significant*

1 *microbial CO<sub>2</sub> production is possible, but by no means certain. To incorporate these*  
2 *uncertainties in the CCA PA, Wang and Brush (1996a, 1996b) developed a conceptual model*  
3 *for microbial activity in the repository. According to this model, there is a probability of 0.50*  
4 *for significant microbial activity. In the event of significant microbial activity, microbes would*  
5 *consume 100 percent of the cellulosic materials in the repository. Furthermore, there is a*  
6 *conditional probability of 0.50 that microbes would consume all plastic and rubber materials*  
7 *after consuming all cellulosic materials. Thus, there is microbial consumption of all cellulosic*  
8 *materials, but no plastic or rubber materials, in about 25 percent of the PA realizations*  
9 *(vectors); microbial consumption of all CPR materials in 25 percent of the vectors; and no*  
10 *microbial activity in the remaining 50 percent of the vectors. This model was used in the CCA*  
11 *PA, the 1997 PAVT, and the CRA-2004 PA. The implementation of this model is described in*  
12 *Appendix PA, Section PA-5.2.*

### 13 BARRIERS-2.3.2.1 Hydration of Magnesium Oxide

14 *Bryan and Snider (2001a, 2001b) and Snider (2002, 2003a) have studied the hydration of*  
15 *Premier MgO, the material currently being emplaced in the WIPP, under humid and*  
16 *inundated conditions. Humid experiments have been carried out with 3 g of uncrushed*  
17 *Premier MgO at a relative humidity (RH) of 35, 50, 75, or 95 percent and temperatures of 25,*  
18 *40, 60, or 80 °C for up to 460 days (Snider 2003a); inundated experiments have been*  
19 *conducted with 5 g of uncrushed Premier MgO in 100 mL of deionized (DI) H<sub>2</sub>O, 4.00-M*  
20 *sodium chloride (NaCl), ERDA-6, or Generic Weep Brine (GWB) at temperatures of 25, 50,*  
21 *70, and 90 °C for up to 360 days (Snider 2003a). ERDA-6 is a synthetic brine representative*  
22 *of fluids in brine reservoirs in the Castile Formation (Popielak et al. 1983). GWB is a*  
23 *synthetic brine typical of intergranular (grain-boundary) fluids from the Salado Formation at*  
24 *or near the stratigraphic horizon of the repository (Snider 2003b).*

25 *Based on these experiments with Premier MgO, the most important hydration reaction*  
26 *expected in the WIPP is:*



28 *Reaction (1) is the only hydration reaction observed to date in the humid experiments.*  
29 *Reaction (1) is also the only hydration reaction observed so far in the inundated runs with*  
30 *ERDA-6 (Snider 2003a). In inundated experiments with GWB, hydration has produced both*  
31 *brucite and an amorphous or crystalline Mg-Cl-OH-H<sub>2</sub>O phase (Snider 2003a). In most of*  
32 *the runs with GWB, the Mg-Cl-OH-H<sub>2</sub>O phase is amorphous and its exact composition has*  
33 *not been determined. In a few experiments at 25 °C, however, a crystalline phase with the*  
34 *composition Mg<sub>3</sub>Cl(OH)<sub>5</sub>·4H<sub>2</sub>O has been identified by XRD analysis. The thermodynamic*  
35 *speciation and solubility code Fracture-Matrix Transport (FMT) (Babb and Novak 1997 and*  
36 *addenda, Wang 1998) also predicts that both brucite and Mg<sub>2</sub>Cl(OH)<sub>3</sub>·4H<sub>2</sub>O are stable in*  
37 *GWB and Salado Primary Constituents (SPC) Brine. SPC Brine is similar to Brine A,*  
38 *another synthetic fluid that has been used to represent intergranular Salado brines (Molecke*  
39 *1983). However, long-term experiments with GWB suggest that brucite may be replacing the*  
40 *amorphous Mg-Cl-OH-H<sub>2</sub>O phase.*

1 *Snider (2002, Figures 1, 2, 6, and 7) observed that hydration of Premier MgO reached*  
 2 *completion after formation of about 85 mol percent brucite in accelerated experiments. Snider*  
 3 *(2003c) calculated that the average brucite content is 84.6 mol percent after complete*  
 4 *hydration, based on the last 8 data points of the inundated hydration experiment with DI H<sub>2</sub>O*  
 5 *at 90 °C (Snider 2002, Figures 1 and 2) and the last 16 data points of the humid hydration run*  
 6 *at 95 percent RH and 80 °C (Snider 2002, Figures 6 and 7). Therefore, Snider (2003d) used a*  
 7 *value of 0.846 to calculate the quantity of reactive constituents in the MgO to be emplaced in*  
 8 *the repository for her determination of the MgO safety factor (see Section 2.5 of this*  
 9 *appendix). Thus, Snider (2003d) assumed that the quantity of constituents that reacted with*  
 10 *aqueous or gaseous H<sub>2</sub>O in these accelerated experiments is identical to that which will react*  
 11 *with aqueous or gaseous CO<sub>2</sub> in the WIPP. Use of this value to calculate the MgO safety*  
 12 *factor does not imply that hydration will necessarily precede carbonation in the repository.*

### 13 BARRIERS-2.3.2.2 Carbonation of Magnesium Oxide

14 *Bryan and Snider (2001a, 2001b), Snider (2002), Snider and Xiong (2002), and Xiong and*  
 15 *Snider (2003) have studied the carbonation of Premier MgO, the material currently being*  
 16 *emplaced in the WIPP, and reagent-grade materials under inundated conditions. Inundated*  
 17 *experiments have been carried out with 5 g of uncrushed Premier MgO in 100 mL of DI H<sub>2</sub>O,*  
 18 *4.00-M NaCl, ERDA-6, or GWB under an atmosphere consisting of compressed, ambient,*  
 19 *laboratory air at room temperature for up to 327 days (Snider and Xiong 2002); inundated*  
 20 *experiments have also been conducted with uncrushed Premier MgO; crushed, prehydrated*  
 21 *Premier MgO; Fisher reagent-grade periclase; or prehydrated Fisher periclase in 100 mL of*  
 22 *ERDA-6 or GWB under an atmosphere containing 5 percent CO<sub>2</sub> for periods up to 91 days*  
 23 *(Snider and Xiong, 2002). Humid experiments have been performed with 2.5 g of prehydrated*  
 24 *Fisher periclase in an atmosphere consisting of compressed, ambient, laboratory air at an RH*  
 25 *of 33, 58, 75, or 95 percent at room temperature and 40 °C.*

26 *Based on these experiments, the most important carbonation reaction expected in the WIPP in*  
 27 *the event of significant microbial CO<sub>2</sub> production is:*



29 *In experiments with ERDA-6 and atmospheric CO<sub>2</sub>, Snider and Xiong (2002) have detected*  
 30 *hydromagnesite with the composition Mg<sub>5</sub>(CO<sub>3</sub>)<sub>4</sub>(OH)<sub>2</sub>·4H<sub>2</sub>O by XRD analysis. No other Mg*  
 31 *carbonates have been detected in runs with ERDA-6 and atmospheric CO<sub>2</sub>. Snider and Xiong*  
 32 *(2002) have detected both hydromagnesite (Mg<sub>5</sub>(CO<sub>3</sub>)<sub>4</sub>(OH)<sub>2</sub>·4H<sub>2</sub>O) and nesquehonite by XRD*  
 33 *analysis in the experiments with ERDA-6 and 5 percent CO<sub>2</sub>, but hydromagnesite is clearly*  
 34 *replacing nesquehonite as these experiments proceed. In experiments with GWB,*  
 35 *hydromagnesite (Mg<sub>5</sub>(CO<sub>3</sub>)<sub>4</sub>(OH)<sub>2</sub>·4H<sub>2</sub>O) is the only Mg carbonate that has been detected by*  
 36 *XRD analysis (Snider and Xiong 2002). Therefore, there is strong evidence that*  
 37 *hydromagnesite (Mg<sub>5</sub>(CO<sub>3</sub>)<sub>4</sub>(OH)<sub>2</sub>·4H<sub>2</sub>O) will be the dominant Mg carbonate for at least part*  
 38 *of the 10,000-year regulatory period.*

39 *However, thermodynamic calculations with EQ3/6 (Daveler and Wolery 1992, Wolery 1992a,*  
 40 *1992b, Wolery and Daveler 1992) and FMT imply the magnesite is stable with respect to both*  
 41 *hydromagnesite (Mg<sub>5</sub>(CO<sub>3</sub>)<sub>4</sub>(OH)<sub>2</sub>·4H<sub>2</sub>O or Mg<sub>4</sub>(CO<sub>3</sub>)<sub>3</sub>(OH)<sub>2</sub>·3H<sub>2</sub>O) and nesquehonite under*

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

17 *Nevertheless, the DOE now concludes that hydromagnesite with the composition*  
18  *$Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$  will be the dominant Mg carbonate in the WIPP during the*  
19 *10,000-year regulatory period in the event of significant microbial  $CO_2$  production. This*  
20 *conclusion is based on the experimental evidence for the formation of hydromagnesite*  
21 *described above and the absence of any experimental evidence, at least so far, for the*  
22 *formation of magnesite. Although thermodynamic calculations imply that magnesite is stable,*  
23 *they do not necessarily imply that magnesite will become the dominant Mg carbonate in*  
24 *10,000 years. However, there is as yet no evidence to rule out this possibility.*

25 **BARRIERS-2.3.2.3 Effects of Magnesium Oxide in the Event of Significant Microbial**  
26 **Activity**

27 *The DOE is emplacing significantly more MgO than would be required to consume the  $CO_2$*   
28 *that could be produced by microbial consumption of all CPR materials in the WIPP (see*  
29 *Section 2.5 of this appendix). Therefore, both brucite and hydromagnesite*  
30  *$(Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O)$ , or brucite, a Mg-Cl-OH- $H_2O$  phase, and hydromagnesite*  
31  *$(Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O)$ , will be present in the repository even if all CPR materials are*  
32 *consumed; and these solids will buffer  $f_{CO_2}$  (see Reaction (2), above). In this and other*  
33 *reactions used for thermodynamic calculations, it has been assumed that the effects of possible*  
34 *substitution of Fe(II) for Mg in Mg-bearing solids such as brucite and hydromagnesite are*  
35 *insignificant. Brush and Xiong (2003a, 2003b) used equilibria among GWB, brucite,*  
36  *$Mg_2Cl(OH)_3 \cdot 4H_2O$ , and hydromagnesite  $(Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O)$ , or among ERDA-6, brucite,*  
37 *and hydromagnesite  $(Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O)$ , to buffer  $f_{CO_2}$  for the actinide-speciation and*  
38 *-solubility calculations for the CRA-2004 PA vectors with microbial activity. Brush and Xiong*  
39 *(2003b, Table 6) reported a value of  $10^{-5.50}$  atm for  $f_{CO_2}$  for both GWB and ERDA-6 and the*  
40 *mineral assemblages provided above. Other minerals, such as halite (NaCl) and anhydrite*  
41  *$(CaSO_4)$ , were also present in these mineral assemblages, but are not reactants or products of*  
42 *the carbonation reaction(s) that buffer  $f_{CO_2}$ .*

1 *The brucite dissolution reaction,*



3 *will buffer pH in the WIPP in the event of significant microbial activity. Brush and Xiong*  
 4 *(2003b, Table 6) reported a pH value of 8.69 for GWB and 9.02 for ERDA-6.*

5 *These values of  $f_{\text{CO}_2}$  and pH were used for the actinide-speciation and -solubility calculations*  
 6 *for the CRA-2004 PA vectors with significant microbial activity (see Appendix PA, Attachment*  
 7 *SOTERM, Section SOTERM-3.0).*

8 *BARRIERS-2.3.2.4 Effects of Magnesium Oxide in the Absence of Significant Microbial*  
 9 *Activity*

10 *Brush and Xiong (2003a) redefined the reaction that will buffer  $f_{\text{CO}_2}$  for those PA vectors*  
 11 *without microbial activity. Brush and Xiong (2003b) evaluated the effects of this change on*  
 12  *$f_{\text{CO}_2}$  and pH, and on the speciation and solubilities of thorium (Th), uranium (U), neptunium*  
 13 *(Np), plutonium (Pu), and americium (Am). Brush and Xiong (2003b) demonstrated that*  
 14 *redefining the reaction that will buffer  $f_{\text{CO}_2}$  does not change  $f_{\text{CO}_2}$ , pH, or actinide solubilities*  
 15 *significantly. However, implementation of this change in the CRA-2004 PA has made the*  
 16 *actinide solubilities used in these calculations consistent with the conceptual model for*  
 17 *microbial activity in the WIPP (see above).*

18 *Calcite is more stable under expected WIPP conditions than magnesite, hydromagnesite*  
 19 *( $\text{Mg}_5(\text{CO}_3)_4(\text{OH})_2 \cdot 4\text{H}_2\text{O}$  or  $\text{Mg}_4(\text{CO}_3)_3(\text{OH})_2 \cdot 4\text{H}_2\text{O}$ ) or nesquehonite. Furthermore, calcite*  
 20 *precipitates readily under the low-temperature conditions expected in the WIPP. Formation*  
 21 *of calcite from the carbonation of lime and/or portlandite has been observed in as little as 16*  
 22 *days in GWB, and by 50 days in ERDA-6, in the carbonation experiments described above.*  
 23 *Therefore, Brush and Xiong (2003a, 2003b) suppressed (prevented the formation of) calcite*  
 24 *(and magnesite) by “disabling” it in their input files, thereby allowing the formation of*  
 25 *hydromagnesite ( $\text{Mg}_5(\text{CO}_3)_4(\text{OH})_2 \cdot 4\text{H}_2\text{O}$ ), the third-most-stable carbonate mineral under*  
 26 *expected WIPP conditions. This was appropriate for the vectors with microbial activity*  
 27 *because the large quantities of  $\text{CO}_2$  produced in these vectors would overwhelm the capacity of*  
 28 *dissolved calcium ( $\text{Ca}^{2+}$ ) to precipitate  $\text{CO}_2$  as calcite, thus leaving most of the microbial  $\text{CO}_2$*   
 29 *to react with periclase, brucite, or  $\text{Mg}_2\text{Cl}(\text{OH})_3 \cdot 4\text{H}_2\text{O}$  and produce hydromagnesite or*  
 30 *(initially) nesquehonite. However, in the absence of microbial  $\text{CO}_2$  production, the quantity of*  
 31  *$\text{Ca}^{2+}$  present would be sufficient to precipitate any  $\text{CO}_2$  present as calcite without formation of*  
 32 *metastable Mg carbonates. Therefore, for the vectors without microbial activity, Brush and*  
 33 *Xiong (2003a, 2003b) allowed calcite to precipitate. The reaction that will buffer  $f_{\text{CO}_2}$  in the*  
 34 *absence of microbial activity is:*



36 *Unlike the brucite-hydromagnesite ( $\text{Mg}_5(\text{CO}_3)_4(\text{OH})_2 \cdot 4\text{H}_2\text{O}$ ) carbonation reaction (see*  
 37 *Reaction (2), above), which buffers  $f_{\text{CO}_2}$  at a unique value of  $10^{-5.50}$  atm, the value of  $f_{\text{CO}_2}$*   
 38 *maintained by the brucite-calcite carbonation reaction (Reaction (4)) depends on the ratio of*



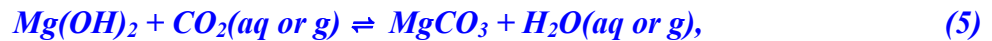
1 *the activities of  $Mg^{2+}$  and  $Ca^{2+}$ , which in turn depends on the composition of the brine after*  
 2 *equilibration with MgO. Brush and Xiong (2003b, Table 6) reported a value of  $10^{-5.48}$  atm for*  
 3 *GWB, brucite, and calcite, and  $10^{-6.15}$  atm for ERDA-6, brucite, and calcite. (Other minerals,*  
 4 *such as halite and anhydrite, were also present.)*

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

8 *These values of  $f_{CO_2}$  and pH were used for the actinide-speciation and -solubility calculations*  
 9 *for the CRA-2004 PA vectors without microbial activity (see Appendix PA, Attachment*  
 10 *SOTERM, Section SOTERM-3.0).*

#### 11 BARRIERS-2.3.2.5 Previous Predictions of the Effects of Magnesium Oxide

12 *Novak et al. (1996) and CCA Appendix BACK concluded that magnesite will be the dominant*  
 13 *Mg carbonate in the repository during the 10,000-year regulatory period, and that the brucite-*  
 14 *magnesite carbonation reaction,*



16 *will buffer  $f_{CO_2}$  in the WIPP whether or not significant microbial  $CO_2$  production occurs.*  
 17 *Novak et al. (1996) calculated actinide solubilities for the CCA PA. They did not report  $f_{CO_2}$ ,*  
 18 *but the EPA (1998d, Tables 4-6 and 4-7) reported a value of  $10^{-6.89}$  atm for both SPC and*  
 19 *ERDA-6 in equilibrium with brucite and magnesite. This value of  $f_{CO_2}$  was used for the*  
 20 *actinide-speciation and -solubility calculations for all CCA PA vectors (both with and without*  
 21 *microbial activity). (Other minerals, such as halite and anhydrite, were also present.) Novak*  
 22 *et al. (1996) used the brucite dissolution reaction (see Reaction (3), above) to buffer the pH in*  
 23 *their actinide-solubility calculations, but did not report their results. The EPA (EPA 1998d,*  
 24 *Tables 4-6 and 4-7) reported pH values of 8.69 and 9.24 for SPC and ERDA-6, respectively, in*  
 25 *equilibrium with the mineral assemblages provided above. These values of pH were used for*  
 26 *the solubility calculations for all CCA PA vectors.*

27 *For the 1997 PAVT, the EPA specified that the brucite-hydromagnesite*  
 28 *( $Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$ ) carbonation reaction (see Reaction (2), above) will buffer  $f_{CO_2}$  in the*  
 29 *WIPP whether or not significant microbial  $CO_2$  production occurs. The EPA (1998b,*  
 30 *Tables 4.10-3 and 4.10-4; 1998d, Tables 4-8 and 4-9) reported a value of  $10^{-5.50}$  atm for both*  
 31 *SPC and ERDA-6 in equilibrium with brucite and hydromagnesite. This value of  $f_{CO_2}$  was*  
 32 *used for the actinide-solubility calculations for all 1997 PAVT vectors (both with and without*  
 33 *microbial activity). (Other minerals, such as halite and anhydrite, were also present.) The*  
 34 *EPA (1998b, Tables 4.10-3 and 4.10-4; 1998d, Tables 4-8 and 4-9) reported pH values of 8.69*  
 35 *and 9.24 for SPC and ERDA-6, respectively, in equilibrium with the mineral assemblages*  
 36 *provided above. These pH values were used for the solubility calculations for all 1997 PAVT*  
 37 *vectors.*

**BARRIERS-2.3.2.6 Summary of Magnesium Oxide Hydration and Carbonation**

*Table BARRIERS-2 compares the values of log f<sub>CO2</sub> and pH calculated for the CRA-2004 PA solubility calculations by Brush and Xiong (2003b) with those calculated for the CCA PA and the 1997 PAVT. Table BARRIERS-2 shows that, despite modest differences in the predicted values of log f<sub>CO2</sub> and pH, reactions among brine, CO<sub>2</sub>, and MgO will consume essentially all CO<sub>2</sub> that could be produced in the repository, buffer f<sub>CO2</sub> within a range of about 10<sup>-5</sup> to 10<sup>-6</sup> atm (or about 10<sup>-7</sup> atm if significant quantities of magnesite form), and buffer the pH at about 9.*

***Table BARRIERS-2. Comparison of Log f<sub>CO2</sub> and pH Calculated for the CRA-2004 PA, the 1997 PAVT, and the CCA PA<sup>1,2,3</sup>***

<i>Property and Brine</i>	<i>CRA,<sup>1</sup> Microbial Vectors</i>	<i>CRA,<sup>1</sup> Nonmicrobial Vectors</i>	<i>1997 PAVT,<sup>3</sup> All Vectors</i>	<i>CCA,<sup>2</sup> All Vectors</i>
<i>Log f<sub>CO2</sub> Salado Brine</i>	<i>-5.50</i>	<i>-5.48</i>	<i>-5.50</i>	<i>-6.9</i>
<i>Log f<sub>CO2</sub> Castile Brine</i>	<i>-5.50</i>	<i>-6.15</i>	<i>-5.50</i>	<i>-6.9</i>
<i>pH, Salado Brine</i>	<i>8.69</i>	<i>8.69</i>	<i>8.69</i>	<i>8.69</i>
<i>pH, Castile Brine</i>	<i>9.02</i>	<i>8.99</i>	<i>9.24</i>	<i>9.24</i>

<sup>1</sup> From Brush and Xiong (2003b). See text for details.

<sup>2</sup> From Novak et al. (1996) and EPA (1998c). See text for details.

<sup>3</sup> From EPA (1998b, 1998c). See text for details.

*These values of f<sub>CO2</sub> are significantly lower than those anticipated in the absence of MgO (see CCA Appendix SOTERM, Figures SOTERM-1 and SOTERM-2).*

**BARRIERS-2.3.3 Effects of Magnesium Oxide on Colloidal Actinide Concentrations**

*Colloids could affect the long-term performance of the WIPP because of their potential ability to bind cationic metals such as the actinide elements in TRU waste and because of their potential mobility under expected repository conditions (Choppin 1988). Colloids are typically defined as phases intermediate in size between dissolved ionic or molecular species and suspended particles large enough to settle by gravity. The size range of colloids is typically on the order of 1 nm to 1 μm.*

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

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

#### 6 ***BARRIERS-2.3.4 Effects of Magnesium Oxide on Other Processes and Conditions***

7 *Hydration of MgO could significantly reduce the quantity of H<sub>2</sub>O in the WIPP (see Section*  
8 *2.3.4.1 of this appendix). However, MgO hydration is not included in PA at this time. (This is*  
9 *probably conservative.) The effects of MgO on hydrogen (H<sub>2</sub>) production from anoxic*  
10 *corrosion of steels and other Fe-base alloys in the repository (Section 2.3.4.2.1 of this*  
11 *appendix), and on room closure (Section 2.3.4.3 of this appendix) are less significant than its*  
12 *effects on the conditions that will affect actinide solubilities. MgO possesses inhibitory or even*  
13 *biocidal properties, but – in the absence of repository-specific experiments – it is not possible*  
14 *to reduce the microbial gas-generation rates used in PA (Section 2.3.4.2.2 of this appendix).*

#### 15 ***BARRIERS-2.3.4.1 Effects of Magnesium Oxide on Repository H<sub>2</sub>O Content***

16 *The hydration of periclase could consume significant quantities of H<sub>2</sub>O in the WIPP (see*  
17 *Reaction (1), above). The carbonation of brucite will not release this H<sub>2</sub>O if, as expected,*  
18 *hydromagnesite (Mg<sub>5</sub>(CO<sub>3</sub>)<sub>4</sub>(OH)<sub>2</sub>·4H<sub>2</sub>O) forms (Reaction (2)). Furthermore, even if*  
19 *significant quantities of magnesite form during the 10,000-year regulatory period (Reaction*  
20 *(5)), there will still be a significant amount of periclase available for hydration because the*  
21 *DOE is emplacing significantly more MgO than the quantity required to consume all CO<sub>2</sub> that*  
22 *could be produced (see Section 2.5 of this appendix). In fact, the safety factor calculated for a*  
23 *homogeneous, 10-panel repository implies that, even if magnesite is the only Mg carbonate*  
24 *formed, 59.2 percent of the original quantity of MgO emplaced in the repository would still be*  
25 *available for hydration after consumption of all CO<sub>2</sub>.*

26 *MgO hydration is not included in PA at this time.*

#### 27 ***BARRIERS-2.3.4.2 Effects of Magnesium Oxide on Gas Generation***

28 *The two gas-producing processes included in PA are anoxic corrosion of steels and other Fe-*  
29 *base alloys, which produces H<sub>2</sub>, and microbial consumption of CPR materials, which produces*  
30 *mainly CO<sub>2</sub> and methane (CH<sub>4</sub>).*

#### 31 ***BARRIERS-2.3.4.2.1 Gas Generation from Anoxic Corrosion of Steels and Other Iron-Base*** 32 ***Alloys***

33 *Telander and Westerman (1993, 1997) studied anoxic corrosion of various metals and*  
34 *concomitant H<sub>2</sub> production under expected WIPP conditions. Wang and Brush (1996a,*  
35 *1996c) used results from three types of experiments carried out by Telander and Westerman*  
36 *(1993, 1997) to establish ranges and probability distributions of H<sub>2</sub>-production rates for the*  
37 *CCA PA: (1) experiments with low-carbon (C) steels in or above Brine A under atmospheres*  
38 *consisting of initially pure CO<sub>2</sub>, nitrogen (N<sub>2</sub>), or hydrogen sulfide (H<sub>2</sub>S) in inert*  
39 *(noncorroding), metallic containers at low-to-intermediate pressures (about 1 to 20 atm); (2)*

1 *experiments with low-C steels in Brine A under H<sub>2</sub>, CO<sub>2</sub>, or N<sub>2</sub> in autoclaves at high pressures*  
2 *(35 to 127 atm); and (3) runs with low-C steels in ERDA-6 at pH values of 2.8 to 10.6 under*  
3 *N<sub>2</sub>. All these experiments were conducted at 30 ± 5 °C. Brine A and ERDA-6 are described*  
4 *above (see Section 3.2.1 of this appendix).*

5 *Anoxic corrosion of low-C steels in Brine A under initially pure N<sub>2</sub> resulted in a pH of 8.3,*  
6 *8.3, and 8.4 after 6, 12, and 24 months, respectively (see Telander and Westerman 1993, Table*  
7 *6-3, Test Containers 10, 17, and 25). Wang and Brush (1996a, 1996c) used the 12-to-24-*  
8 *month data from these experiments to establish a range and probability distribution of*  
9 *inundated, anoxic-corrosion rates of steels and other Fe-base alloys of 0 to 0.5 μm/year for the*  
10 *CCA PA. This is equivalent to a range of 0 to 1.59 × 10<sup>-14</sup> m/s. Data on the effects of pH on*  
11 *corrosion rates (Telander and Westerman 1997, Table 6-5) have demonstrated that rates*  
12 *obtained at a pH of 8.3 or 8.4 are somewhat higher than those at a pH of 8.69, 8.99, or 9.02,*  
13 *the values expected for the brucite dissolution reaction (see Reaction (3), above). Therefore,*  
14 *the anoxic-corrosion rates established by Brush and Wang (1996a, 1996c) for the CCA*  
15 *incorporated the effects of MgO on pH.*

16 *For the 1997 PAVT, the EPA specified that the upper limit of the range of the inundated*  
17 *anoxic-corrosion rate be increased from 1.59 × 10<sup>-14</sup> m/s to 3.17 × 10<sup>-14</sup> m/s (Trovato 1997a,*  
18 *Enclosure 2; EPA 1998c, Table ES-4, Section 5.15, and Tables 6.3 and 6.4; Hansen and Leigh*  
19 *2003). A range of 0 to 3.17 × 10<sup>-14</sup> m/s was also used for the CRA-2004 PA (see Appendix PA,*  
20 *Section PA-5.2).*

#### 21 **BARRIERS-2.3.4.2.2 Microbial Gas Generation**

22 *Francis and Gillow (1994, 2000), Francis et al. (1997), and Gillow and Francis (2001a, 2001b,*  
23 *2002a, 2002b) did not include MgO or the effects of pH in their study of microbial gas*  
24 *generation under expected WIPP conditions. Instead, they included bentonite in about half of*  
25 *their experiments because a backfill consisting of 70 wt percent crushed salt and 30 wt percent*  
26 *bentonite had been proposed as an alternative to a backfill consisting entirely of crushed salt,*  
27 *the design-basis backfill in January 1992 when these microbial gas-generation experiments*  
28 *were started. No microbial experiments have been carried out with MgO since the use of this*  
29 *material was proposed in 1996 to consume CO<sub>2</sub> and control f<sub>CO<sub>2</sub></sub> and pH in the WIPP.*

30 *The brucite dissolution reaction (see Reaction (3), above) will buffer the pH of any brines*  
31 *present at about 9 whether or not significant microbial activity occurs in the WIPP. This*  
32 *mildly basic value is somewhat higher than the mildly acidic values of pH produced by*  
33 *dissolution of microbial CO<sub>2</sub> in the experiments described by Francis and Gillow (1994, 2000),*  
34 *Francis et al. (1997), and Gillow and Francis (2001a, 2001b, 2002a, 2002b). However,*  
35 *emplacement of MgO in the WIPP and a consequent, mildly basic pH of 9 will not in and of*  
36 *itself preclude significant microbial activity in the repository. This conclusion is based on the*  
37 *common observation of viable alkalophilic microbes in alkaline lakes with pH values of 9*  
38 *to 10. Such alkaline lakes occur frequently in arid and semiarid environments, such as*  
39 *southeastern New Mexico and adjacent areas of west Texas, and could be one of the sources*  
40 *of the halophilic microbes observed in the WIPP.*

1 *However, several investigators have reported that MgO and compounds derived from MgO*  
2 *possess inhibitory or even biocidal properties (Asghari and Farrah 1993, Chapman et al.*  
3 *1995; Koper et al. 2002; Sawai 2003; Sawai et al. 1995a, 1995b, 1996, 2000a, 2000b;*  
4 *Stoimenov et al. 2002; Yamamoto et al. 1998). Some of the results of these studies may be*  
5 *applicable to the WIPP.*

6 *First, the inhibitory or biocidal effects of MgO probably result from the presence of brucite,*  
7 *not periclase (Sawai et al. 1995a), because most of the experiments cited above were conducted*  
8 *in aqueous solutions or in growth media that contained H<sub>2</sub>O, and most of these experiments*  
9 *were long enough for significant nucleation and growth of brucite on periclase surfaces*  
10 *exposed to these solutions or media.*

11 *Second, the inhibitory or biocidal effects of MgO do not seem to be caused by the mildly basic*  
12 *pH that results from the presence of brucite in aqueous solutions or growth media. Sawai*  
13 *et al. (1997) reported that the survival of Escherichia coli (E. coli) was unaffected by a*  
14 *MgO-free, alkaline growth medium at pH values of 10, 10.25, and 10.5, but that E. coli*  
15 *survival decreased significantly in the same medium at pH values of 10.75 and 11. This result*  
16 *agrees with the conclusion that a mildly basic pH of about 9 caused by the brucite dissolution*  
17 *reaction (see Reaction (3), above) will not by itself preclude microbial activity in the WIPP.*

18 *Third, the presence of solid Mg peroxide (MgO<sub>2</sub>) (Asghari and Farrah 1993) and/or the*  
19 *anionic dioxygenyl radical (O<sub>2</sub><sup>•-</sup>) (Sawai et al. 1995b) along with periclase may be largely*  
20 *responsible for the inhibitory or biocidal effects of MgO. MgO<sub>2</sub> could be produced by*  
21 *reactions between dissolved hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>), which will be produced by α radiolysis*  
22 *of H<sub>2</sub>O in WIPP brines, and periclase, brucite, or perhaps other Mg-bearing solids. Radiolysis*  
23 *will also produce anionic O<sub>2</sub><sup>•-</sup>.*

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

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

30 *Application of these results to microbial activity in the WIPP is difficult in the absence of*  
31 *long-term experiments under expected repository conditions. Biocides are often used for*  
32 *sterilization of solid materials, but become ineffective as the volume of the material(s) to be*  
33 *sterilized increases. This is because it becomes progressively more difficult to ensure uniform*  
34 *distribution of the biocide throughout these materials, and hence to ensure contact between*  
35 *the biocide and the microbes, as the volume increases. Therefore, sterilization methods such*  
36 *as autoclaving and radiation are used for materials with large volumes. In the case of MgO,*  
37 *Sawai et al. (2000a) reported that inhibition of microbial activity seems to require contact*  
38 *between MgO particles and microbes. Although room closure will rupture the supersacks and*  
39 *disperse the MgO into the interstices among and within the ruptured waste containers, this*  
40 *will not ensure contact between MgO particles and microbes. Furthermore, survival of*  
41 *microbes in samples subjected to treatment with an inhibitory or biocidal agent such as MgO,*

1 *especially those that have had some contact with particulate MgO, would probably result in*  
2 *the development of increased resistance to MgO.*

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

#### 8 **BARRIERS-2.3.4.3 Effects of Magnesium Oxide on Room Closure**

9 *In the CCA PA, the 1997 PAVT, and the CRA-2004 PA calculations, room closure initially*  
10 *proceeded as if the rooms were open. The free air space was eliminated early in the*  
11 *calculations by unmitigated creep closure. Eventually, the salt contacted the waste and*  
12 *deformed it according to the waste response model. At the same time, corrosion and gas*  
13 *production pressurized the rooms. The coupled processes involved compression owing to the*  
14 *superincumbent rock counterbalanced by gas production, which was obtained from sampled*  
15 *parameters. Thus, room closure was due to salt creep modified by the structural response of*  
16 *the waste and by gas production. MgO had no effect on room closure.*

#### 17 **BARRIERS-2.4 Effects of Magnesium Oxide on Far-Field Actinide Transport**

18 *MgO could affect the matrix distribution coefficients ( $K_{ds}$ ) used to predict transport of*  
19 *dissolved Th, U, Pu, and Am through the Culebra (see Brush 1996 or Brush and Storz 1996*  
20 *for a definition of matrix  $K_{ds}$ ). For the CCA PA, data from an empirical sorption study, a*  
21 *mechanistic sorption study, and a column-transport study were used to establish ranges and*  
22 *probability distributions of  $K_{ds}$  for Th, U, Pu, and Am.*

23 *Most of these  $K_{ds}$  were obtained from six-week, empirical sorption experiments carried out*  
24 *with 1 g of dolomite-rich rock crushed to a size range of 75 to 500  $\mu\text{m}$ ; 20 mL of Brine A,*  
25 *ERDA-6, AISinR, or H-17 with dissolved Th(IV), U(VI), Np(V), Pu(V), or Am(III); and a*  
26 *controlled atmosphere containing 0.24, 1.4, or 4.1 percent  $\text{CO}_2$  to simulate the expected range*  
27 *of  $f_{\text{CO}_2}$  in the Culebra, about  $10^{-3.5}$  to  $10^{-1.50}$  atm (see Brush 1996; Brush and Storz 1996).*

28 *Brine A and ERDA-6 are described above (see Section 2.3.2.1 of this appendix); AISinR is a*  
29 *synthetic brine representative of fluids sampled from the Culebra in the WIPP Air Intake*  
30 *Shaft; and H-17 simulates Culebra brine from the H-17 Hydropad.*

31 *Brush (1996) and Brush and Storz (1996) extended the empirical  $K_{ds}$  obtained with Brine A*  
32 *and ERDA-6 to a pH of about 9 or 10 with data from a mechanistic sorption study that*  
33 *quantified the effects of  $f_{\text{CO}_2}$ , pH and ionic strength on the sorption of Th(IV), U(VI), Np(V),*  
34 *Pu(V), and Am(III) from synthetic NaCl solutions by well-characterized, pure dolomite.*  
35 *Therefore, the  $K_{ds}$  for Brine A and ERDA-6 used for the CCA PA included the effects of MgO*  
36 *on pH. The  $K_{ds}$  for the Culebra brines, however, did not include the effects of MgO on pH*  
37 *because it was assumed that, if mixing is sufficient to produce fluids with compositions similar*  
38 *to those of Culebra brines, the pH of these mixtures will also be similar to those of Culebra*  
39 *brines (Brush 1996; Brush and Storz 1996).*

1 *For the 1997 PAVT, the EPA specified that the probability distributions for the  $K_{ds}$  be*  
2 *changed from uniform to log uniform (Trovato 1997b, Enclosure 2; EPA 1998c, Tables ES-3*  
3 *and ES-4, Sections 5.34 to 5.38 and Tables 6.3 and 6.4; Hansen and Leigh 2003). However,*  
4 *the EPA did not change any of the  $K_{ds}$ .*

5 *Brush and Storz (1996) corrected some of the ranges of  $K_{ds}$  established by Brush (1996) for*  
6 *the CCA PA. These corrections were too late for the far-field transport calculations for the*  
7 *CCA PA, and were not included in the far-field transport calculations for the 1997 PAVT.*  
8 *Hansen and Leigh (2003), however, incorporated them in the PA database, and the CRA-2004*  
9 *PA used the corrected  $K_{ds}$  along with the log-uniform probability distributions specified by the*  
10 *EPA (see Appendix PA, Section PA-5.2). The  $K_{ds}$  for Brine A and ERDA-6 used for the CRA-*  
11 *2004 PA included the effects of MgO on pH (Reaction (3) in Section 2.3.2.3 of this appendix),*  
12 *but the  $K_{ds}$  for the Culebra brines do not (see above).*

### 13 **BARRIERS-2.5 Magnesium Oxide Safety Factor**

14 *The MgO safety factor is the quantity of MgO to be emplaced in the WIPP divided by the*  
15 *quantity required to consume all CO<sub>2</sub> that would be produced by microbial consumption of all*  
16 *CPR materials in the repository. The safety factor must be greater than or equal to 1.00 for*  
17 *MgO to serve as an effective engineered barrier by consuming all CO<sub>2</sub> in the repository and*  
18 *buffering  $f_{CO_2}$  and pH within ranges favorable from the standpoint of actinide solubilities.*

#### 19 **BARRIERS-2.5.1 Calculation of Magnesium Oxide Safety Factor**

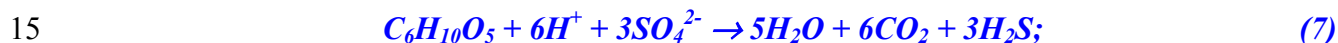
20 *Snider (2003d) calculated the MgO safety factor for the CRA-2004 PA by: (1) using the*  
21 *conceptual model of sequential use of electron acceptors by microorganisms, part of the*  
22 *overall model for possible microbial activity in the WIPP (Brush 1990, 1995; Wang and Brush*  
23 *1996a, 1996b) and the quantities of CPR materials, nitrate (NO<sub>3</sub><sup>-</sup>), and sulfate (SO<sub>4</sub><sup>2-</sup>) in the*  
24 *repository to determine the quantity of CO<sub>2</sub> that would be produced by microbial consumption*  
25 *of all CPR materials, and (2) dividing the quantity of MgO in the repository (corrected by*  
26 *subtracting the nonreactive constituents from the total quantity of MgO to be emplaced) by the*  
27 *quantity required to consume all CO<sub>2</sub>.*

28 *The conceptual model of sequential use of electron acceptors is based on the well-known*  
29 *observations that: (1) microbes use the electron acceptor (oxidant) that yields the most free*  
30 *energy per mole of organic C consumed; (2) after depletion of the best available electron*  
31 *acceptor, these microbes – or other microbes – begin to consume the next best electron*  
32 *acceptor; and (3) this process continues until all substrate (CPR materials in the case of the*  
33 *WIPP) is consumed, an essential nutrient is consumed, or some other limiting condition is*  
34 *attained. Sequential use of electron acceptors has been observed in a diverse array of natural*  
35 *environments, such as lacustrine, riverine, estuarine, and oceanic sediments; soils; and in*  
36 *anthropogenic environments, such as landfills. In these environments, the order of use*  
37 *observed is oxygen (O<sub>2</sub>) (referred to as aerobic respiration), NO<sub>3</sub><sup>-</sup> (denitrification),*  
38 *manganese(IV) (Mn(IV)) oxides and hydroxides (Mn reduction), Fe(III) oxides and*  
39 *hydroxides (Fe reduction), SO<sub>4</sub><sup>2-</sup> (SO<sub>4</sub><sup>2-</sup> reduction), and CO<sub>2</sub> (fermentation and*  
40 *methanogenesis) (Froelich et al. 1979; Berner 1980; Criddle et al. 1991; Chapelle 1993; Wang*  
41 *and Van Cappellen 1996; Schlesinger 1997; Hunter et al. 1998; Fenchel et al. 2000). (In the*

1 following discussion, fermentation and methanogenesis are usually referred to as  
2 “methanogenesis” for simplicity.)

3 In the WIPP, the quantities of O<sub>2</sub>, Mn(IV) oxides and hydroxides, and Fe(III) oxides and  
4 hydroxides will be very small relative to that of CPR materials (Brush 1990, 1995; Wang and  
5 Brush 1996a). Therefore, aerobic respiration, Mn reduction, and Fe reduction can be  
6 dismissed as completely insignificant from the standpoint of their potential effects on the long-  
7 term performance of the repository. However, NO<sub>3</sub><sup>-</sup> and SO<sub>4</sub><sup>2-</sup> will be present in the waste to  
8 be emplaced in the WIPP (Appendix DATA, Attachment F); and CO<sub>2</sub> could be produced by  
9 denitrification, SO<sub>4</sub><sup>2-</sup> reduction, and even methanogenesis (Brush 1990, 1995; Wang and  
10 Brush 1996a). Therefore, denitrification, SO<sub>4</sub><sup>2-</sup> reduction, and methanogenesis are  
11 potentially significant microbial respiratory pathways in the repository.

12 The overall reactions used to represent possible denitrification, SO<sub>4</sub><sup>2-</sup> reduction, and  
13 methanogenesis in the WIPP (Wang and Brush 1996a) are:



17 For these reactions, the CO<sub>2</sub> yields are 1 mol of CO<sub>2</sub> per mol of organic C consumed from  
18 denitrification and SO<sub>4</sub><sup>2-</sup> reduction, and 0.5 mol of CO<sub>2</sub> per mol of C from methanogenesis.

19 The total quantity of CPR materials in the inventory, including both the waste and the waste  
20 containers, greatly exceeds the quantities of NO<sub>3</sub><sup>-</sup> and SO<sub>4</sub><sup>2-</sup> (see Appendix DATA,  
21 Attachment F). This was also the case at the time of the CCA (DOE 1996a). Therefore, the  
22 quantity of CPR materials consumed by methanogenesis will greatly exceed that consumed by  
23 denitrification and SO<sub>4</sub><sup>2-</sup> reduction, if significant microbial activity occurs and if all CPR  
24 materials are consumed. Furthermore, the overall CO<sub>2</sub> yield will be close to 0.5 mol of CO<sub>2</sub>  
25 per mol of C consumed, if all CPR materials are consumed. Use of the extremely conservative  
26 assumption that all CPR materials in the waste and waste containers will be consumed  
27 provides a lower bound on the MgO safety factor because partial consumption of CPR  
28 materials would require less MgO to consume all CO<sub>2</sub> in the repository.

29 Snider (2003d) calculated the MgO safety factor for a homogeneous, 10-panel repository  
30 containing  $1.69 \times 10^5 \text{ m}^3$  of contact-handled- (CH-) TRU waste and  $7.08 \times 10^3 \text{ m}^3$  of remote-  
31 handled- (RH-) TRU waste. The sum of  $1.69 \times 10^5 \text{ m}^3$  of CH-TRU waste and  $7.08 \times 10^3 \text{ m}^3$  of  
32 RH-TRU waste,  $176,080 \text{ m}^3$ , is equal to  $6.2 \times 10^6 \text{ ft}^3$ , the maximum quantity of TRU waste that  
33 can be emplaced in the WIPP (WIPP Land Withdrawal Act, Pub. L. No. 102-579, 110 Stat.  
34 2422 (1992), as amended by 104-201 (1996). Snider (2003d) used these volumes of CH-TRU  
35 and RH-TRU waste, the densities of CPR materials in CH-TRU and RH-TRU waste, and the  
36 total masses of NO<sub>3</sub><sup>-</sup> and SO<sub>4</sub><sup>2-</sup> (see Appendix DATA, Attachment F) to calculate that, if all  
37 CPR materials are consumed: (1) 4.72 mol percent of the CPR materials will be consumed by  
38 denitrification, 0.82 mol percent by SO<sub>4</sub><sup>2-</sup> reduction, and 94.46 mol percent by  
39 methanogenesis; (2) the overall CO<sub>2</sub> yield will be 0.528 mol of CO<sub>2</sub> per mol of organic C



1 consumed; and (3) the safety factor will be 2.45. Table BARRIERS-3 compares these results  
 2 to those obtained for the CCA inventory with and without minisacks.

3 **BARRIERS-2.5.2 Alternative Method for the Calculation of Magnesium Oxide Safety**  
 4 **Factor**

5 *An alternative method has been used to calculate the quantity of MgO required to consume all*  
 6 *CO<sub>2</sub> that would be produced by microbial consumption of all CPR materials in the WIPP*

7 **Table BARRIERS-3. Comparison of MgO Safety Factors Calculated for the CRA and the**  
 8 **CCA Inventories.**

<i>CPR materials Consumed or Safety Factor</i>	<i>Repository with Supersacks but No Minisacks, CRA Inventory<sup>1</sup></i>	<i>Repository with Both Supersacks and Minisacks, CCA Inventory<sup>2,3</sup></i>	<i>Repository with Supersacks but No Minisacks, CCA Inventory<sup>2,3</sup></i>
<i>CPR Materials Consumed by Denitrification (mol %)</i>	4.72	3	3
<i>CPR Materials Consumed by SO<sub>4</sub><sup>2-</sup> Reduction (mol %)</i>	0.82	2	2
<i>CPR Materials Consumed by Methanogenesis (mol %)</i>	94.46	95	95
<i>MgO Safety Factor</i>	2.45	3.73	3.23

<sup>1</sup> Mol % CPR Materials consumed by denitrification, SO<sub>4</sub><sup>2-</sup> reduction, and methanogenesis, and MgO safety factor from Snider (2003b).

<sup>2</sup> Mol % CPR Materials consumed by denitrification, SO<sub>4</sub><sup>2-</sup> reduction, and methanogenesis from Wang (2000).

<sup>3</sup> Safety factors from DOE (2000, Table 1).

9 *(Peterson 1996) and the MgO safety factor (EPA 1997, Section 44.A.5 and 44.A.6; EPA*  
 10 *2001b, Table 1). This method is based on the assumption that the overall CO<sub>2</sub> yield from*  
 11 *microbial consumption of all CPR materials will be 1.0 mol of CO<sub>2</sub> per mol of organic C*  
 12 *consumed. For this assumption to be valid, all CPR materials would have to be consumed by*  
 13 *denitrification and/or SO<sub>4</sub><sup>2-</sup> reduction (see Reactions (6) and (7), above).*

14 *The assumption that all organic C in the CPR materials will be converted to CO<sub>2</sub> by*  
 15 *denitrification and/or SO<sub>4</sub><sup>2-</sup> reduction is inconsistent with: (1) the conceptual model of*  
 16 *sequential use of electron acceptors by microbes in the WIPP; (2) past and current estimates*  
 17 *of the quantities of CPR materials, NO<sub>3</sub><sup>-</sup>, and SO<sub>4</sub><sup>2-</sup> in the waste and waste containers to be*  
 18 *emplaced in the repository (DOE 1996a; Appendix DATA, Attachment F); and (3) recent*  
 19 *results of the laboratory study of microbial gas generation under expected WIPP conditions*  
 20 *(see below).*

21 *Because the quantity of CPR materials in the repository will greatly exceed that of NO<sub>3</sub><sup>-</sup> and*  
 22 *SO<sub>4</sub><sup>2-</sup>, denitrification and SO<sub>4</sub><sup>2-</sup> reduction will only consume 5.54 mol percent of the CPR*  
 23 *materials with a CO<sub>2</sub> yield of 1.00 mol per mol of organic C consumed (see Table BARRIERS-*  
 24 *3). If all CPR materials are consumed, methanogenesis (Reaction (8)) will convert most of the*  
 25 *CPR materials (94.46 mol percent) to an equimolar mixture of CH<sub>4</sub> and CO<sub>2</sub>, and the overall*  
 26 *CO<sub>2</sub> yield will be 0.528 mol per mol of C.*

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

21 *Since the CCA PA, however, methanogenesis has been observed in numerous experiments*  
22 *carried out under several combinations of conditions (Francis and Gillow 2000, pp. 2, 3, and*  
23 *10; Gillow and Francis 2001, pp. 3-4 and 3-5; Gillow and Francis 2002a, pp. 2.1 - 12 to 2.1 -*  
24 *14; and Gillow and Francis 2002b, pp. 3.1 - 5 to 3.1 - 6). Several definitive conclusions can be*  
25 *drawn from these results.*

26 *It is now clear that the absence of experimental evidence for methanogenesis at the time of*  
27 *CCA PA was because microbial activity in the initially aerobic experiments had not progressed*  
28 *through aerobic respiration, denitrification, and  $SO_4^{2-}$  reduction to methanogenesis; and that*  
29 *microbial activity in the initially anaerobic experiments had not progressed through*  
30 *denitrification and  $SO_4^{2-}$  reduction to methanogenesis. The requirement that these steps be*  
31 *completed prior to the onset of methanogenesis is a consequence of the conceptual model of*  
32 *sequential use of electron acceptors (see above), according to which methanogenesis does not*  
33 *start until any and all  $NO_3^-$  and  $SO_4^{2-}$  are depleted, or until some other process renders the*  
34 *environment unsuitable for denitrification and  $SO_4^{2-}$  reduction. Although methanogenesis*  
35 *had not been observed by the time of the CCA PA in experiments carried out for up to 1,228*  
36 *days (3.36 years), it was later observed in inundated experiments after 2,718 days (7.44 years)*  
37 *and in humid experiments after 2,653 days (7.26 years).*

38 *Therefore, it is also clear now that: (1) there exist communities of halophilic, fermentative,*  
39 *and methanogenic microbes capable of metabolizing complex organic substrates, such as*  
40 *cellulosic materials, under expected WIPP conditions; (2) such microbes are present - and*  
41 *viable - in one or more of the materials used to inoculate these experiments; and (3) these*  
42 *microbes are capable of surviving exposure to  $O_2$ . Methanogens are obligate anaerobes and,*  
43 *as such, are extremely sensitive to exposure to  $O_2$ . The fact that they produced  $CH_4$  after*

1 *exposure to O<sub>2</sub> implies that they are capable of producing resistant forms that can survive*  
2 *initially oxic conditions in these experiments.*

3 *Furthermore, results from the microbial gas-generation study have confirmed that viable*  
4 *halophilic fermenters and methanogens capable of metabolizing cellulosic materials under*  
5 *expected near-field conditions are present in the WIPP underground workings. Francis and*  
6 *Gillow (2000, pp. 2 and 10) detected CH<sub>4</sub> in initially oxic, unamended, and uninoculated*  
7 *experiments, and in initially anoxic, unamended, and uninoculated experiments. The most*  
8 *likely explanation for microbial gas production in these uninoculated experiments is that G*  
9 *Seep, the brine used for these inundated experiments, was collected from the WIPP*  
10 *underground workings. This brine contained a small but viable microflora, including*  
11 *methanogens, and was not sterilized prior to use. The fact that these microbes produced CH<sub>4</sub>*  
12 *after exposure to O<sub>2</sub> in the air used to ventilate G Drift and in initially oxic experiments*  
13 *implies that they are capable of producing resistant forms that can withstand initially oxic*  
14 *conditions in the repository.*

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

24 *Finally, exclusive use of Reaction (8) (gas-producing methanogenesis) to represent*  
25 *methanogenesis in PA (the current implementation of this respiratory pathway) is probably*  
26 *conservative because Reaction (8) produces an equimolar mixture of CH<sub>4</sub> and CO<sub>2</sub>. However,*  
27 *another methanogenic reaction,*



29 *which actually consumes CO<sub>2</sub> and H<sub>2</sub>, is likely in the WIPP because it is energetically favored*  
30 *with respect to Reaction (8) (see, for example, Madigan et al. 2003, pp. 454-455). Reaction (9)*  
31 *has been simplified somewhat inasmuch as microbes that use this respiratory pathway*  
32 *typically use acetate (CH<sub>3</sub>CO<sub>2</sub><sup>-</sup>) or other organic acids along with H<sub>2</sub> to reduce CO<sub>2</sub> to CH<sub>4</sub>.*  
33 *(Reactions (6), (7), and (8) have also been simplified somewhat, as is typically the case when*  
34 *used for geochemical applications such as predicting the CO<sub>2</sub> yield from microbial*  
35 *consumption of CPR materials in the WIPP.) Nevertheless, if CO<sub>2</sub> and H<sub>2</sub> (and acetate) are*  
36 *present, Reaction (9) (gas-consuming methanogenesis, or – strictly speaking – gas-consuming*  
37 *acetotrophic methanogenesis) will probably proceed instead of Reaction (8). Alternatively,*  
38 *Reaction (9) could probably proceed along with Reaction (8). In either case, Reaction (9)*  
39 *could consume significant quantities of CO<sub>2</sub>.*

40 *In the event of significant microbial activity in the WIPP, CO<sub>2</sub> and H<sub>2</sub> (and acetate) will be*  
41 *present because: (1) consumption of CPR via Reaction (6), (7), or (8) will produce CO<sub>2</sub>, (2)*

1 *anoxic corrosion of steels and other Fe-base alloys in waste containers and in the waste will*  
2 *produce H<sub>2</sub> (if brine is present), and (3) acetic acid and sodium acetate are present in the TRU*  
3 *waste to be emplaced in the WIPP (see Appendix DATA, Attachment F) and will dissolve in*  
4 *any brines that enter the repository, possibly reaching a concentration of  $3.57 \times 10^{-3}$  M (Brush*  
5 *and Xiong 2003c). Therefore, gas-consuming methanogenesis (Reaction (9)) is likely in the*  
6 *WIPP even if gas-producing methanogenesis (Reaction (8)) occurs, and the MgO-oxide safety*  
7 *factor calculated assuming a CO<sub>2</sub> yield of about 0.50 mol per mol of organic C consumed is*  
8 *probably conservative.*

### 9 ***BARRIERS-3.0 DISPOSAL SYSTEM BARRIERS***

#### 10 ***BARRIERS-3.1 Definition of a Disposal System Barrier***

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

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

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

##### 19 ***BARRIERS-3.2.1 Panel Closures***

20 *Panel closures are included for Resource Conservation and Recovery Act (RCRA) disposal*  
21 *unit closure to prevent potentially unacceptable levels of volatile organic compound (VOC)*  
22 *release during waste management operations, and to protect against the effects of a postulated*  
23 *deflagration in a closed panel. While the panel closures provide a solid structure within the*  
24 *drifts, they were not intended to support long-term repository performance. Of the four*  
25 *options proposed in the CCA, the EPA specified that one of these, Option D, should be used.*  
26 *This Option consists of a concrete barrier emplaced after removing the disturbed rock zone*  
27 *(DRZ), and an explosion wall. EPA also specified that SMC be used for the barrier (EPA*  
28 *1998a), which was a potential alternative to ordinary portland cement noted in the CCA.*

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

36 *The EPA responded in a letter dated November 15, 2002 that concluded that the panel closure*  
37 *system design change request would require a rulemaking. Because the rulemaking likely*  
38 *would not be completed before this application would be submitted, the EPA deferred review*  
39 *of the proposal until after the recertification decision. The EPA did agree to construction of*

1 *the explosion wall and a delay in construction of the Option D concrete monolith after*  
2 *completion of waste emplacement in Panel 1 until a regulatory decision was made on the*  
3 *proposed new panel closure design (Docket A-98-49, II-B-3, Item 44). Until a design change is*  
4 *approved by the EPA and the State of New Mexico, the regulatory baseline includes the*  
5 *modified Option D Panel Closure System.*

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

8 ***BARRIERS-3.2.1.1 Overview***

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

16 ***BARRIERS-3.2.1.2 Design***

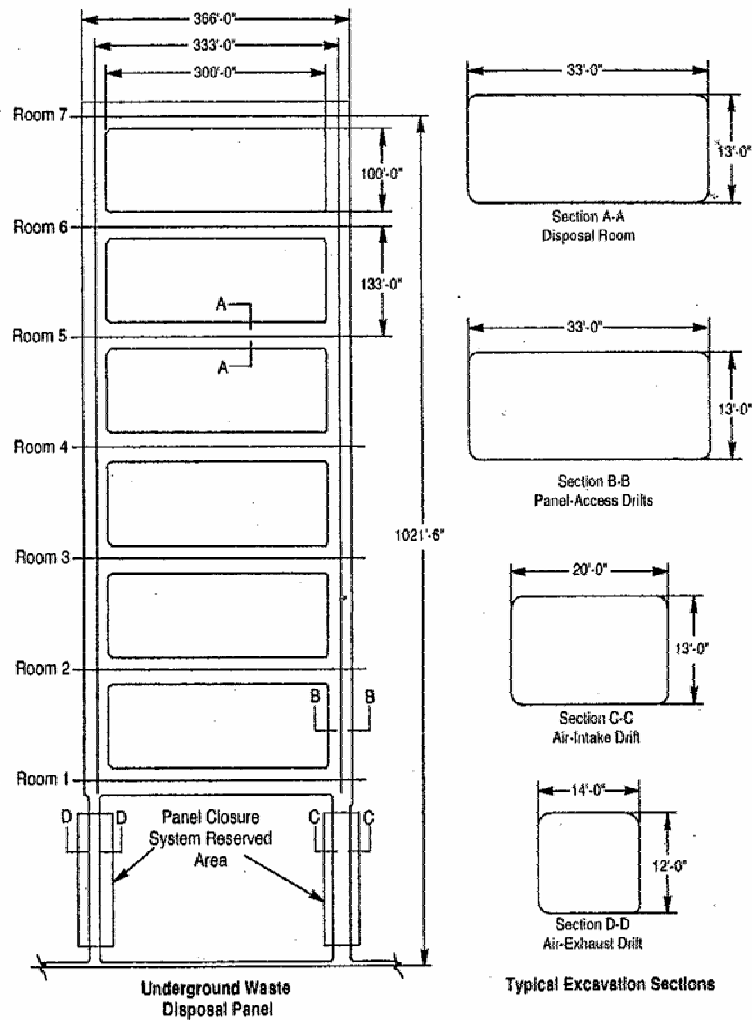
17 *The mandated panel closure system is an enlarged tapered concrete barrier that will be*  
18 *grouted along the interface and an explosion-isolation wall. Figure BARRIERS-2 illustrates*  
19 *this design. The design concept for the enlarged concrete barrier incorporates:*

- 20 • *A concrete barrier that is tapered to promote the rapid stress buildup on the host rock.*  
21 *The stiffness was selected to provide rapid buildup of compressive stress and reduction*  
22 *in shear stress in the host rock.*
- 23 • *The enlarged barrier requires DRZ removal to keep the tapered shape approximately*  
24 *spherical. DRZ removal limits potential VOC flow through the panel closure system.*
- 25 • *The design of the panel closure system includes an explosion-isolation wall designed to*  
26 *provide strength and deformational serviceability during the operational period. The*  
27 *length was selected to assure that uniform compression develops over a substantial*  
28 *portion of the structure and that end-shear loading that might result in fracturing of*  
29 *salt into the back is reduced. While no requirements for barricading waste areas exist*  
30 *under the MSHA, the intent of the regulations is to safely isolate abandoned areas*  
31 *from active workings using barricades of “substantial construction.” The CCA*  
32 *examined the potential issue of methane gas generation from TRU waste in closed*  
33 *areas. The principal concern is the postulated occurrence of an explosive mixture of*  
34 *methane and an ignition source, which would result in deflagration. An explosion-*  
35 *isolation wall has been designed of sufficient thickness to resist dynamic loads from*  
36 *such a deflagration and creep loads from closure of the salt around the wall.*

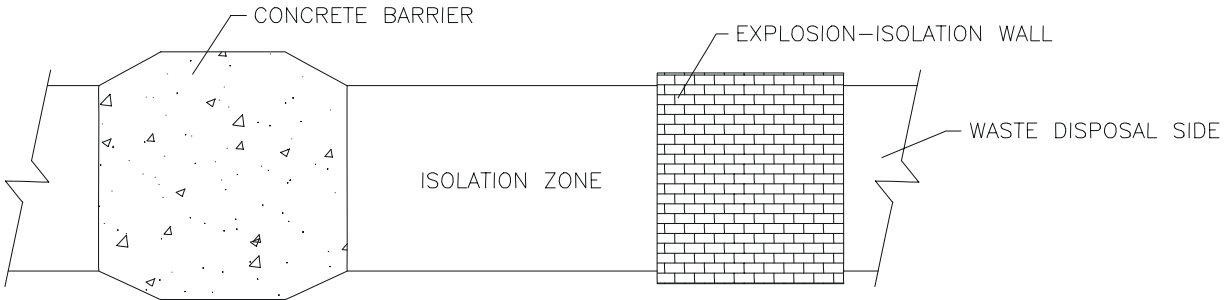
1 *The CRA-2004 PA calculations implement a conceptual design consistent with Option D, as*  
 2 *described above. As noted above, the DOE has reevaluated this panel closure design and*  
 3 *believes that a modification is warranted.*

4 ***BARRIERS-3.2.1.3 Design Components***

5 *The following subsections present system and components design features.*



6  
 7 ***Figure BARRIERS-1. Typical Facilities--Typical Disposal Panel After Westinghouse (1996c)***  
 8 ***(Note: Figure is not to Scale. All Dimensions Shown are Nominal)***



1  
2 **Figure BARRIERS-2. Option D. Explosion-Isolation Wall and Concrete Barrier with DRZ**  
3 **Removed**

4 **BARRIERS-3.2.1.3.1 Concrete Barrier**

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

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

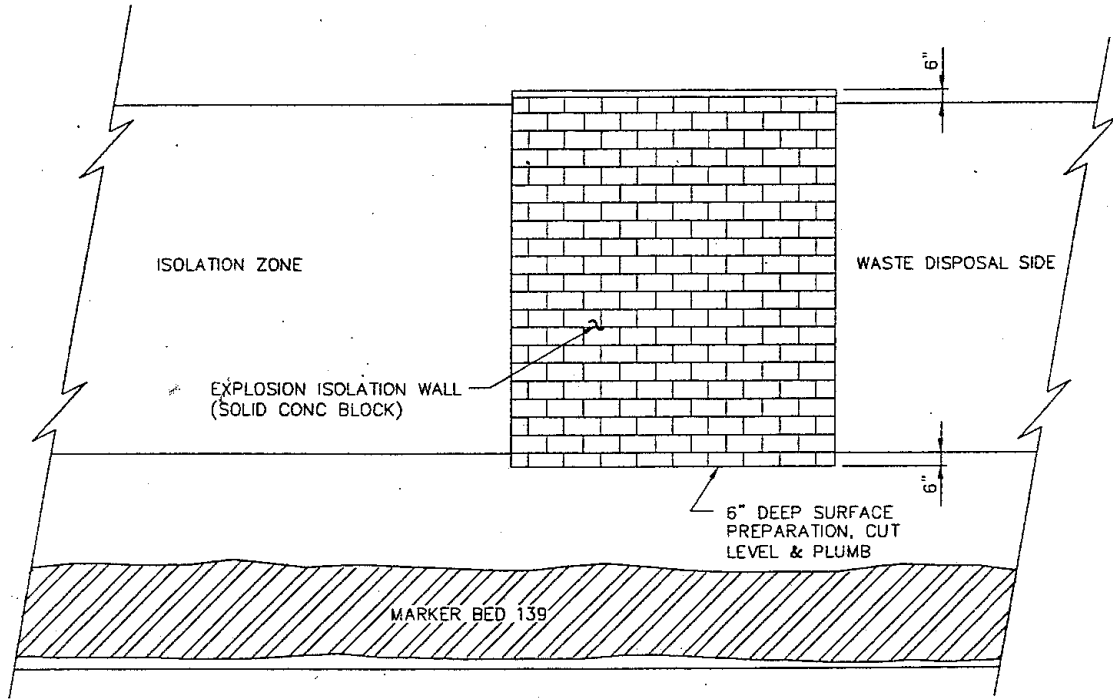
22 **BARRIERS-3.2.1.3.2 Explosion Wall**

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

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

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

- 4 • *The mortar shall conform to ASTM C 270 type M, using the property specification*  
 5 *3000 psi (20.88 MPa) at 28 days, as a minimum requirement. (The wording of the*  
 6 *specification was changed slightly, but the compressive strength requirement is*  
 7 *unchanged.)*



8  
 9 **Figure BARRIERS-3. Explosion-Isolation Wall (not to scale)**

- 10 • *The concrete masonry units shall be solid (no cavities or cores), load-bearing, high-*  
 11 *strength individual units, having a minimum compressive strength of 5500 psi (37.92*  
 12 *MPa) (average of three units) or 5000 psi (34.47 MPa) for individual unit.*  
 13 *(Compressive strength increased from 3500 psi (average of three units) and 3000 psi*  
 14 *for individual units.)*
- 15 • *The compressive strength of masonry in each masonry unit shall exceed 5000 psi. (The*  
 16 *HWFP specifications do not include this test, which must be performed for each*  
 17 *2000 ft<sup>3</sup> (56.63 m<sup>3</sup>) of masonry structure.)*

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



1 ***BARRIERS-3.2.1.3.3 Interface Grouting***

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

8 ***BARRIERS-3.2.1.4 Panel-Closure System Construction***

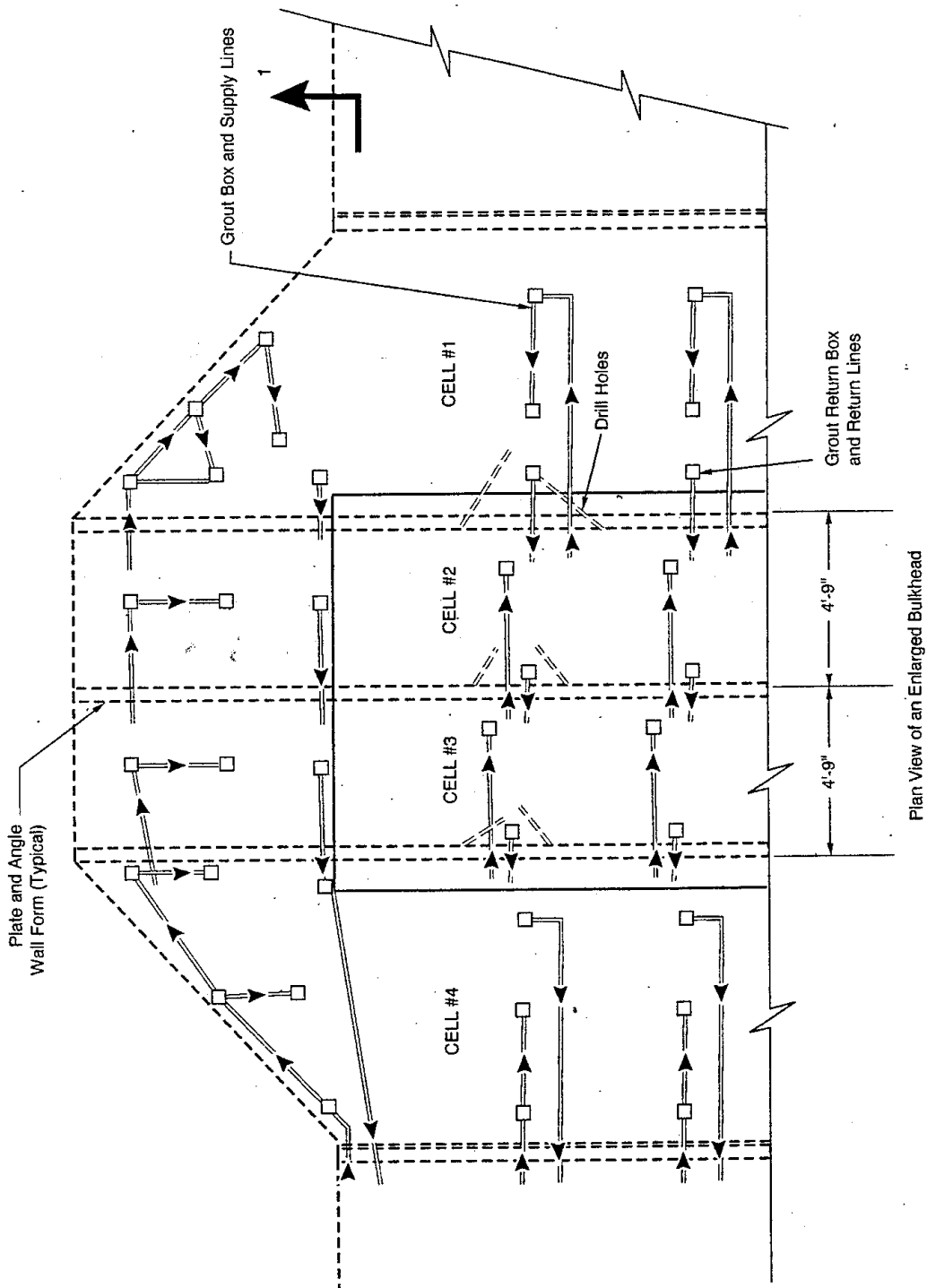
9 *The design uses common construction practices according to existing standards. The*  
10 *proposed construction sequence follows completion of the waste-emplacement activities in*  
11 *each panel: (1) perform subsurface exploration to determine the optimum location for the*  
12 *panel closure system,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

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

21 *Excavation for the enlarged concrete barrier will be performed using mechanical means, such*  
22 *as a cutting head on a suitable boom. The existing roadheader at the main barrier location in*  
23 *each drift is capable of excavating the back and the portions of the ribs above the floor level.*  
24 *Some manual excavation may be required in this situation as well. If mechanical means are*  
25 *not available, drilling boreholes and an expansive agent can be used to fragment the rock*  
26 *(Fernandez et al. 1989). Excavation will follow the lines and grades established for the*  
27 *design. The tolerances for the enlarged concrete-barrier excavation are +6 to 0 inches (+15 to*  
28 *0 cm). In addition, loose or spalling rock from the excavation surface will be removed to*  
29 *provide an appropriate surface abutting the enlarged concrete barrier. The excavations will*  
30 *be performed according to approved ground control plans.*

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

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



*Figure BARRIERS-4. Grouting Details*

1  
2  
3

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

7 ***BARRIERS-3.2.1.5 Conclusion***

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

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

- 24 • *Based on an air-flow model used to predict the mass flow rate of carbon tetrachloride*  
25 *through the panel-closure system for the alternatives, the air-flow analysis suggests*  
26 *that the fully enlarged barrier is protective for restricting potential VOCs during the*  
27 *operational period of 35 years.*
- 28 • *Interface grouting would be performed at the upper boundary of the concrete barrier.*
- 29 • *The results of the transverse plane-strain models show that high stresses could form in*  
30 *nearby brittle marker beds following excavation, but that after installation of the panel*  
31 *closure system, an increase in barrier-confining stress and a reduction in shear stress*  
32 *would result. The concrete barrier would provide substantial uniform confining*  
33 *stresses as the barrier is subjected to secondary salt creep.*
- 34 • *The removal of the fractured salt prior to installation of the main concrete barrier*  
35 *would reduce the potential for flexure.*

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

- 1 • *Existing information on the heat of hydration of the concrete supports placing*  
2 *concrete with a low cement content to reduce the temperature rise associated with*  
3 *hydration. Plasticizers might be used to achieve the required slump at the required*  
4 *strength. A thermal analysis, coupled with a salt creep analysis, suggests installation of*  
5 *the enlarged barrier at or below ambient temperatures to adequately control hydration*  
6 *temperatures.*
  
- 7 • *The trace amounts of brine from the salt at the repository horizon will not degrade the*  
8 *main concrete barrier for at least 35 years.*
  
- 9 • *In 20 years, the open passage above the waste stack in the rooms would be reduced in*  
10 *size. Furthermore, rooms with bulkheads at each end would be isolated in the panel. It*  
11 *is unlikely that a long passage with an open geometry would exist; therefore, the*  
12 *dynamic analysis considered a deflagration with a peak explosive pressure of 240 psi*  
13 *(1.7 MPa).*
  
- 14 • *The heat-transfer analysis shows that elevated temperatures would occur within the*  
15 *salt and the explosion-isolation wall; however, the elevated temperatures will be*  
16 *isolated by the panel closure system. Temperature gradients will not significantly affect*  
17 *the stability of the wall.*
  
- 18 • *The fractures in the roof and floor could be affected by expanding gas products*  
19 *reaching pressures on the order of 240 psi (1.7 MPa). Because the peak internal*  
20 *pressure from the deflagration is only one fifth of the pressure, fractures could not*  
21 *propagate beyond the barrier.*

## 22 ***BARRIERS-3.2.2 Shaft Seals***

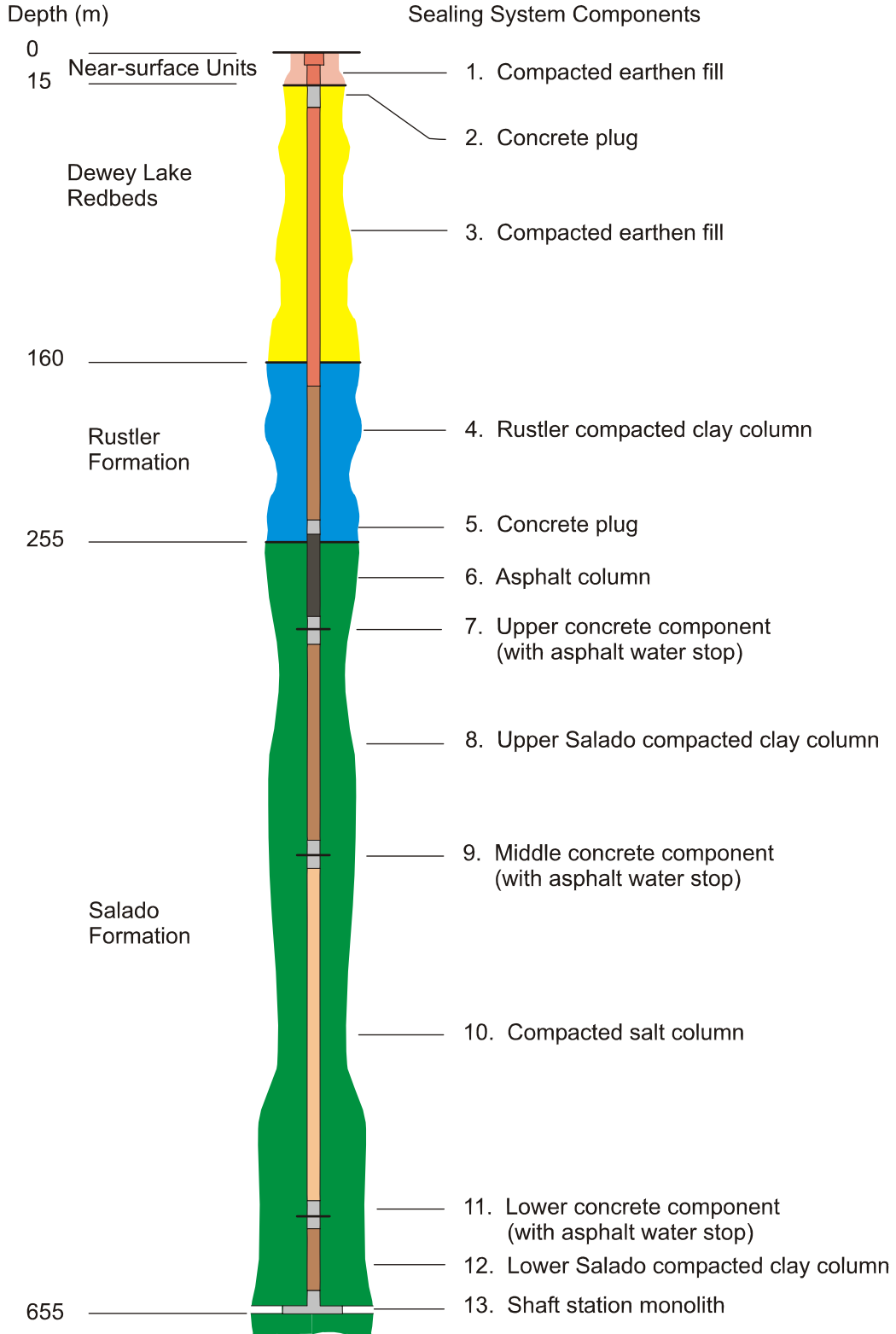
23 *There have been no changes to the shaft seals since the CCA. A description of the shaft seals,*  
24 *initially provided in CCA Appendix SEAL, is discussed in Sections 3.2.2.1 through 3.2.2.4 of*  
25 *this appendix. The representation of the shaft seals in PA has been simplified; see Appendix* 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

### 27 ***BARRIERS-3.2.2.1 Overview***

28 *The WIPP underground facilities are accessed by four shafts commonly referred to as the*  
29 *waste, air intake, exhaust, and salt handling shafts. These shafts were constructed between*  
30 *1981 and 1988. Each of the four shafts from the surface to the underground repository must*  
31 *be sealed to limit hazardous material release to the accessible environment and to limit*  
32 *groundwater flow into the repository. Although the seals will be permanent, the regulatory*  
33 *period applicable to the repository system analyses is 10,000 years.*

### 34 ***BARRIERS-3.2.2.2 Seal Components***

35 *The shaft sealing system comprises 13 elements that completely fill the shaft with engineered*  
36 *materials possessing high density and low permeability (Figure BARRIERS-5). Salado*  
37 *components provide the primary regulatory barrier by limiting fluid transport along the shaft*



1  
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CCA-094-2

**Figure BARRIERS-5. Shaft Sealing System Components**

1 *during and beyond the 10,000-year regulatory period. Components within the Rustler*  
2 *Formation limit commingling between brine-bearing members, as required by state*  
3 *regulations. Components from the Rustler Formation to the surface fill the shaft with*  
4 *common materials of high density, consistent with good engineering practice. A synopsis of*  
5 *each component is given 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-*  
11 *handling shaft have sumps which will also be filled with salt-saturated concrete as part of the*  
12 *monolith. The monoliths function to support the shaft wall and adjacent drift roof, thus*  
13 *preventing damage 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.*  
21 *The locations for the upper and lower clay columns were selected based on the need to limit*  
22 *fluid migration into the compacting salt column. The lower clay column stiffness is sufficient*  
23 *to 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*  
26 *and 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*  
30 *period and thereafter. Design length of the Rustler clay column is about 71 m (234 to 235 ft)*  
31 *in the four 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*  
35 *plug. The concrete specified is SMC. In all cases, the component's overall design length is*  
36 *15 m (50 ft).*

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

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

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

23 *The position of the concrete components was first determined by the location of the salt and*  
24 *clay columns. The components were then moved upward or downward from their initial*  
25 *design location to assure the components were located in regions where halite was*  
26 *predominant. This positioning, coupled with variations in stratigraphy, is responsible for the*  
27 *variations in the 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*  
30 *added to the natural material. The compacted salt column will be constructed of crushed salt*  
31 *taken from the Salado. The length of the salt column varies from 170 to 172 m (556 to 567 ft)*  
32 *in the four shafts. The compacted salt column is sized to allow the column and concrete-*  
33 *asphalt waterstops at either end to be placed between the Vaca Triste Unit and MB 136. The*  
34 *salt will be placed and compacted to a density approaching 90 percent of the average density of*  
35 *intact Salado salt. The effects of creep closure will cause this density to increase with time,*  
36 *further reducing permeability. The salt column will offer limited resistance to fluid migration*  
37 *immediately after emplacement, but it will become less permeable as creep closure further*  
38 *compacts the salt. Salt creep increases rapidly with depth; therefore, at any time, creep*  
39 *closure of the shaft will be greater at greater depth. The location and initial compaction*  
40 *density of the compacted salt column were chosen to assure consolidation of the compacted*  
41 *slat column in the 100 years following repository closure. The state of salt consolidation,*  
42 *results of analyses predicting the creep closure of the shaft, consolidation and healing of the*

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

#### 6 **BARRIERS-3.2.2.2.5 Asphalt Column**

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

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

#### 19 **BARRIERS-3.2.2.2.6 Concrete Plugs**

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

#### 30 **BARRIERS-3.2.2.2.7 Earthen Fill**

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



1 *materials to inhibit the migration of surface waters into the shaft cross-section. The length of*  
2 *this column varies from 136 to 148 m (447 to 486 ft) in the four shafts.*

3 ***BARRIERS-3.2.2.3 Material***

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

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

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

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

37 *Among longevity concerns, degradation of concrete is the most recognized. At this stage of the*  
38 *design, it is established that only small volumes of brine ever reach the concrete elements*  
39 *(CCA Appendix SEAL, Appendix C, Section C4). Further analysis concerned with borehole*  
40 *plugging using cementitious materials shows that at least 100 pore volumes of brine in an*  
41 *open system would be needed to begin degradation processes. In a closed system, such as the*

1 *hydrologic setting in the WIPP shafts, phase transformations create a degradation product of*  
2 *increased volume. Net volume increase owing to phase transformation in the absence of mass*  
3 *transport would decrease rather than increase permeability of concrete seal elements.*

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

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

#### 19 ***BARRIERS-3.2.2.4 Conclusion***

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

#### 32 ***BARRIERS-3.2.3 Borehole Plugs***

##### 33 ***BARRIERS-3.2.3.1 Overview***

34 *Exploration drilling has been in progress in the vicinity of the WIPP since 1928 (nine*  
35 *township area). This drilling is done primarily for oil, gas, and potash exploration, although*  
36 *several water wells have been drilled. The drilling and abandonment practices for oil and gas*  
37 *wells or potash exploration holes are regulated by either the Bureau of Land Management*  
38 *(BLM) for federal land or the State of New Mexico for State and private land. The WIPP site*  
39 *has no control over the plugging and abandonment (P&A) of oil and gas wells in the vicinity*

1 *of the site. See Section 3.2.3.3 of this appendix for a description of the regulations that apply*  
2 *to these oil and gas wells.*

3 *The New Mexico State Engineers Office has regulatory authority over the P&A of*  
4 *groundwater production and monitoring wells in the state. The State of New Mexico has*  
5 *several groundwater basins, with each basin having its own district office providing oversight*  
6 *of groundwater issues. The WIPP area is under the jurisdiction of the Roswell, New Mexico*  
7 *branch of the State Engineers Office. The Roswell office will be the principal regulatory body*  
8 *to approve the WIPP plans for well P&A. In all cases, the permit process will be carried out*  
9 *through the appropriate regulatory agency. This will be the State of New Mexico, State*  
10 *Engineers Office for P&A of all water wells (DOE 1999).*

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

24 ***BARRIERS-3.2.3.2 Monitoring Wells***

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

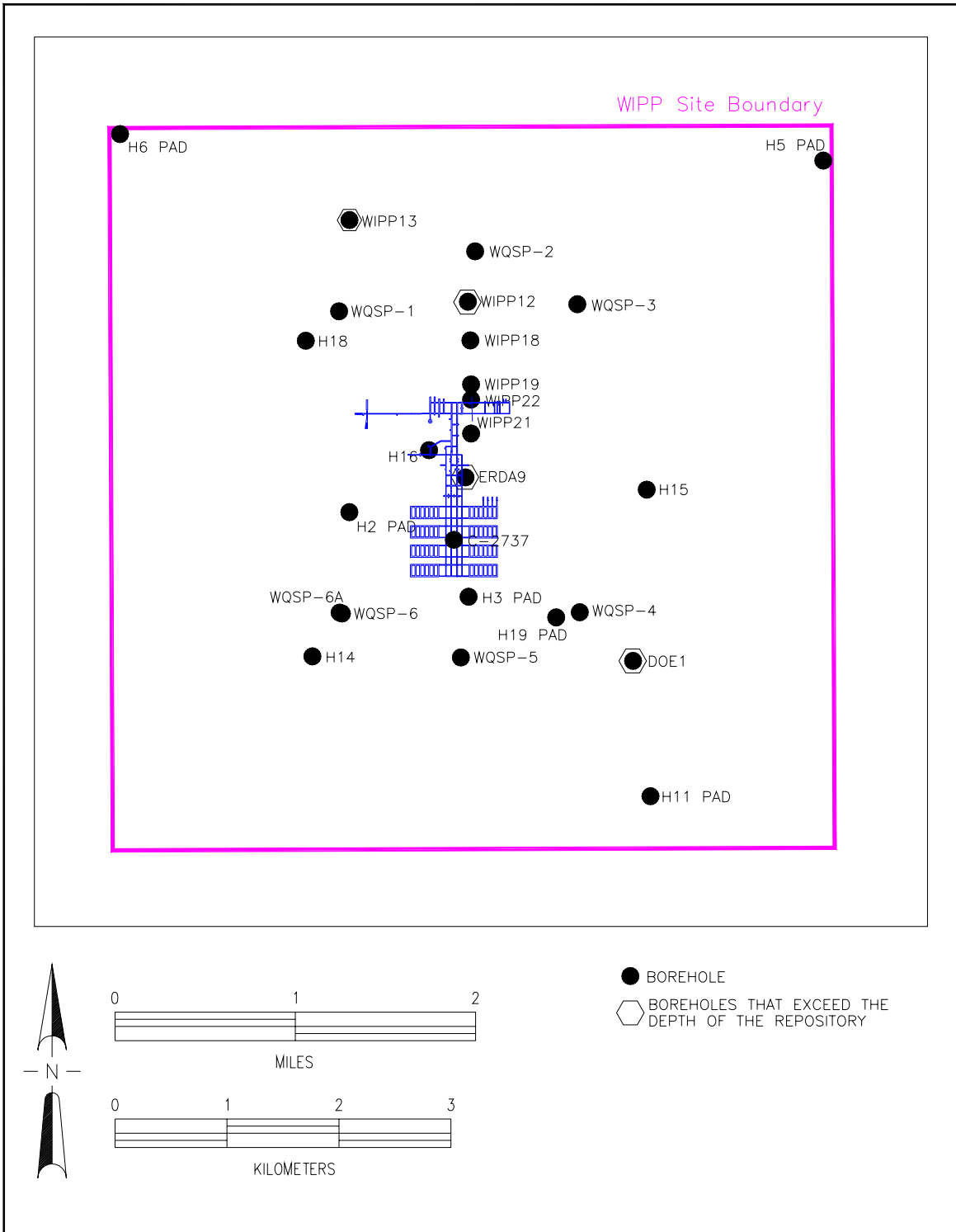
31 *Existing boreholes within the controlled area are identified in Figure BARRIERS-6. Of these*  
32 *boreholes, four exceed the depth of the repository and the rest are shallow boreholes that do*  
33 *not reach the repository horizon.*

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

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

38

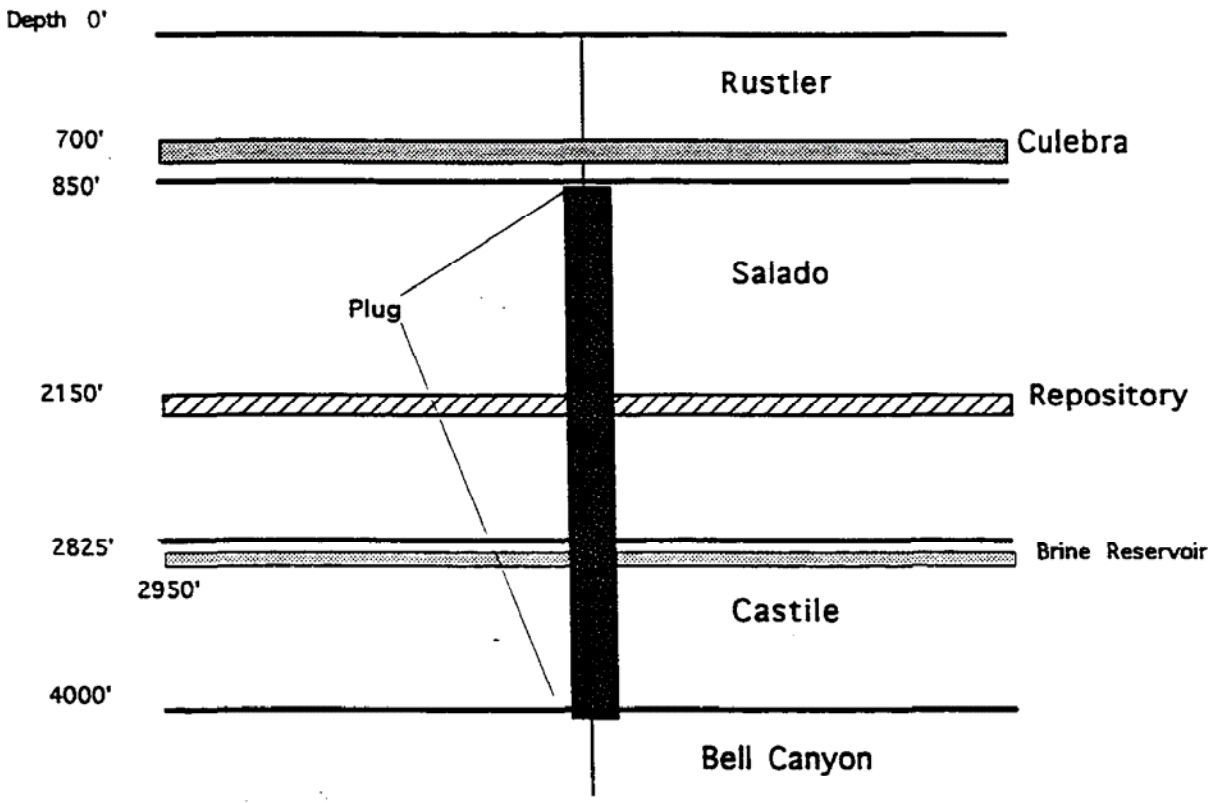
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**Figure BARRIERS-6. Approximate Locations of Unplugged Boreholes**



*Figure BARRIERS-7. Schematic Diagram for a Continuous Plug*

- *A salt protection string of casing must be installed at least 100 feet (30 meters) below and not more than 600 ft (183 m) below the base of the salt section. Cementing requirements for both shallow wells (above 5,000 ft [1,524 m]) and deep wells (below 5,000 ft [1,524 m]) above or below the Delaware Mountain Group are specified.*
- *All oil and gas wells drilled within the potash area must provide a solid cement plug through the salt section and any water bearing horizon and prevent liquids or gases from entering the hole above or below the salt section.*
- *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.*

1 ***BARRIERS-3.2.3.3 Well Plugging and Abandonment Practices***

2 *A description of the plugging and abandonment practices in the area around the WIPP,*  
3 *initially provided in CCA Appendix DEL, is discussed in Sections 3.2.3.3.5 through 3.2.3.4 of*  
4 *this appendix. The representation of borehole plugs in PA is presented in Chapter 6.0, Section*  
5 *6.4.7.2.*

6 ***BARRIERS-3.2.3.3.1 BLM Oil and Gas Plugging and Abandonment***

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

10 ***BARRIERS-3.2.3.3.1.1 Oil and Gas Well Plugging Sequence***

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

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

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

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

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

#### 8 ***BARRIERS-3.2.3.3.1.2 Plugging of Temporarily Abandoned Wells***

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

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

#### 21 ***BARRIERS-3.2.3.3.1.3 Plugging in the Potash Resource Area***

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

#### 30 ***BARRIERS-3.2.3.3.1.4 Most Common Technical Violations for Oil and Gas Well Plugging***

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

1 *Plugging bonds are required to ensure that wells are plugged and abandoned properly and*  
2 *within a reasonable time frame (see CCA Appendix DEL, Sections DEL.6.1.5 and DEL.6.2.1).*  
3 *Both NMOCD and BLM have experienced higher rates recently of what they refer to as*  
4 *“orphan wells.” These are wells that should be plugged and abandoned, but the owners of*  
5 *these wells cannot be located. When this occurs, plugging of these wells becomes the*  
6 *responsibility of the agency upon whose land they are located. Both agencies have orphan-*  
7 *well-plugging funds that are funded partially through plugging bonds that have not been*  
8 *returned and money from their operating budgets. These orphan wells are a matter of*  
9 *concern to both agencies, and they are working to conserve financial resources for plugging.*

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

11 *The NMOCD regulations on well plugging and abandonment are discussed in CCA Appendix*  
12 *DEL, Sections DEL.6.2.2 and DEL.6.2.3. They are similar in many respects to the BLM*  
13 *requirements.*

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

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

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

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

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

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



1 ***BARRIERS-3.2.3.3.3 Plugging of Oil and Gas Service Wells***

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

7 ***BARRIERS-3.2.3.3.4 Plugging of Potash Coreholes***

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

16 ***BARRIERS-3.2.3.3.5 Plugging of Water Wells***

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

24 ***BARRIERS-3.2.3.4 Conclusion***

25 *The WIPP is surrounded by land where oil and gas drilling is taking place. Plugging and*  
26 *abandonment of these oil and gas wells is regulated by either the BLM or the State of New*  
27 *Mexico, depending on the ownership of the land. Water wells also exist in the vicinity of WIPP*  
28 *and are regulated by the State of New Mexico. WIPP has no control over the plugging and*  
29 *abandonment of these wells.*

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

33

## REFERENCES

- 1  
2 *Adams, J.E. 1944. "Upper Permian Ochoa Series of Delaware Basin, West Texas and*  
3 *Southeastern New Mexico," American Association of Petroleum Geologists Bulletin. Vol. 28,*  
4 *1596-1625.*
- 5 *American Institute of Steel Construction (AISC), 1989, "Specification for the Design of*  
6 *Structural Steel Buildings," AISC Manual of Steel Construction, American Institute of Steel*  
7 *Construction, Inc., New York, New York.*
- 8 *Asghari, A., and S.R. Farrah. 1993. "Inactivation of Bacteria by Solids Coated with*  
9 *Magnesium Peroxide," Journal of Environmental Science and Health. Vol. A28, No. 4, 779-*  
10 *793.*
- 11 *Babb, S.C., and C.F. Novak. 1997 and addenda. "User's Manual for FMT Version 2.3: A*  
12 *Computer Code Employing the Pitzer Activity Coefficient Formalism for Calculating*  
13 *Thermodynamic Equilibrium in Geochemical Systems to High Electrolyte Concentrations."*  
14 *Unpublished report. Albuquerque, NM: Sandia National Laboratories. ERMS 243037.*
- 15 *Bates, R.L., and J.A. Jackson, eds. 1984. Dictionary of Geological Terms, Third Ed. New*  
16 *York, NY: Anchor Books (Doubleday).*
- 17 *Berner, R.A. 1980. Early Diagenesis: A Theoretical Approach. Princeton University Press.*  
18 *Princeton, NJ.*
- 19 *Brush, L.H. 1990. Test Plan for Laboratory and Modeling Studies of Repository and*  
20 *Radionuclide Chemistry for the Waste Isolation Pilot Plant. SAND90-0266, Sandia National*  
21 *Laboratories. Albuquerque, NM.*
- 22 *Brush, L.H. 1995. "Systems Prioritization Method - Iteration 2 Baseline Position Paper: Gas*  
23 *Generation in the Waste Isolation Pilot Plant." Unpublished report, March 17, 1995. Sandia*  
24 *National Laboratories. Albuquerque, NM. ERMS 228740*
- 25 *Brush, L.H. 1996. "Ranges and Probability Distributions of  $K_{ds}$  for Dissolved Pu, Am, U, Th,*  
26 *and Np in the Culebra for the PA Calculations to Support the CCA." Unpublished*  
27 *memorandum to M.S. Tierney, June 10, 1996. ERMS 238801, Attachment 15-3 to CCA*  
28 *Appendix MASS. Sandia National Laboratories. Albuquerque, NM.*
- 29 *Brush, L.H., and L.J. Storz. 1996. "Revised Ranges and Probability Distributions of  $K_{ds}$  for*  
30 *Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA Calculations to Support the*  
31 *CCA." Unpublished memorandum to M.S. Tierney, July 24, 1996. ERMS 238231. Sandia*  
32 *National Laboratories. Albuquerque, NM.*
- 33 *Brush, L.H., and Y. Xiong. 2003a. "Calculation of Actinide Solubilities for the WIPP*  
34 *Compliance Recertification Application, Analysis Plan AP-098," Rev 1. Unpublished analysis*  
35 *plan. Sandia National Laboratories. Carlsbad, NM. ERMS 527714.*

- 1 *Brush, L.H., and Y. Xiong. 2003b. "Calculation of Actinide Solubilities for the WIPP*  
2 *Compliance Recertification Application." Unpublished analysis report, May 8, 2003. Sandia*  
3 *National Laboratories. Carlsbad, NM. ERMS 529131.*
- 4 *Brush, L.H., and Y. Xiong. 2003c. "Calculation of Organic Ligand Concentrations for the*  
5 *WIPP Compliance Recertification Application and for Evaluating Assumptions of*  
6 *Homogeneity in WIPP PA." Unpublished analysis report, September 11, 2003. Sandia*  
7 *National Laboratories. Carlsbad, NM. ERMS 531488.*
- 8 *Bryan, C.R., and A.C. Snider. 2001a. "MgO Hydration and Carbonation at SNL/Carlsbad,"*  
9 *"Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.4, Repository*  
10 *Investigations, Milestone RI010, January 31, 2001." Sandia National Laboratories.*  
11 *Carlsbad, NM. ERMS 516749. 66-83.*
- 12 *Bryan, C.R., and A.C. Snider. 2001b. "MgO Experimental Work Conducted at SNL/CB:*  
13 *Continuing Investigations with Premier Chemicals MgO," "Sandia National Laboratories*  
14 *Technical Baseline Reports, WBS 1.3.5.4, Repository Investigations, Milestone RI020, July*  
15 *31, 2001." Sandia National Laboratories. Carlsbad, NM. ERMS 518970. 5-1 to 5-15.*
- 16 *Chapelle, F.H. 1993. Ground-Water Microbiology and Geochemistry. John Wiley and Sons.*  
17 *New York, NY.*
- 18 *Chapman, M.A.S., J. Abercrombie, D.M. Livermore, and N.S. Williams. 1995. "Antibacterial*  
19 *Activity of Bowel-Cleansing Agents: Implications of Antibacteroides Activity of Senna,"*  
20 *British Journal of Surgery. Vol. 82, 1053.*
- 21 *Choppin G.R. 1988. "Humic and Radionuclide Migration," Radiochimica Acta. Vol. 44/45,*  
22 *23-28.*
- 23 *Criddle, C.S., L.A. Alvarez, and P.L. McCarty. 1991. "Microbial Processes in Porous*  
24 *Media," Transport Processes in Porous Media. Eds. J. Bear and M.Y. Corapcioglu. Kluwer*  
25 *Academic Publishers. Amsterdam, Netherlands. 639-691.*
- 26 *Daveler, S.A., and T.J. Wolery. 1992. EQPT, A Data File Preprocessor for the EQ3/6*  
27 *Software Package: User's Guide and Related Documentation (Version 7.0).*  
28 *UCRL-MA-110662 PT II. Lawrence Livermore National Laboratory. Livermore, CA.*
- 29 *Fenchel, T., G.M. King, and T.H. Blackburn. 2000. Bacterial Biogeochemistry: The*  
30 *Ecophysiology of Mineral Cycling, Second Ed. Academic Press. San Diego, CA.*
- 31 *Fernandez, J.A., T. E. Hinkebein, and J. B. Case, 1989, "Selected Analyses to Evaluate the*  
32 *Effect of the Exploratory Shafts on Repository Performance at Yucca Mountain," SAND85-*  
33 *0598, Sandia National Laboratories, Albuquerque, New Mexico.*
- 34 *Francis, A.J. and J.B. Gillow. 1994. Effect of Microbial Processes on Gas Generation under*  
35 *Expected Waste Isolation Pilot Plant Repository Conditions: Progress Report through 1992.*  
36 *SAND93-7036. Sandia National Laboratories. Albuquerque, NM.*

- 1 *Francis, A.J., and J.B. Gillow. 2000. "Progress Report: Microbial Gas Generation*  
2 *Program." Unpublished memorandum to Y. Wang, January 6, 2000. Brookhaven National*  
3 *Laboratory. Upton, NY. ERMS 509352.*
- 4 *Francis A.J., Gillow, J.B., and M.R. Giles. 1997. Microbial Gas Generation under Expected*  
5 *Waste Isolation Pilot Plant Repository Conditions. SAND96-2582. Sandia National*  
6 *Laboratories. Albuquerque, NM.*
- 7 *Froelich, P.N. Klinkhammer, G.P., Bender, M.L., Luedtke, N.A., Heath, G.R., Cullen,*  
8 *D., Dauphin, P., Hammond, D., Hartman, B., and V. Maynard. 1979. "Early Oxidation of*  
9 *Organic Matter in Pelagic Sediments of the Eastern Equatorial Atlantic: Suboxic*  
10 *Diagenesis," Geochimica et Cosmochimica Acta. Vol. 43, 1075-1090.*
- 11 *Garber, R.A., Harris, P.M., and J.M. Borer. 1990. "Occurrence and Significance of*  
12 *Magnesite in Upper Permian (Guadalupian) Tansil and Yates Formations, Delaware Basin,*  
13 *New Mexico," American Association of Petroleum Geologists Bulletin. Vol. 74, No. 2, 119-*  
14 *134.*
- 15 *Gillow, J.B., and A.J. Francis. 2001a. "Re-evaluation of Microbial Gas Generation under*  
16 *Expected Waste Isolation Pilot Plant Conditions: Data Summary Report, January 24, 2001,"*  
17 *"Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.4, Repository*  
18 *Investigations Milestone RI010, January 31, 2001." Sandia National Laboratories. Carlsbad,*  
19 *NM. ERMS 516749. 19-46.*
- 20 *Gillow J.B., and A.J. Francis. 2001b. "Re-evaluation of Microbial Gas Generation under*  
21 *Expected Waste Isolation Pilot Plant Conditions: Data Summary and Progress Report*  
22 *(February 1 – July 13, 2001)," "Sandia National Laboratories Technical Baseline Reports,*  
23 *WBS 1.3.5.4, Repository Investigations Milestone R1020, July 31, 2001." Sandia National*  
24 *Laboratories. Carlsbad, NM. ERMS 518970. 3-1 to 3-21.*
- 25 *Gillow J.B., and A.J. Francis. 2002a. "Re-evaluation of Microbial Gas Generation under*  
26 *Expected Waste Isolation Pilot Plant Conditions: Data Summary and Progress Report (July*  
27 *14, 2001 – January 31, 2002), January 22, 2002" "Sandia National Laboratories Technical*  
28 *Baseline Reports, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4, Repository*  
29 *Investigations, Milestone RI110, January 31, 2002." Sandia National Laboratories. Carlsbad,*  
30 *NM. ERMS 520467. 2.1 - 1 to 2.1 - 26.*
- 31 *Gillow J.B., and A.J. Francis. 2002b. "Re-evaluation of Microbial Gas Generation under*  
32 *Expected Waste Isolation Pilot Plant Conditions: Data Summary and Progress Report*  
33 *(February 1 – July 15, 2002), January 18, 2002" "Sandia National Laboratories Technical*  
34 *Baseline Reports, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4, Repository*  
35 *Investigations, Milestone RI130, July 31, 2002." Sandia National Laboratories. Carlsbad,*  
36 *NM. ERMS 523189. 3.1 - 1 to 3.1 - A10.*
- 37 *Gray, M.N. 1993. OECD/NEA International Stripa Project. Overview Volume III: Engineered*  
38 *Barriers. SKB, Swedish Nuclear Fuel and Waste Management Company. Stockholm, Sweden.*

- 1 *Hansen, C.W., and C.D. Leigh. 2003. "A Reconciliation of the CCA and the PAVT*  
2 *Parameter Baselines." Unpublished analysis report, Rev. 3, April 30, 2003. Sandia National*  
3 *Laboratories. Carlsbad, NM. ERMS 528582.*
- 4 *Hazen, R.M., and E. Roedder. 2001. "How Old Are Bacteria from the Permian Age?"*  
5 *Nature. Vol.411, 155.*
- 6 *Hunter, K.S., Y. Wang, and P. Van Cappellan. 1998. "Kinetic Modeling of Microbially*  
7 *Driven Redox Chemistry of Subsurface Environments: Coupling, Transport, Microbial*  
8 *Metabolism, and Geochemistry," Journal of Hydrology. Vol. 209, 53-80.*
- 9 *Koper, O.B., Klabunde, J.S., Marchin, G.L., Klabunde, K.J., Stoimenov, P., and L. Bohra.*  
10 *2002. "Nanoscale Powders and Formulations with Biocidal Activity Toward Species and*  
11 *Vegetative Cells of Bacillus Species, Viruses, and Toxins," Current Microbiology. Vol. 44, 49-*  
12 *55.*
- 13 *Krumhansl, J.L., Kelly, J.W., Papenguth, H.W., and R.V. Bynum. 1997. "MgO Acceptance*  
14 *Criteria." Unpublished memorandum to E.J. Nowak, December 10, 1997. Sandia National*  
15 *Laboratories. Albuquerque, NM. ERMS 248997.*
- 16 *Lang, W.B. 1939. "Salado Formation of the Permian Basin," American Association of*  
17 *Petroleum Geologists Bulletin. Vol. 23, 1569-1572.*
- 18 *Lowenstein, T.K. 1983. "Deposition and Alteration of an Ancient Potash Evaporite: The*  
19 *Permian Salado Formation of New Mexico and West Texas." Unpublished Ph.D.*  
20 *dissertation. The Johns Hopkins University. Baltimore, MD.*
- 21 *Lowenstein, T.K. 1988. "Origin of Depositional Cycles in a Permian 'Saline Giant': The*  
22 *Salado (McNutt Zone) Evaporites of New Mexico and Texas," Geological Society of America*  
23 *Bulletin. Vol. 100, 592-608.*
- 24 *Madigan, M.T., J.M. Martinko, and J. Parker. 2003. Brock Biology of Microorganisms, 10<sup>th</sup>*  
25 *Edition. Prentice Hall. Upper Saddle River, NJ.*
- 26 *Mine Safety and Health Administration, 1987. "Safety Standards for Methane in Metal and*  
27 *Non-metal Mines," Title 30. Code of Federal Regulations 30 CFR 57, U.S. Department of*  
28 *Labor, Mine Safety and Health Administration, Washington, D.C.*
- 29 *Molecke, M.A. 1983. A Comparison of Brines Relevant to Nuclear Waste Experimentation.*  
30 *SAND83-0516. Sandia National Laboratories. Albuquerque, NM.*
- 31 *Papenguth, H.W. 1999. "Evaluation of Candidate MgO Materials for Use as Backfill at*  
32 *WIPP." Unpublished memorandum to M.G. Marietta, November 12, 1999. Sandia National*  
33 *Laboratories. Albuquerque, NM. ERMS 520314.*
- 34 *Peterson, A.C. 1996. "Mass of MgO That Could Be Added as Backfill in the WIPP and the*  
35 *Mass of MgO Required to Saturate the Brine and React with the CO<sub>2</sub> Generated by Microbial*

- 1 *Processes.” Unpublished analysis report, March 11, 1996. Sandia National Laboratories.*  
2 *Albuquerque, NM. ERMS 236214.*
- 3 *Popielak, R.S., Beauheim, R.L., Black, S.R., Coons, W.E., Ellingson C.T., and R.L. Olsen.*  
4 *1983. Brine Reservoirs in the Castile Formation, Waste Isolation Pilot Plant Project,*  
5 *Southeastern New Mexico. TME 3153. U.S. Department of Energy WIPP Project Office.*  
6 *Carlsbad, NM.*
- 7 *Powers, D.W., Vreeland, R.H., and W.D. Rosenzweig. 2001. “Reply to ‘How Old Are Bacteria*  
8 *from the Permian Age?’” Nature. Vol. 411. 155.*
- 9 *Sawai, J. 2003. “Quantitative Evaluation of Antibacterial Activities of Metallic Oxide*  
10 *Powders (ZnO, MgO, CaO) by Conductimetric Assay,” Journal of Microbiological Methods.*  
11 *Vol. 54, 177-182.*
- 12 *Sawai, J., Igarashi, H., Hashimoto, A., Kokugan, T., and M. Shimizu. 1995a. “Evaluation of*  
13 *Growth Inhibitory Effect of Ceramics Powder Slurry on Bacteria by Conductance Method,”*  
14 *Journal of Chemical Engineering of Japan. Vol. 28, No. 3, 288-293.*
- 15 *Sawai, J., Igarashi, H., Hashimoto, A., Kokugan, T., and M. Shimizu. 1996. “Effect of*  
16 *Particle Size and Heating Temperature of Ceramic Powders on Antibacterial Activity of Their*  
17 *Slurry,” Journal of Chemical Engineering of Japan. Vol. 29, No. 2, 288-293.*
- 18 *Sawai, J., Kojima, H., Igarashi, H., Hashimoto, A., Shoji, S., Sawaki, T., Hakoda, A.,*  
19 *Kawada, E., Kokugan, T., and M. Shimizu. 2000a. “Antibacterial Characteristics of*  
20 *Magnesium Oxide Powder,” World Journal of Microbiology and Biotechnology. Vol. 16, 187-*  
21 *194.*
- 22 *Sawai, J., Kojima, H., Igarashi, H., Hashimoto, A., Shoji, S., Sawaki, T., Kokugan, T., and*  
23 *M. Shimizu. 2000b. “Escherichia coli Damage by Ceramic Powder Slurries,” Journal of*  
24 *Chemical Engineering of Japan. Vol. 30, No. 6, 1034-1039.*
- 25 *Sawai, J., Kojima, H., Saito, I., Kanou, F., Igarashi, H., Hashimoto, A., Kokugan, T., and*  
26 *M. Shimizu. 1995b. “Mutagenecity Test of Ceramic Powder[s] Which Have Growth*  
27 *Inhibitory Effect on Bacteria,” Journal of Chemical Engineering of Japan. Vol. 28, No. 3,*  
28 *352-354.*
- 29 *Schlesinger, W.H. 1997. Biogeochemistry: An Analysis of Global Change. Academic Press.*  
30 *New York, NY.*
- 31 *Snider, A.C. 2002. “MgO Studies: Experimental Work Conducted at SNL/Carlsbad.*  
32 *Efficacy of Premier Chemicals MgO as an Engineered Barrier,” Sandia National*  
33 *Laboratories Technical Baseline Reports, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4,*  
34 *Repository Investigations, Milestone RI110, January 31, 2002. Sandia National Laboratories.*  
35 *Carlsbad, NM. ERMS 520467. 3.1-1 to 3.1-18.*
- 36 *Snider, A.C. 2003a. “Hydration of Magnesium Oxide in the Waste Isolation Pilot Plant,”*  
37 *Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.3, Compliance*

- 1 *Monitoring; WBS 1.3.5.4, Repository Investigations, Milestone RI 03-210, January 31, 2003.*  
2 *Sandia National Laboratories. Carlsbad, NM. ERMS 526049. 4.2-1 to 4.2-6.*
- 3 *Snider, A.C. 2003b. "Verification of the Definition of Generic Weep Brine and the*  
4 *Development of a Recipe for This Brine." Unpublished analysis report, April 8, 2003. Sandia*  
5 *National Laboratories. Carlsbad, NM. ERMS 527505.*
- 6 *Snider, A.C. 2003c. "Calculation of the Quantities of MgO Required for Consumption of*  
7 *CO<sub>2</sub> for the WIPP Compliance Recertification Application." Unpublished analysis report,*  
8 *July 3, 2003. Sandia National Laboratories. Carlsbad, NM. ERMS 530220.*
- 9 *Snider, A.C. 2003d. "Calculation of MgO Safety Factors for the WIPP Compliance*  
10 *Recertification Application and for Evaluating Assumptions of Homogeneity in WIPP PA."*  
11 *Unpublished analysis report, September 11, 2003. Sandia National Laboratories. Carlsbad,*  
12 *NM. ERMS 531508.*
- 13 *Snider, A.C., and Y. L. Xiong. 2002. "Carbonation of Magnesium Oxide," "Sandia National*  
14 *Laboratories Technical Baseline Reports, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4,*  
15 *Repository Investigations, Milestone RI130, July 31, 2002." Sandia National Laboratories.*  
16 *Carlsbad, NM. ERMS 523189. 4.1-1 to 4.1-28.*
- 17 *State of New Mexico, Oil Conservation Division, Energy, Minerals, and Natural Resources*  
18 *Department. 1988. Order R-111-P, Potash Areas of Eddy and Lea Counties, NM. Case 9316,*  
19 *Revision to Order R-111-P. April 21, 1988. Santa Fe, NM.*
- 20 *Stein, C.L. 1985. Mineralogy in the Waste Isolation Pilot Plant (WIPP) Facility Stratigraphic*  
21 *Horizon. SAND85-0321. Sandia National Laboratories. Albuquerque, NM.*
- 22 *Stoimenov, P.K., Klinger, R.L., Marchin, G.L., and K.J. Klabunde. 2002. "Metal Oxide*  
23 *Nanoparticles as Bactericidal Agents," Langmuir. Vol. 18, 6679-6686.*
- 24 *Telander, M.R., and R.E. Westerman. 1993. Hydrogen Generation by Metal Corrosion in*  
25 *Simulated Waste Isolation Pilot Plant Environments. SAND92-7347. Sandia National*  
26 *Laboratories. Albuquerque, NM.*
- 27 *Telander, M.R., and R.E. Westerman. 1997. Hydrogen Generation by Metal Corrosion in*  
28 *Simulated Waste Isolation Pilot Plant Environments. SAND96-2538. Sandia National*  
29 *Laboratories. Albuquerque, NM.*
- 30 *Triay, I. 2000. Untitled letter with attachments from I. Triay to F. Marcinowski to requesting*  
31 *EPA approval of the elimination of MgO minisacks from the WIPP, July 21, 2000. U.S.*  
32 *Department of Energy Carlsbad Field Office. Carlsbad, NM. ERMS 519362.*
- 33 *Trovato, E.R. 1997a. Untitled letter from E.R. Trovato to G. Dials with enclosures*  
34 *(parameters that are no longer of concern and parameters that DOE must use for the PAVT),*  
35 *April 17, 1997. U.S. Environmental Protection Agency Office of Radiation and Indoor Air.*  
36 *Washington, DC. ERMS 247196.*

- 1 *Trovato, E.R. 1997b. Untitled letter from E.R. Trovato to G. Dials with enclosures*  
2 *(parameters that are no longer of concern and parameters that DOE must use for the PAVT),*  
3 *April 25, 1997. U.S. Environmental Protection Agency Office of Radiation and Indoor Air.*  
4 *Washington, DC.*
- 5 *U.S. Congress. 1992. "WIPP Land Withdrawal Act." Public Law 102-579, 110 Stat. 2422, as*  
6 *amended by 104-201 (1996). U.S. Congress. Washington, DC.*
- 7 *U.S. Department of Energy (DOE). 1980. Final Environmental Impact Statement, Waste*  
8 *Isolation Pilot Plant. DOE/EIS-0026, Vol. 1 and 2. U.S. Department of Energy, Washington,*  
9 *D.C.*
- 10 *U.S. Department of Energy (DOE). 1996a. Title 40 CFR Part 191 Compliance Certification*  
11 *Application for the Waste Isolation Pilot Plant, DOE/CAO-1996-2184. October 1996, Carlsbad*  
12 *Field Office, Carlsbad, NM.*
- 13 *U.S. Department of Energy (DOE). 1996b. Transuranic Waste Baseline Inventory Report,*  
14 *Rev. 3. DOE/CAO-95-1121. U.S. Department of Energy Carlsbad Area Office. Carlsbad,*  
15 *NM.*
- 16 *U.S. Department of Energy (DOE). 1999. Waste Isolation Pilot Plant Borehole Plugging and*  
17 *Abandonment Program Plan, May 1996, Carlsbad Field Office, Carlsbad, NM.*
- 18 *U.S. Department of Energy (DOE), 2000. "MgO Mini-Sack Elimination Proposal."*  
19 *Unpublished report, July 21, 2000. U.S. Department of Energy Carlsbad Area Office.*  
20 *Carlsbad, NM. ERMS 519362.*
- 21 *U.S. Department of Energy Carlsbad Field Office (CBFO). October 7, 2002. (Mailroom*  
22 *number 0205715) Letter from DOE to EPA submitting proposed change request related to*  
23 *Panel Closure, Option D.*
- 24 *U.S. Environmental Protection Agency (EPA). November 15, 2002. Letter from EPA to DOE*  
25 *regarding Proposed Change Request, Panel Closure Option D.*
- 26 *U.S. Environmental Protection Agency (EPA). 1993. "40 CFR Part 191 Environmental*  
27 *Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel,*  
28 *High-Level and Transuranic Radioactive Wastes; Final Rule, Federal Register. Vol. 58,*  
29 *66,398-66,416. U.S. Environmental Protection Agency Office of Radiation and Indoor Air.*  
30 *Washington, DC.*
- 31 *U.S. Environmental Protection Agency (EPA). 1996. "40 CFR Part 194: Criteria for the*  
32 *Certification and Re-Certification of the Waste Isolation Pilot Plants Compliance With the 40*  
33 *CFR Part 191 Disposal Regulations: Final Rule," Federal Register. Vol. 61, No. 28,*  
34 *5224-5245.*
- 35 *U.S. Environmental Protection Agency (EPA). 1997. "Compliance Application Review*  
36 *Documents for the Criteria for the Certification and Recertification of the Waste Isolation*  
37 *Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations: Final Certification*



- 1 *Decision. CARD 44: Engineered Barrier.” EPA Air Docket A-93-02-V-B-2. U.S.*  
2 *Environmental Protection Agency Office of Radiation and Indoor Air. Washington, DC.*
- 3 *U.S. Environmental Protection Agency (EPA). 1998a. “40 CFR 194, Criteria for the*  
4 *Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the*  
5 *Disposal Regulations: Certification Decision: Final Rule,” Federal Register. Vol. 63, 27354-*  
6 *27406.*
- 7 *U.S. Environmental Protection Agency (EPA). 1998b. “Technical Support Document for*  
8 *Section 194.23 – Models and Computer Codes.” EPA Air Docket A93-02-V-B-6. U.S.*  
9 *Environmental Protection Agency Office of Radiation and Indoor Air. Washington, DC.*
- 10 *U.S. Environmental Protection Agency (EPA). 1998c. “Technical Support Document for*  
11 *Section 194.23: Parameter Justification Report.” EPA Air Docket A93-02-V-B-14. U.S.*  
12 *Environmental Protection Agency Office of Radiation and Indoor Air. Washington, DC.*
- 13 *U.S. Environmental Protection Agency (EPA). 1998d. “Technical Support Document for*  
14 *Section 194.24: EPA’s Evaluation of DOE’s Actinide Source Term.” EPA Air Docket A-93-*  
15 *02-V-B-17. U.S. Environmental Protection Agency Office of Radiation and Indoor Air.*  
16 *Washington, DC.*
- 17 *U.S. Environmental Protection Agency (EPA). 2001a. Docket A-98-49, II-B-3, Item 15.*  
18 *Approval of Elimination of Minisacks.*
- 19 *U.S. Environmental Protection Agency (EPA). 2001b. “MgO Minisack Review.” U.S.*  
20 *Environmental Protection Agency Office of Radiation and Indoor Air. Washington, DC.*  
21 *ERMS 519362 (EPA 2001, enclosure).*
- 22 *U.S. Environmental Protection Agency (EPA). 2002. “EPA comments/approval of proposed*  
23 *changes in the closure schedule for Panel in the WIPP.” EPA Air Docket A-98-49, II-B-3,*  
24 *Item 44. U.S. Environmental Protection Agency Office of Radiation and Indoor Air.*  
25 *Washington. DC.*
- 26 *Vreeland, R.H., Rosenzweig, W.D., and D.W. Powers. 2000. “Isolation of a 250-Million-*  
27 *Year-Old Halotolerant Bacterium from a Primary Salt Crystal,” Nature. Vol. 407, 897-900.*  
28 *See also Parkes (2000.).*
- 29 *Wang, Y. 1998. “WIPP PA Validation Document for FMT (Version 2.4), Document Version*  
30 *2.4.” Unpublished report. Carlsbad, NM: Sandia National Laboratories. ERMS 251587.*
- 31 *Wang, Y. 2000. “Methanogenesis and Carbon Dioxide Generation in the Waste Isolation*  
32 *Pilot Plant (WIPP).” Unpublished memorandum to B.A. Howard, January 5, 2000. Sandia*  
33 *National Laboratories. Carlsbad, NM. ERMS 519362.*
- 34 *Wang, Y. and L.H. Brush. 1996a. “Estimates of Gas-Generation Parameters for the Long-*  
35 *Term WIPP Performance Assessment.” Unpublished memorandum to M.S. Tierney, January*  
36 *26, 1996. Sandia National Laboratories. Albuquerque, NM. ERMS 231943.*

- 1 *Wang, Y. and L.H. Brush. 1996b. "Modify the Stoichiometric Factor  $\gamma$  in the BRAGFLO to*  
2 *Include the Effect of MgO Added to WIPP Repository as a Backfill." Unpublished*  
3 *memorandum to M.S. Tierney, February 23, 1996. Sandia National Laboratories.*  
4 *Albuquerque, NM. ERMS 232286.*
- 5 *Wang, Y., and L.H. Brush. 1996c. "An Adjustment for Using Steel Corrosion Rates in*  
6 *BRAGFLO to Reflect Repository Chemical Condition Changes Due to Adding MgO as*  
7 *Backfill." Unpublished memorandum to P. Vaughn, February 29, 1996. Sandia National*  
8 *Laboratories. Albuquerque, NM. ERMS 235181.*
- 9 *Wang, Y., and P Van Cappellan. 1996. "A Multicomponent Reactive-Transport Model of*  
10 *Early Diagenesis: Application of Redox Cycling in Coastal Marine Sediments,"* *Geochimica*  
11 *et Cosmochimica Acta. Vol. 60, 2993-3014.*
- 12 *Wing, N.R., and G.W. Gee. 1994. "Quest for the Perfect Cap,"* *Civil Engineering. Vol. 64, No.*  
13 *10, 38-41.*
- 14 *Wolery, T.J. 1992a. EQ3/6, A Software Package for Geochemical Modeling of Aqueous*  
15 *Systems: Package Overview and Installation Guide (Version 7.0). UCRL-MA-110662 PT I.*  
16 *Lawrence Livermore National Laboratory. Livermore, CA.*
- 17 *Wolery, T.J. 1992b. EQ3NR, A Computer Program for Geochemical Aqueous Speciation-*  
18 *Solubility Calculations: Theoretical Manual, User's Guide, and Related Documentation*  
19 *(Version 7.0). UCRL-MA-110662 PT III. Lawrence Livermore National Laboratory.*  
20 *Livermore, CA.*
- 21 *Wolery, T.J., and S.A. Daveler. 1992. EQ6, A Computer Program for Reaction-Path*  
22 *Modeling of Aqueous Geochemical Systems: Theoretical Manual, User's Guide, and Related*  
23 *Documentation (Version 7.0). UCRL-MA-110662 PT IV. Lawrence Livermore National*  
24 *Laboratory. Livermore, CA.*
- 25 *Washington TRU Solutions LLC (WTS). 2003 "Specification for Prepackaged MgO*  
26 *Backfill." Unpublished specification, D-0101, Rev. 5. Washington TRU Solutions LLC*  
27 *(WTS). Carlsbad, NM.*
- 28 *Xiong, Y.-L., and A.C. Snider. 2003. "Carbonation Rates of the Magnesium Oxide Hydration*  
29 *Product Brucite in Various Solutions," "Sandia National Laboratories Technical Baseline*  
30 *Reports, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4, Repository Investigations,*  
31 *Milestone RI 03-210, January 31, 2003." Sandia National Laboratories. Carlsbad, NM.*  
32 *ERMS 526049. 4.3-1 to 4.3-11.*
- 33 *Yamamoto, O. Sawai, J., Hotta, M., Kojima, H., and T. Sasamoto. 1998. "Growth Inhibition*  
34 *of Bacteria by MgO-ZnO Solid-Solution Powders,"* *Journal of the Ceramic Society of Japan.*  
35 *Vol. 106, no. 12, 1252-1254.*