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SIMCO
Salado Isolation
Mining Contractors

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April 20, 2023

Dr. Anderson Ward
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U.S. Department of Energy
P.O. Box 3090
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Subject: Report Entitled, *Analyses to Bound the Permeability of Degraded Fill Materials in Intrusion Boreholes for WIPP Performance Assessment*

Dear Dr. Ward:

The purpose of this memo is to transmit the report entitled, *Analyses to Bound the Permeability of Degraded Fill Materials in Intrusion Boreholes for WIPP Performance Assessment.* This report was co-authored by Mike Gross of MG Enterprises and Gordan Gjerapic of WSP under subcontract with Salado Isolation Mining Contractors, LLC (SIMCO). Per the terms of each subcontract, this work was required to be performed in accordance the *Nuclear Waste Partnership LLC Quality Assurance Program Description* (WP 13-1), the requirements of which are based on the Carlsbad Field Office *Quality Assurance Program Document* (DOE/CBFO 94-1012).

Los Alamos Technical Associates and SIMCO have reviewed this document and determined it to be technically acceptable and aligned with the requirements of WP 13-1.

If you have any questions, please contact me at (575) 234-3225.

Sincerely,

Rick Chavez, Manager
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jla

Enclosure

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ANALYSES TO BOUND THE PERMEABILITY OF DEGRADED FILL MATERIALS IN INTRUSION BOREHOLES FOR WIPP PERFORMANCE ASSESSMENT

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Executive Summary

This report provides data and analyses to redefine the upper bound for permeability of the degraded steel casings and degraded cement plugs in intrusion boreholes for WIPP performance assessment (PA). A review of the current upper bounds for borehole fill permeabilities used in WIPP PA indicates higher permeability values than can be achieved in laboratory or field testing relevant for the WIPP-specific environment. The current upper bounds correspond to permeability values for granular sandy or gravelly materials that are typically assigned to drainage layers in engineering applications. In contrast, the main purpose of cement plugs in boreholes is to prevent flow by stabilizing and sealing the borehole.

The focus of this work is on the PA parameter BH_SAND:PRMX_LOG, which defines the borehole fill permeability for WIPP PA. The proposed upper limit for BH_SAND:PRMX_LOG is based on new data that have become available since the original report on the permeability of inadvertent intrusion boreholes by Thompson et al. (1996). Additionally, this parameter has since been modified by the U.S. Environmental Protection Agency for the Performance Assessment Verification Test in 1997 (SNL 1997).

For the purposes of PA, the cement plugs above the repository are assumed to degrade 200 years after the time of the drilling intrusion (DOE 2019, Appendix PA, Table PA-26). From that time onward, the borehole is assumed to be filled with a silty sand-like material consisting of degraded cement and casing corrosion products (Thompson et al. 1996). After 200 years, the degraded borehole fill materials continue to be exposed to long-term deformation of the borehole caused by creep closure in the surrounding host rock. A more realistic upper bound is proposed based on a review of historical performance and field-testing data, and available laboratory testing relevant for the cement plug configurations. Updated literature data and numerical models for geomechanical response of an open borehole is also presented. This is supporting information because no change is proposed to the factor of 10 reduction in the permeability of the lower borehole that begins at 1,200 years after the time of the intrusion.

Upper limits for degraded borehole fill materials were developed based on the available information and data, including:

- Documented historical performance – see e.g., Bonen (1996)
- Field-testing data – see e.g., Christensen and Hunter (1980) and Popielak et al. (1983)
- Laboratory testing – see e.g., Onofrei et al. (1992) and Stormont et al. (2018)
- Updated literature data on cement materials and numerical models – see e.g. Matteo and Scherer (2012), Reedlunn et al. (2022)
- Updated literature data on iron-based materials in environmental applications – see e.g. TAPRBI (2002) and Moraci et al. (2016)

Estimates of the upper bound permeability for degraded borehole fill materials involve complex chemical and hydro-geo-mechanical processes affecting the long-term performance of cement plugs and steel casing. Considering the complexity of the problem, available laboratory and

numerical estimates were scrutinized against data collected for WIPP-specific conditions with an emphasis placed on long-term geo-mechanical and hydrological performance. Based on case studies for geological formations containing potash minerals (Popp et al. 2018, Reedlunn 2022) as well as WIPP-specific monitoring data (Wagner and Hillesheim 2009), it is reasonable to expect the cement plugs in the Salado formation will experience significantly larger confinement than originally predicted by Thompson et al. (1996). Consequently, degraded cement and steel casing are likely to exhibit larger normal and shear stresses than originally anticipated. In this state, the borehole fill materials will exhibit a more favorable hydrological performance than predicted by Thompson et al. (1996). These findings are also supported by recent data for the geomechanical behavior of halite under lower deviatoric stresses (Reedlunn et al. 2017, 2022).

Due to the sparsity of data on hydraulic performance of corroded steel, the upper bound permeability estimate for the corroded steel casing is conservatively assumed to correspond to that of granular iron. While the intact steel casing can be considered impervious, the granular iron is a man-made material manufactured to promote filtration using a porous structure with a very high hydraulic conductivity (see e.g., TAPRBI 2002). Hence, the long-term permeability for the granular iron (reported under conditions that are similar to or more favorable than WIPP conditions, see e.g., Moraci et al. 2016) is adopted as an upper bound estimate for the corroded steel casing permeability. Long-term permeability of degraded steel is expected to be lower than the long-term permeability of granular iron reported by Moraci et al. (2016) because the solids and gas formation in the WIPP environment is likely to be significantly higher due to higher concentration of chlorides and higher gas exsolution rates (Popielak et al. 1983) than observed in laboratory and field experiments referenced by Moraci et al. (2016).

The maximum permeability for the borehole fill materials, in terms of chemical degradation under expected stresses, is expected for the "equivalent" borehole fill resembling the behavior of granular soil with a grain-size distribution approximating the particle size distribution of cement powders (i.e., assuming that the degraded cement grout behaves as a material before inception of the hydration process). In this case, the maximum hydraulic conductivity can be estimated directly from the particle size distribution data (see e.g., Carrier 2003). Other formulations, such as the Kozeny-Carman relationship (see Carrier 2003, Odong 2007) are based on the capillary tube model considering additional soil parameters (e.g., porosity, void ratio, specific surface area and tortuosity), as well as permeating fluid parameters.

Based on the permeability estimates for materials with a grain size distribution similar to cement powders, the upper bound permeability estimate for degraded cement is not likely to exceed 10.0 md (10^{-14} m^2 or 10^{-5} cm/s). This value is considered a reasonable upper bound for the permeability of the borehole debris fill dominated by cement materials as it assumes flow through the granular matrix under limited confinement and the potential presence of larger pore sizes (macro-pores) exposed to WIPP brines. The upper bound permeability for the confined cement grouts, however, is likely to be an order of magnitude lower, on the order of 1.0 md (10^{-15} m^2 or 10^{-6} cm/s) or possibly lower based on the available laboratory data (Onofrei et al. 1992) and field data specific to the WIPP environment (Christensen and Hunter 1980). Laboratory hydraulic conductivity testing on crushed reconsolidated cement grout samples (see

e.g., Onofrei et al. 1992 results reported by Thompson et al. 1996) indicate long-term permeability of about 10^{-15} m^2 or less, i.e., on the order of 10^{-6} cm/s or less, after 200 days.

Based on the available laboratory data and the observed field behavior, the values in Table ES-1 were selected as representative estimates for degraded borehole fill materials represented by BH_SAND:PRMX_LOG. Note that no change is proposed to the lower bound of the log-uniform distribution for BH_SAND:PRMX_LOG, no change is proposed to the permeability of an open borehole for the first 200 years after the borehole intrusion, and no change is proposed to the factor of 10 reduction in the permeability of fill materials in the lower borehole (BH_CREEP materials) for times greater than 1,200 years after the borehole intrusion.

Table ES-1. Borehole Permeability, *k*, and Hydraulic Conductivity, *K*, Upper Bounds – Current and Proposed Maximum Values

Description of BH_SAND:PRMX_LOG[1,2]	***k*** **(m^2)**	***k*** **(md)**	***K*** **(cm/s)**
Upper borehole beyond 200 years after drilling intrusion – **BH_SAND current PA values**	1×10^{-11}	10,000	1.0×10^{-2}
Upper borehole beyond 200 years after drilling intrusion – **BH_SAND proposed PA values**	1×10^{-14}	10.0	1.0×10^{-5}
Lower borehole beyond 1,200 years after drilling intrusion – **BH_CREEP current PA values**	1×10^{-12}	1,000	1.0×10^{-3}
Lower borehole beyond 1,200 years after drilling intrusion – **BH_CREEP proposed PA values**	1×10^{-15}	1.0	1.0×10^{-6}

Notes:

1) Lower borehole permeability is assigned BH_SAND values from 200 to 1,200 years after drilling intrusion.
2) Lower borehole permeability is assigned BH_CREEP values from 1,200 years after the drilling intrusion and beyond. The value of BH_CREEP is defined as one tenth the sampled value of the BH_SAND distribution.

The borehole fill permeability values in Table ES-1 are proposed as upper bound for the fully degraded borehole configuration, i.e., the equivalent borehole permeability in PA calculations is not expected to exceed 1×10^{-14} m^2 beyond 200 years after the time of the intrusion.

1 INTRODUCTION

1.1 Regulatory and Background Information for Borehole Intrusions

The Waste Isolation Pilot Plant (WIPP) repository, located in southeastern New Mexico, has been developed by the U.S. Department of Energy (DOE) for the geologic (deep underground) disposal of transuranic (TRU) waste. Containment of TRU waste within the WIPP repository must be in accordance with the standards set forth in Title 40 of the Code of Federal Regulations (CFR), Part 191. The U.S. Environmental Protection Agency (EPA) assessment of the DOE's ability to comply with the containment requirements of the WIPP repository is based, in part, on performance assessment (PA) calculations. Waste Isolation Pilot Plant PA calculations are performed by the DOE using linked computer models that calculate the potential for cumulative radionuclide releases from the disposal system during the 10,000 years following closure of the repository. These potential releases may occur through several release pathways: 1) releases of contaminated waste directly to the ground surface through intrusion boreholes, 2) releases via groundwater that flows upward from waste panels through intrusion boreholes to the Culebra water-bearing zone within the Rustler formation or to the ground surface, or 3) releases via radionuclide transport that flows from waste panels through interbeds in the Salado formation to the accessible environment. Given the importance of flow through boreholes, the properties for the intrusion boreholes are an important element in the PA calculations.

Waste Isolation Pilot Plant PA includes the consequences of inadvertent and intermittent borehole intrusion into the repository during drilling for natural resources. A borehole intrusion is the most severe inadvertent human intrusion scenario that could affect long-term performance of the disposal system (40 Code of Federal Regulations § 194.33(b)(1)). Human intrusion scenarios simulate the penetration of an intrusion borehole into the waste disposal region. There are two release mechanisms associated with this drilling process: (i) releases during the initial drilling event, and (ii) possible releases from long-term groundwater flows in the disposal system after the borehole casing and cement plugs have degraded.

Long-term releases to the ground surface or into the groundwater in overlying units may occur after an intrusion borehole has been plugged and abandoned. As required by regulation, plugging and abandonment of future boreholes is assumed to be "*consistent with practices in the Delaware Basin at the time a compliance application is prepared*" (40 CFR § 194.33(c)(1)). A review of current practices in the Delaware Basin indicates that recently abandoned boreholes were plugged to meet state or federal regulatory requirements protecting groundwater and natural resources (DOE, 2022). These plugs will initially prevent flow in abandoned boreholes for some period of time but may eventually fail, potentially allowing radionuclides to be transported in brine flowing upward in an intrusion borehole (DOE, 1996, Section 6.4.7.2).

Per regulatory requirements, boreholes are plugged and abandoned with some combination of solid cement plugs to isolate different fluid-bearing horizons from each other and from the ground surface. Six different plug configurations have been identified in the Delaware Basin that are potentially relevant to abandoned boreholes at WIPP. The six configurations have been

simplified into three conceptual plugging patterns for WIPP PA: a two-plug configuration, a three-plug configuration, and a continuous plug configuration (DOE, 2019, Appendix PA-2019, Section PA-3.7). The probabilities of occurrence for each of the three plugging patterns are reassessed before each compliance recertification application (CRA) for WIPP. The latest probabilities of occurrence are documented in (DOE, 2022). As described in Thompson et al. (1996), the continuous plug is not expected to degrade during the 10,000-year post-closure period of the WIPP repository. Therefore, the remainder of this report will focus on the two- and three-plug configurations, as they are the only plugs expected to degrade during the time period of interest (see Drawing 2).

1.2 Objective and Conceptual Model

The objective of this analysis is to develop a quantitative methodology to bound the permeability of degraded borehole fill materials (degraded steel casing and degraded cement plugs) in an intrusion borehole. The permeability of the degraded material in the borehole is represented in WIPP PA by the sampled value of the BH_SAND:PRMX_LOG parameter and this parameter is the focus of this analysis. BH_SAND:PRMX_LOG has the units of $\log_{10}[m^2]$.

For the purposes of PA, the plugs above the repository are assumed to degrade 200 years after the drilling intrusion (DOE, 2019, Appendix PA, Table PA-26). From that point onward, the borehole is assumed to be filled with a silty sand-like material consisting of degraded cement and iron corrosion products, including any material that sloughs off the walls of the borehole (Thompson et al. 1996). The degraded borehole fill materials continue to be exposed to long-term deformation of the borehole caused by creep closure and by sliding along discontinuities (such as clay seams) in the surrounding host rock. Creep closure continues long after the geochemical processes of steel and cement degradation are complete.

This conceptual model has not changed since the EPA mandated parameter changes subsequent to the Performance Assessment Verification Test (PAVT) (SNL, 1997) which was performed after the CCA. The parameter changes relative to the CCA are documented in (Hansen and Leigh 2003, Section 2.4). There were two changes related to the intrusion borehole:

1. The distribution for the $\log_{10}$ of the permeability of degraded borehole fill material, (parameter BH_SAND:PRMX_LOG in PA), was changed from Uniform [−14, −11] to Uniform [−16.3, −11] in the units of $\log_{10}(m^2)$. (Hansen and Leigh, 2003, Table 1.1 and Section 2.4).
2. The cement plug for the CCA had a constant $\log_{10}$ permeability of −16.3 (k=5×10^{-17} m^2) during the first 200 years after the intrusion. This parameter is denoted as CONC_PLG:PRMX_LOG in PA. Subsequent to the PAVT, this constant value was changed to a uniform distribution [−19, −17] (Hansen and Leigh, 2003, Section 2.4 and Table 2.1)

These parameter revisions were included in the CRA-2004 (DOE 2004, Appendix PA, Section PA-4.2.9) and in all subsequent recertification PAs, including the PA for CRA-2019.

The relevant parameters to conduct PA calculations are summarized in Table 1.

Table 1. Intrusion Borehole Material Parameters in PA

Description	PA Material/ Property	Minimum (m^2)	Maximum (m^2)	Median or Constant (m^2)
Permeability of open sections of the borehole (m^2), 0 – 200 years	BH_OPEN: PRMX_LOG	n/a	n/a	1.0×10^{-09}
Permeability of cement plugs, 0 – 200 years	CONC_PLG: PRMX_LOG	1.0×10^{-19}	1.0×10^{-17}	1.0×10^{-18}
Permeability of borehole fill material beyond 200 years after intrusion event	BH_SAND: PRMX_LOG	5.0×10^{-17}	1.0×10^{-11}	2.24×10^{-14}
Permeability of lower borehole fill material beyond 1,200 years after the intrusion event	BH_CREEP: BHPRM*	5.0×10^{-18}	1.0×10^{-12}	2.24×10^{-15}

* The value of BHPRM is defined as one tenth of the sampled value for BH_SAND:PRMX_LOG. BH_CREEP is a calculated, not a sampled, parameter.

1.3 Contents of this Report

Section 1 of this report provides regulatory background and historical relevance of the upper bound permeability parameters used in PA calculations since the CCA in 1996. Section 2 describes an upper bound for the permeability of degraded borehole fill materials based on more recent data since the CCA. The analyses in Section 2 specifically evaluate the permeability and hydraulic conductivity of corroded steel casing and degraded cement plugs that can fill a borehole by 200-years after an intrusion, while considering the effects of local defects, thermal, stress and hydraulically induced fractures, and flow along interface discontinuities. Section 3 presents summaries of the geo-mechanical calculations performed for borehole closure due to creep of halite and an analysis of the volume of degraded borehole materials. Section 4 summarizes the conclusions. Appendix A provides a detailed description of the geo-mechanical calculations performed with the Sierra Solid Mechanics code using a modified Munson-Dawson constitutive model for the creep of halite. Appendix B documents the calculations for the volume of degraded borehole fill materials and provides more details on the upper bound borehole permeability calculations.

2 UPPER BOUND PERMEABILITY OF BOREHOLE FILL MATERIALS

To estimate a reasonable upper bound for the permeability of degraded fill materials, one can consider the range of permeability values for similar or coarser materials. Since hydraulic parameters in the literature are often reported as hydraulic conductivity values assuming water as the percolating fluid, it is useful to convert values for intrinsic permeability (m^2) to the corresponding values for hydraulic conductivity (cm/s) using Equation (1):

$$K = \frac{k\gamma_w}{\mu} \times 100, \quad (1)$$

where K is the hydraulic conductivity (cm/s),
k is the intrinsic permeability (m^2),
μ is the dynamic viscosity of water, 10^{-3} Pa • s, and
γ_w is the unit weight of water, 9,810 N/m^3.

Using Equation (1) to convert the upper bound values for borehole fill permeability into the corresponding hydraulic conductivities, the current upper bound value for borehole hydraulic conductivity is set to approximately 10^{-3} or 10^{-2} cm/s as a function of time since the borehole intrusion, as shown in Table 2.

Table 2. Current Upper Bounds for Hydraulic Conductivity of Borehole Fill Materials

Parameter	k (m^2)	K (cm/s)
Upper and lower borehole fill material from 200 – 1,200 years	1.0×10^{-11}	0.98×10^{-2}
Lower borehole fill material after 1,200 years	1.0×10^{-12}	0.98×10^{-3}

The range of hydraulic conductivity values in Table 2, between 10^{-2} and 10^{-3} cm/s, is typically attributed to gravelly (GW, GP)[1] or sandy materials (SW, SP) acting as drainage layers (see e.g. EPA documentation prepared in support of Title 40 CFR Part 258[2]). However, the available literature indicates that cement-based grouts are likely to behave as silt-dominated mixtures with hydraulic conductivity on the order of 10^{-5} cm/s or lower even when considering results for the cement based grouts prepared or tested in conditions that are less favorable than the WIPP environment (see e.g. Saiyouri et al. 2011, Allan and Philippacopoulos 1999). It follows that the upper bounds for the borehole fill materials that are currently used in PA calculations overestimate hydraulic conductivity by a factor of 100 to 1,000.

The borehole fill materials (degraded steel casing and degraded cement grout) are the primary determinants of long-term borehole hydraulic conductivity values. Other important factors are borehole closure due to creep deformation and sliding along clay seams in the halite (rock salt) surrounding the borehole and the volumetric expansion of the degraded fill materials. The long-

[1] The soil classifications GW and GP indicate well-graded and poorly-graded gravels and the soil classifications SW and SP indicate well-graded and poorly-graded sands.
[2] https://archive.epa.gov/epawaste/nonhaz/municipal/web/pdf/subpartd.pdf, https://archive.epa.gov/epawaste/nonhaz/municipal/web/pdf/subpartf.pdf)

term corrosion of steel casing and the geochemical degradation of cement grout are difficult to predict for the anticipated drilling intrusion scenarios. However, it is possible to establish the range of hydraulic conductivities for both cement grout and steel casing based on the available literature data while recognizing the actual WIPP conditions to avoid excessive conservatism.

2.1 Upper Bound Hydraulic Conductivity of Degraded Steel

The upper bound permeability of the degraded steel casing is estimated by using granular iron as a bounding analogue under WIPP relevant conditions, as explained below.

When estimating the permeability of degraded steel, one needs to consider the range of pore sizes (i.e., the development of a conductive porous matrix) during the steel corrosion process. Based on the available information on corrosion rates in the WIPP environment (Zeitler 2018a, Zeitler 2018b, Roselle 2013), the intermediate casing (see Drawing 3) is not likely to fully degrade during the 10,000-year period under expected mean conditions but may exhibit full degradation under the maximum reported corrosion rates.

The steel degradation process results in the creation of chemical compounds with larger final volume than the initial volume of non-degraded steel (see e.g., Thompson et al. 1996, Appendix B, Section B.5.4). Consequently, the steel degradation process is likely to result in a continuous increase of confinement of the degraded borehole materials, especially in sections of the borehole where the cement plugs are installed. This increasing confinement will reduce the expected porosity of the degraded steel casing and, in terms of pore sizes, the degraded steel permeability is expected to be lower than the long-term permeability of granular iron, which is an artificially manufactured material characterized by a highly permeable porous matrix. In summary, the granular iron, a man-made iron-based material manufactured to promote filtration using a porous structure with a very high hydraulic conductivity, provides an upper bound for the permeability of the degraded steel casing in the intrusion borehole.

The initial permeability of granular iron, e.g., as used to construct a permeable reactive barrier (PRB) for groundwater remediation, has an upper bound on the order of 10^{-10} m^2 (K~0.1 cm/s) based on TAPRBI (2002). The intact/uncorroded permeability of granular iron can also be estimated from Hazen's equation (see e.g., Carrier 2003) using the PRB particle size distribution curve reported by Moraci et al. (2016) as shown in Figure 1.

Bilardi et al. (2016) and Moraci et al. (2016) report a decrease of the PRB hydraulic conductivity due to iron corrosion, clogging, gas formation and precipitation of mineral reaction products within the granular iron matrix. These processes are expected to occur in the WIPP, and result in a decrease in PRB hydraulic conductivity that is illustrated in Figure 2.

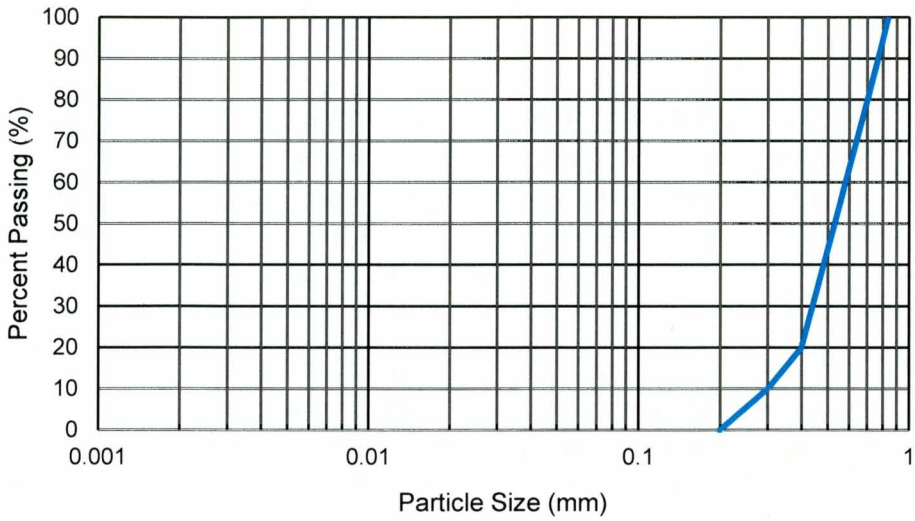


Figure 1. Particle size distribution curve for permeable reactive barrier (PRB) material. Based on data in (Moraci et al. 2016)

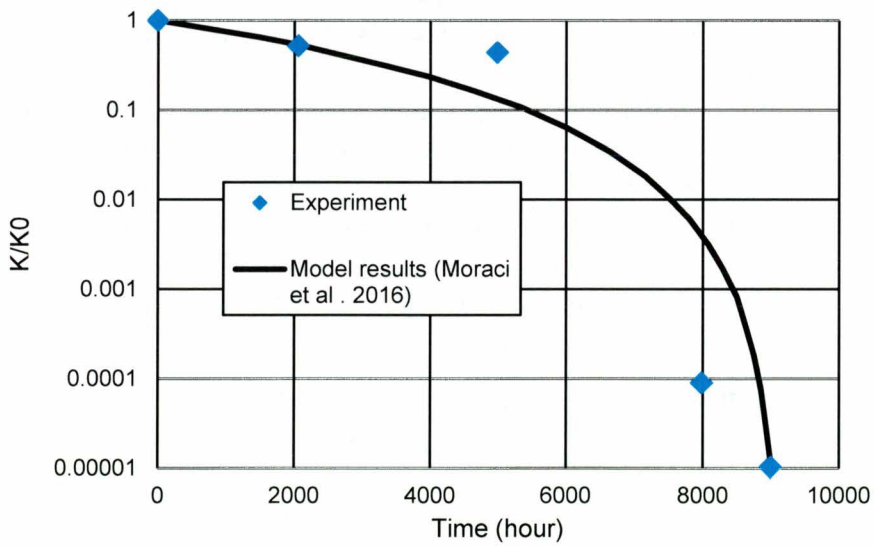


Figure 2. Long-term hydraulic conductivity reduction for PRB material (Moraci et al. 2016)

The presence of WIPP brines creates a relatively aggressive environmental condition. For example, Popielak et al. (1983) reported gypsum and halite precipitation, exsolution of gases under reduced pressures and wellhead and casing corrosion when testing the brine reservoirs encountered in the vicinity of the WIPP site. Hence, it is reasonable to expect the long-term effective permeability of the degraded steel will be lower than the long-term permeability of granular iron (PRB) under similar or more favorable environmental conditions. Therefore, the upper bound for the long-term permeability of degraded steel at WIPP may be estimated as:

$$k_{long\ term} = k_0 \times \text{reduction coefficient} = k_0 \times K/K_0, \quad (2)$$

where k_0 is the initial permeability of the PRB material and the reduction coefficient, K/K_0, is based on the data from Moraci et al. (2016) in Figure 2.

Based on the maximum estimated initial permeability for the granular iron of 10^{-10} m^2 (see e.g., TAPRBI 2002) and the reduction coefficient, $K/K_0 = 10^{-5}$ after 9,000 hours (375 days) (see Figure 2), the upper bound permeability for the degraded steel casing is likely to be lower than (10^{-10} m^2 x 10^{-5}) = 10^{-15} m^2 (~10^{-6} cm/s). This value is a factor of 1,000 to 10,000 lower than the current maximum PA values of 10^{-12} to10^{-11} m^2 for BH_CREEP and BH_SAND materials shown in Table 1.

The degraded steel permeability in areas that are subjected to significant confining pressures is expected to be even lower than the above estimated upper bound value of 10^{-15} m^2 (e.g., within sections of the borehole where the cement plugs are installed), due to increased confinement, non-uniform particle distribution of corroded casing material, gas exsolution and mineral precipitation in the WIPP environment.

2.2 Upper Bound Hydraulic Conductivity of Degraded Cement

The effective hydraulic conductivity of the initially emplaced cement grout may either improve or degrade with time under WIPP specific conditions. According to Backe et al. (1999), cement slurries typically exhibit permeabilities of less than 100 md (10^{-13} m^2) when fresh and on the order of 1 md (10^{-15} m^2) when starting to cure. Cured cement grouts are expected to have permeabilities of about 0.001 md (10^{-18} m^2) or lower based on Zhang and Wang (2015) and Christensen and Hunter (1980). When cured in less favourable conditions (Zhang and Wang, 2015) or based on field tests on successfully installed cement plugs (Christensen and Hunter, 1980), typical cement grout permeabilities are lower than about 0.1 md (10^{-16} m^2). For field tests exhibiting potential leakage issues, Christensen and Hunter (1980) report the maximum effective permeability of about 0.6 md (6×10^{-16} m^2).

Thompson et al. (1996) suggested favorable behaviour of confined cement grouts based on Alcorn et al. (1992) who report that the alteration phases in Portland cement, including tobermorite, quartz, gypsum, calcite, clays and zeolite (produced at the expense of soluble and unstable materials such as portlandite and hydrogarnet) occupy more volume than the original solids. Consequently, Thompson et al. (1996) report the potential for the long-term permeability of cement grout to decrease as the porosity decreases based on the research by Coons at al. (1989).

Thompson et al. (1996) also used the laboratory results by Onofrei et al. (1992) to project the behavior of crushed reconsolidated grouts and obtained long-term permeability values around or below approximately 1.0 md (10^{-15} m^2 or 10^{-6} cm/s), see data in Appendix B, Figure B-3. Field observations of the cement plugs in the Delaware Basin, installed decades ago in potash exploratory holes, indicate that geochemical alterations are expected only near the contact surface of the cement plug with water (Thompson et al. 1996). Even at relatively short distances from the plug surface, the cement plug exhibits original texture and mineralogy (e.g., portlandite) as reported by Bonen (1996). Therefore, field results by both Bonen (1996) and Christensen and

Hunter (1980) indicate that the installed cement plugs are expected to maintain relatively intact interfaces between steel casing and cement as well as between cement and halite formation.

For unconfined plugs, however, Thompson et al. (1996) suggest that the spalling mechanism due to geochemical alterations near the contact surface, coupled with the continuous alteration of cement grout, will result in a degradation rate of up to 1 mm/year based on data from Atkinson et al. (1985). Thompson et al. (1996) indicate that the estimated loss of plug volume over 10,000 years would be equivalent to a plug length reduction of approximately 5 to 10 meters from an initial length of 36 m assuming axial diffusion. For conservatism, Thompson et al. (1996) assumed that the corrosion process may produce a hydraulically conductive interface between the plug and the casing which may result in radial spalling and a relatively fast loss of the plug volume (in approximately 120 years). However, Thompson et al. (1996) stated that the radial spalling mechanism would be applicable only for relatively short plugs and that the minimum plug length was not determined as a part of their study. Field results by Bonen (1996) and Christensen and Hunter (1980) do not support a plug failure mechanism due to radial spalling. In addition, numerical models by Onofrei et al. (1992) and Matteo and Scherer (2012) indicate that only partial degradation of up to approximately 10 meters or less over the period of 10,000 years would be possible.

Data from Berner (1990) indicate that the critical volume of flow that would trigger physical failure of an unconfined cement plug due to continuous alteration of the calcium silicate hydrate (CSH) matrix and unconstrained micro-fracturing, is around 100 pore volumes (Thompson et al. 1996, Section 3.3). The assumed breakdown of the CSH matrix, therefore, requires the loss of confinement combined with a sufficient flow of brine through the alkaline CSH matrix (at a rate that is sufficient to allow for dissolution and transport of portlandite out of the CSH matrix before the deposition of new solids can occur). For simplicity, one can assume complete degradation of the cement matrix and assume that the pore size distribution of the degraded cement grout is caused by the granular amorphous packing of minerals creating a network of flow conduits. Consequently, the upper bound permeability for this type of pore structure can be estimated from appropriate analogues in the literature and based on an appropriate grain size distribution curve (e.g., using the Hazen equation), as described in the next section.

2.2.1 Permeability of Cements with Amorphous Structure

To establish the potential upper bound for the initial permeability of the cementitious materials upon original emplacement, it is useful to review reported data for wellbores completed in adverse conditions of temperature and/or pressure. The permeability of cements with an amorphous polymer structure has been investigated by Curtice and Mallow (1979) who researched cements suitable for use in high temperature geothermal wells. These cements are cured in more aggressive environments and under less favorable conditions than cements used for plugging of boreholes in the Delaware Basin and are, therefore, expected to exhibit larger micro-fractures and higher permeabilities. The range of permeability values reported by Curtice and Mallow (1979) for samples that were cured in saturated steam for more than 14 days is summarized in Table 3.

Table 3. Summary of Permeability Values for Samples of Hydrothermal Cement Cured more than 14 Days

Permeability Percentile	k (m^2)	k (md)	K (cm/s)
Min	1.48×10^{-15}	1.5	1.45×10^{-6}
10%	1.54×10^{-15}	1.6	1.51×10^{-6}
20%	1.74×10^{-15}	1.8	1.70×10^{-6}
Mean	1.20×10^{-14}	12.2	1.18×10^{-5}
80%	6.93×10^{-14}	70.2	6.80×10^{-5}
90%	1.85×10^{-13}	188	1.82×10^{-4}
Max	2.20×10^{-13}	223	2.16×10^{-4}

2.2.2 Hydraulic Conductivity of Granular Material Based on Particle Size Distribution

The hydraulic conductivity of granular material with a known uniform particle distribution is often estimated based on Hazen's equation (see e.g., Carrier 2003):

$$K = Cd_{10}^2 \tag{3}$$

where K is the hydraulic conductivity (cm/s),
C is Hazen's coefficient typically set to unity if d_{10} is in (mm) and K is in (cm/s), and
d_{10} is particle size representing the 10th-percentile value on the grain size distribution curve (mm).

The range of particle size distribution (PSD) curves for the cement powder used by Ferraris et al. (2004) to conduct a round-robin testing program is summarized in Figure 3 (see Appendix B for more details).

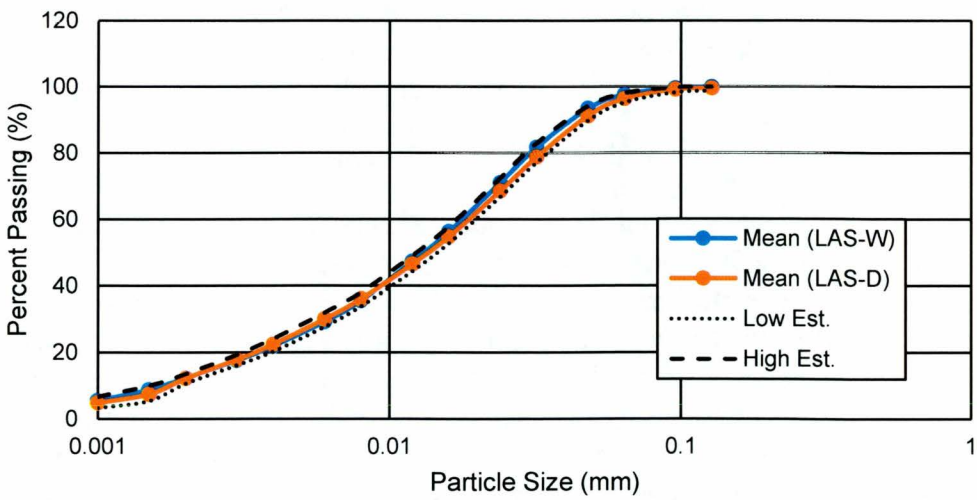


Figure 3. PSD for cement powder standard reference material (Ferraris et al. 2004)

The Hazen equation is typically applied to uniformly graded materials with the uniformity coefficient, C_u, defined as:

$$C_u \equiv \frac{d_{60}}{d_{10}} < 5, \tag{4}$$

for particle sizes between 0.1 and 3.0 mm. For materials with $d_{10} < 1\ mm$ and $C_u > 5$ (such as the material in Figure 3), the Hazen's coefficient in Equation (3) is likely smaller than 1.0 due to larger values of the surface area and tortuosity than for uniformly graded sands for which the Hazen's equation is directly applicable (see e.g. USDA 1991 and Carrier 2003). Therefore, the upper bound hydraulic conductivity for the cement material with the PSD reported in Figure 3 can be conservatively estimated as:

$$K = 1.0 \times d_{10}^2 \tag{5}$$

For the range of d_{10} values in Figure 3, the upper bound estimate for the cement permeability is summarized in Table 4.

Table 4. Upper Bound Permeability Estimate for Degraded Cement based on Hazen's Equation Applied to Cement Powders

Range	d_{10} (mm)	k (m^2)	k (md)	K (cm/s)
Min	0.0015	2.3×10^{-15}	2.3	2.3×10^{-6}
Max	0.0019	3.6×10^{-15}	3.6	3.6×10^{-6}

The CSH matrix degradation of cement plugs in WIPP boreholes is expected to result in long-term permeability values of degraded cement that are similar to hydraulic properties typical of silty materials (see e,g., Thompson et al. 1996 based on data from Onofrei et al. 1992). Consequently, the upper bound values for the permeability of degraded cement materials are expected to be similar to the permeability of cement clinker minerals (cement powders) at a relatively high confinement prior to the commencement of the hydration process. In addition, the values in Table 4 were cross-checked with a closer analogue to the actual material (amorphous silica gel) formed during the cement degradation. Matteo and Scherer (2012) reported that the main reaction product of cement degradation is an amorphous silica gel that remains in the reactive zone after the rest of the cement matrix has been altered. Assuming that the degraded cement is dominated by compounds consisting of amorphous silica, the upper bound permeability can be estimated from the corresponding PSD curves (see, e.g. Marín et al. 2018 and Appendix B) resulting in the upper bound permeability values on the same order of magnitude as shown in Table 4. Even after accounting for micro-fractures and discontinuities along the interfaces between the cement grout, steel casing and the surrounding rock formation (see e.g., Stormont et al. 2018), the estimated upper bound permeability values in Table 4 are not likely to be exceeded based on the expected geochemical conditions (high alkalinity and relatively low concentration of carbonic acid) as well as the expected geomechanical conditions (increased confinement due to creep). Furthermore, the upper bound permeability values in

Table 4 agree favorably with (i.e., are within the same range as) the reported permeability values for geothermal cements that were cured under less favourable conditions (e.g., exposed to saturated brines and high temperatures) and under lower confining stresses than expected at WIPP.

After considering permeability measurements for the cement materials with amorphous structure, the range of permeabilities based on the PSD relationships for cement powders (silty materials), laboratory measurements of permeabilities along the cement-steel casing interfaces, and the anticipated chemical and stress conditions at WIPP, the upper bound estimate for the degraded cement permeability is not likely to exceed 10^{-14} m^2 (10.0 md or 10^{-5} cm/s).

2.3 Upper Bound Permeability of Confined Borehole Fill

In summary, based on the upper bound permeability estimates for corroded steel (see Section 2.1) and for degraded cement (see Section 2.2), one can estimate a range for the upper bound permeability of the confined borehole fill as 10^{-15} m$^2 \leq k_{fill} \leq 10^{-14}$ m^2. These maximum values for the confined borehole fill permeability are two to three orders of magnitude less than the current maximum values for BH_CREEP and BH_SAND materials of 10^{-12} m^2 to 10^{-11} m^2 as shown in Table 1.

3 SUPPORTING ANALYSES FOR BOREHOLE CREEP CLOSURE AND FOR EXPANSION OF DEGRADED BOREHOLE FILL

3.1 Impact of Borehole Creep Closure on Upper Bound Permeability of Unconfined Borehole Fill

The unplugged sections of the borehole subjected to chemical and physical degradation (due to corrosion of casing and degradation of cement) are also subjected to creep of the surrounding rock mass. Current PA calculations use a permeability value of 1.0×10^{-9} m^2 for the open borehole areas and assign upper bound permeabilities of 1.0×10^{-11} and 1.0×10^{-12} m^2 to the degraded borehole fill materials as a function of time since intrusion and of location in the borehole (see Table 1 and Table 2 for additional details).

Maximum permeability values for the crushed cement grout at the onset of the reconsolidation process reported by Thompson et al. (1996) and based on data from Onofrei et al. (1992) are below 1.0×10^{-13} m^2 while the maximum permeability for the corroded steel (based on the permeability of granular iron) is estimated as 1.0×10^{-10} m^2. Assuming the borehole diameter is 12.25 in (0.31115 m) and the inside diameter of internal casing is 7.921 in (0.20119 m), one can estimate the maximum creep volume loss as (7.921 in/12.25 in)^2 = 41.8% of the initial borehole volume.

Viscoplastic (creep) modeling of borehole closure was conducted using the constitutive model developed by Reedlunn et al. (2022). The steady-state creep strain rate for WIPP salt from the Reedlunn et al. (2022) model is plotted as a function of the equivalent stress (an analogue for the von Mises stress) in Figure 4.

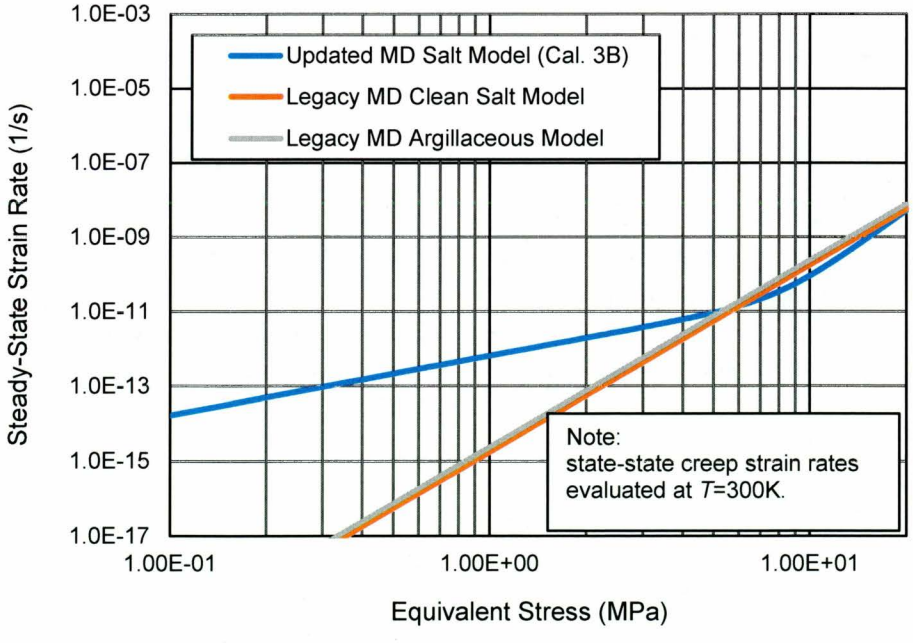


Figure 4. Viscoplastic strain rate estimates for rock salt – Reedlunn et al. (2022)

The Reedlunn et al. (2022) model exhibits faster steady-steady creep than the legacy Munson-Dawson (MD) model utilized by Thompson et al. (1996) for the equivalent stress magnitude below approximately 6 MPa (see Figure 4). Consequently, this model predicts faster rates of borehole closure, especially at lower depths (with lower confining stresses) above the repository, than previously predicted by Thompson et al. (1996). The updated creep calculations based on the Reedlunn et al. (2022) model are discussed in detail in Appendix A.

Assuming that the degraded borehole fill exhibits negligible compressibility (in comparison with the surrounding rock salt), one can calculate the volume loss at different borehole depths. In this study, the creep calculations were conducted at borehole depths of 250, 450, 650 and 850 meters for the following three modeling scenarios (see Appendix A for more details):

- Case 1 – dry borehole scenario,
- Case 2 – hydrostatic scenario. This model assumes hydrostatic backpressure inside the borehole; and
- Case 3 – WIPP-12 scenario. This model assumes backpressure based on the initial WIPP-12 wellhead pressure reported by Popielak et al. (1983).

Initial stresses and borehole backpressures used for creep model simulations at different depths are summarized in Table 5 for depths of 250 and 650 meters (representing conditions at the top of the Salado and at the repository level).

Table 5. Boundary conditions for creep calculations

Depth (m)	Boundary stress @ R_{max} (kPa)	Case 1 backpressure (kPa)	Case 2 backpressure (kPa)	Case 3 backpressure (kPa)
250	5,641	0.0	2,943	4,377
650	14,666	0.0	7,652	9,086

The calculated borehole volume losses at a depth of 250 meters are summarized in Figure 5.

Results in Figure 6 indicate that the intrusion borehole is likely to close its porous structure associated with the increased consolidation of the borehole fill within approximately 660 years. Assuming the maximum borehole fill permeability of $k_0 = 1.0\times10^{-10}$ m^2, one can now determine the reduction in the permeability values with time based on the Kozeny-Carman relationship (see e.g., Thompson et al. 1996 and Appendix A):

$$k = \alpha \frac{\phi^3}{(1-\phi)^2}, \tag{6}$$

where ϕ denotes the effective porosity and α is defined from the initial conditions:

$$\alpha = k_0 \frac{(1-\phi_0)^2}{\phi_0^3} \tag{7}$$

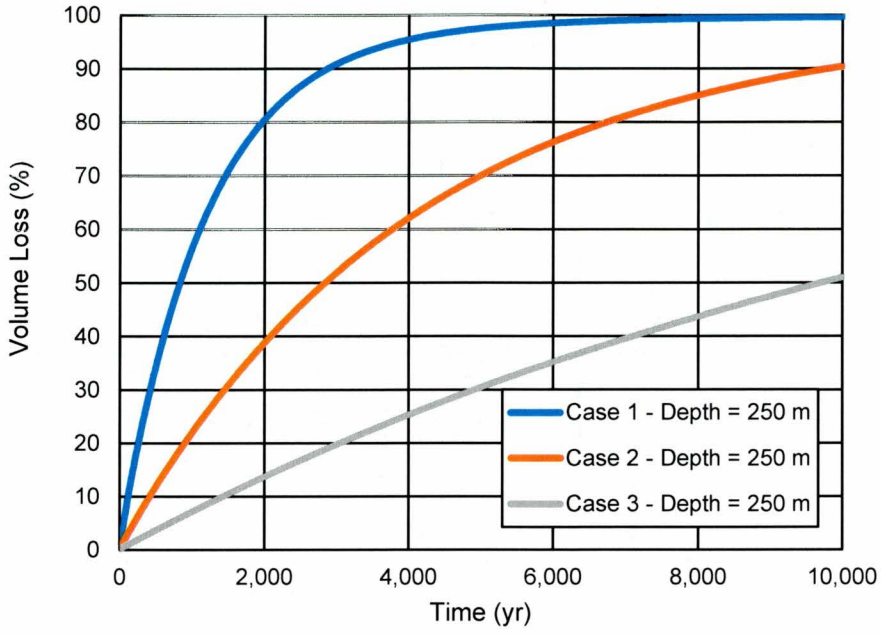


Figure 5. Borehole volume loss at a depth of 250 meters.

The calculated borehole volume losses at a depth of 650 meters are summarized in Figure 6.

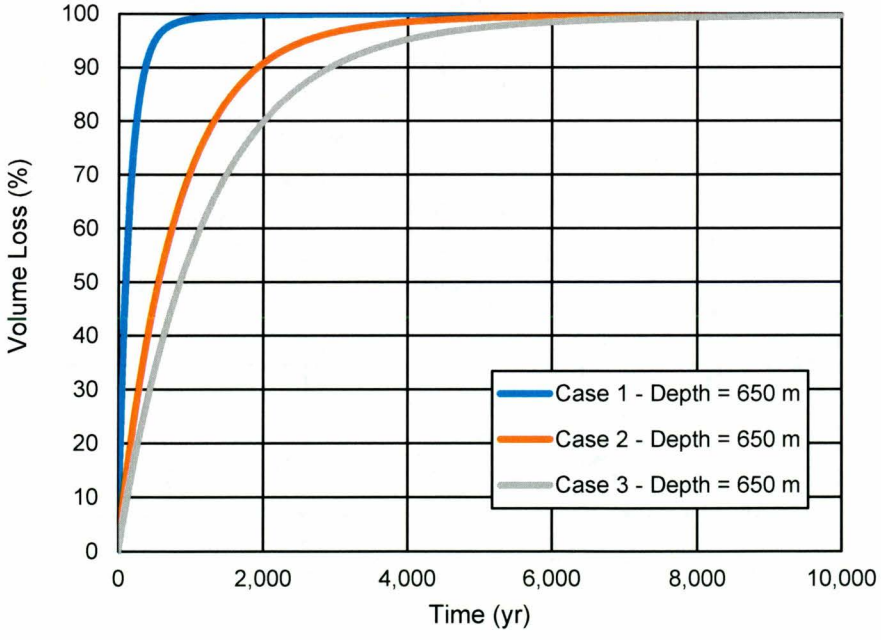


Figure 6. Borehole volume loss at a depth of 650 meters.

The initial borehole porosity, ϕ_0, in Equation (7) corresponds to the maximum creep volume loss of 41.8 percent. Calculated permeabilities for the unconfined borehole fill at a depth of 250 meters are shown in Figure 7.

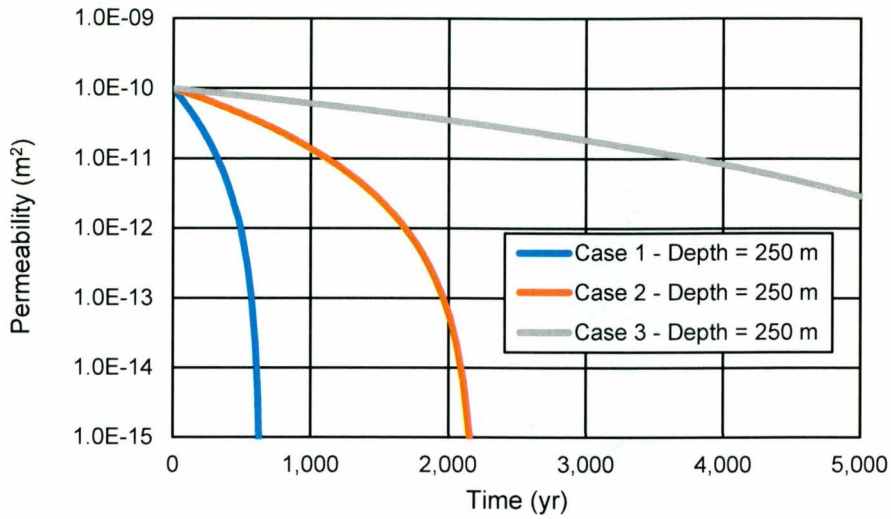


Figure 7. Borehole permeability values at a depth of 250 meters.

Calculated permeabilities for the unconfined borehole fill at a depth of 650 meters are shown in Figure 8.

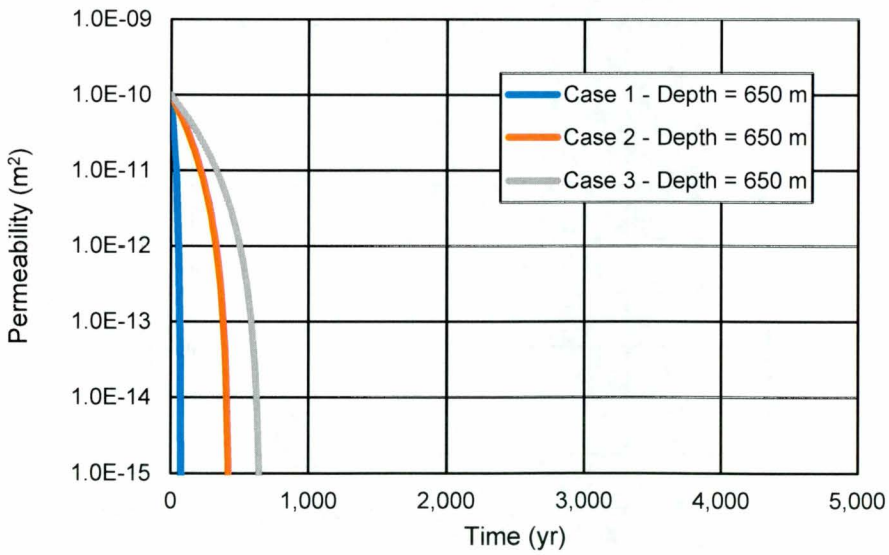


Figure 8. Borehole permeability values at a depth of 650 meters.

At the repository depth of 650 meters, the borehole infill is expected to fully consolidate within approximately 660 years for any of the 3 borehole pressure cases, resulting in the reduction of permeability by nearly five orders of magnitude (over 660 years). Consequently, the factor of 10

in Table 1 (used to reduce the lower borehole permeability beyond 1,200 years after the intrusion in PA calculations) significantly underestimates the potential for creep closure to reduce the permeability after 1,200 years in the lower borehole fill material.

3.2 Impact of Volumetric Expansion of Degraded Fill Materials on Upper Bound Permeability of Unconfined Borehole Fill

The degraded volume of borehole materials can be estimated based on the assumed geological stratification (Drawing 1), a specific plug configuration (Drawing 2) and the configuration of different steel casings (Drawing 3). The volume of the borehole fill debris was calculated assuming the bulking factor for degraded hydrated cement of 1.3 and the volume expansion of steel of 3.5 based on Thompson et al. (1996, Appendices C and D). The bulking factor for the cement was adopted assuming particle disaggregation of hydrated cement during the geochemical degradation process, and the steel expansion factor was selected assuming that the majority of steel will degrade into iron-hydroxide during the corrosion process. The borehole fill debris volume was calculated for two conditions:

- Condition 1 - borehole geometry without plugs and without annulus grouting, i.e., assume stubbing of the production casing 20 meters above the Castile/Bell Canyon interface; and
- Condition 2 – borehole geometry without plugs and with annulus grouting, i.e., assume that the production casing is extended to the ground surface.

The vertical extent of geological formations used to calculate the debris volume was based on ERDA-9 stratifications, as illustrated in Drawing 1 and summarized in Table 6.

Table 6. ERDA-9 Stratification

Formation Layer	Base Elevation (m amsl*)	Depth (m)
Ground Surface	1039.0	0
Gatuña and Santa Rosa Formation	1023.3	15.7
Dewey Lake Redbeds	874.0	165.0
Rustler Formation	779.7	259.3
Vaca Triste	627.6	411.4
McNutt Potash Zone	511.6	527.4
WIPP Repository MB 138	396.4	642.6
WIPP Repository MB 139	379.0	660.0
Salado (Lower Member)	178.1	860.9
Castile	-207.9	1246.9

* "m amsl" is meters above mean sea level

For conservatism, all debris volume calculations were conducted assuming the absence of cement plugs. However, these volumes can be added to the overall debris volume based on the assumed borehole diameter for the surface casing (SC), the intermediate casing (IC) and the production casing (PC) shown in Drawing 3.

For the surface plug length of 15 meters and the top plug (at the Rustler-Salado Contact) length of 30 meters (see Drawing 2), the resulting plug volumes are summarized in Table 7.

Table 7. Cement Plug Volumes

Plug Location	Volume – SC & IC (m^3)	Volume – PC only (m^3)
Surface plug volume	1.21	0.19
Top plug volume	1.69	0.37
Degraded (surface + top) plug volumes	3.76	0.73

The calculated borehole debris volumes are documented in Appendix B and summarized in Table 8. Values in Table 8 illustrate that the volume of degraded fill material is larger than the available borehole volume. Consequently, the long-term degradation process is likely to result in a significant confinement of borehole fill materials even without considering the additional volume of individual cement plugs, deformations due to creep and sliding along clay seams. More specifically, the borehole permeability evaluations due to creep closure[3] do not account for sliding along the clay seams which is expected to result in a full borehole occlusion for at least 6 to 10 percent of the WIPP intrusion boreholes (Wagner and Hillesheim 2009), effectively rendering a relatively significant portion of the intrusion boreholes impervious to brine flows.

Table 8. Borehole Fill Debris Volumes

Scenario	Degraded Cement Volume (m^3)	Corroded Steel Volume (m^3)	Borehole Debris Volume (m^3)	$V_{Debris}/V_{Borehole}$† (m^3)
Condition No. 1 – without annulus grouting	85.5	34.8	120.3	1.04
Condition No. 2 – with annulus grouting	112.1	47.6	159.7	1.38

† The ratio between the borehole debris fill and the clear borehole volumes was calculated assuming no spalling during the borehole development. The clear borehole volume, $V_{Borehole}$, is 115.3 m^3.

[3] The geomechanics calculations for borehole closure are radially symmetric and cannot represent displacements along horizontal clay seams or horizontal marker beds in the Salado formation. The model could be expanded in the z-direction (along the axis of the borehole) but this level of complexity was not deemed necessary for this study.

4 CONCLUSIONS AND RECOMMENDATIONS FOR PA

This report has provided data and analyses to estimate upper bounds for permeability of degraded steel casing and degraded cement plugs in WIPP intrusion boreholes. In addition, calculations for borehole debris volumes show that the volume of degraded fill material is larger than the available borehole volume. Consequently, the long-term degradation process is likely to result in a significant confinement of borehole fill materials even without consideration of the additional debris volume from degradation of individual cement plugs, and without consideration of volume loss from deformation due to creep closure and sliding along clay seams in the halite surrounding the borehole and casing.

Based on the available laboratory data and the observed field behavior, the values in Table 9 were selected as representative estimates for the upper bound permeability of degraded borehole fill materials (degraded cement grout and degraded steel casing) defined by the BH_SAND:PRMX_LOG parameter in PA. No change is proposed to the lower bound of the log-uniform distribution for BH_SAND:PRMX_LOG, no change is proposed to the permeability of an open borehole up to 200 years after the borehole intrusion, and no change is proposed to the factor of 10 reduction in the permeability of fill materials in the lower borehole beyond 1,200 years after the intrusion.

Table 9. Upper Bound Borehole Permeability – Current (PA) and Proposed Values

Location	k (m^2)	k (md)	K (cm/s)
Upper Borehole – current	1×10^{-11}	10,000	1.0×10^{-2}
Lower Borehole – current	1×10^{-12}	1,000	1.0×10^{-3}
Upper Borehole – proposed	1×10^{-14}	10.0	1.0×10^{-5}
Lower Borehole – proposed	1×10^{-15}	1.0	1.0×10^{-6}

5 REFERENCES

Alcorn, S.R., Coons, W.E., Christian-Frear, T.L., and M.G. Wallace, 1992, "Theoretical Investigations of Grout Seal Longevity," Final Report, Stripa Project TR 92-23, SKB, Stockholm, Sweden.

Allan, M.L. and Philippacopoulos, A.J. 1999. Properties and Performance of Cement-Based Grouts for Geothermal Heat Pump Applications – final report FY 1999 prepared for Office of Geothermal Technologies, United States Department of Energy under Contract No. DE-AC02-98CH10886, by Brookhaven National Laboratory, Materials and Chemical Sciences Division, Department of Applied Science, November.

Atkinson, A., Goult, D.J., and Hearne, J.A., 1985, "An Assessment of the Long-Term Durability of Concrete in Radioactive Waste Management." Materials Research Society Symposium Proceedings: Scientific Basis for Nuclear Waste Management IX, v. 50, pp. 239-246.

Backe, K.R., Lile, O.B., Lyomov, S.K., Elvebakk, H. and Skalle, P. 1999. Characterizing Curing-Cement Slurries by Permeability, Tensile Strength and Shrinkage, SPE Drilling & Completion, Vol. 14, No. 3, pp. 162-167.

Berner, U., 1990, "A Thermodynamic Description of the Evolution of Pore Water Chemistry and Uranium Speciation During the Degradation of Cement," Technical Report 90-12, Paul Scherrer, Villligen, Switzerland.

Bilardi, S., Ielo, D., Moraci, N. and Calabrò, P.S. 2016. Reactive and hydraulic behavior of Permeable Reactive Barriers constituted by Fe0 and granular mixtures of Fe0/pumice, VI Italian Conference of Researchers in Geotechnical Engineering - Geotechnical Engineering in Multidisciplinary Research: from Microscale to Regional Scale CNRIG2016.

Bonen, D., 1996, "Petrographic Analyses of Concrete and Grout Recovered from the WIPP," The Technological Institute, Northwestern University, Interim Report, January 15, 1996, 9pp.

Carrier, W D. 2003. Goodbye, Hazen; Hello, Kozeny-Carman. ASCE Journal of Geotechnical and Geoenvironmental Engineering, November, pp. 1054–1056.

Christensen, C.L. and Hunter, T.O.1980. "The Bell Canyon Test and Results" SAND80-2414C. Sandia National Laboratories, Albuquerque NM. https://www.osti.gov/servlets/purl/7177549.

Coons, W.E. and S.R. Alcorn, 1989, "Estimated Longevity of Performance of Portland Cement Grout Seals," in Sealing of Radioactive Waste Repositories, Conference Proceedings, Braunschweig, Germany, May 22-25, 1989.

Craeger, W.P., Justin, J.D. and Hinds, J. 1947. Engineering for Dams, Volume II, John Wiley and Sons, New York, June 1947, pp. 649.

Curtice, D.K and Mallow W.A. 1979. Hydrothermal Cements for Use in the Completion of Geothermal Wells, report prepared by the Southwest Research Institute, BNL Contract No. 427964-S, BNL-51183, UC-66d - Geothermal Utilization Technology- TID-4500 for the

Geothermal Materials Group, Department of Energy and Environment, Brookhaven National Laboratory Associated Universities Inc., under contract No. DE-AC02-76CH00016 with the United States Department of Energy

Ferraris, C.F., Hackley, V. and Avilés, A.I. 2004. Measurement of Particle Size Distribution in Portland Cement Powder: Analysis of ASTM Round Robin Studies, in Cement, Concrete and Aggregates, Vol. 26, No. 2., https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=860497.

Hansen, C. and Leigh, C. 2003. A Reconciliation of the CCA and PAVT Parameter Baselines, Rev. 3. Sandia National Laboratories. Carlsbad, NM. Sandia WIPP Central Files ERMS # 528582.

Marín, R.R.R, Babick, F., Lindner, G.G., Wiemann, M. and Stintz, M. 2018. Effects of Sample Preparation on Particle Size Distributions of Different Types of Silica in Suspensions, in Nanomaterials (Basel). Published on Jun 21, 2018; 8(7):454. doi: 10.3390/nano8070454. PMID: 29933581; PMCID: PMC6070795.

Matteo, E.N. and Scherer, G.W. 2012. Experimental study of the diffusion-controlled acid degradation of Class H Portland cement, International Journal of Greenhouse Gas Control, Vol 7, pp. 181-191, ISSN 1750-5836, DOI: 10.1016/j.ijggc.2011.07.012

Moraci, N., Ielo, D., Bilardi, S and Calabro, P.S. 2016. Modelling Long Term Hydraulic Conductivity Behavior of Zero Valent Iron Column Tests for PRB Design. Canadian Geotechnical Journal, Vol. 53, No. 6. June 2016.

Odong, J. 2007. Evaluation of Empirical Formulae for Determination of Hydraulic Conductivity based on Grain-Size Analysis, Journal of American Science, Vol. 3, No. 3, pp. 54-60, ISSN:1545-1003.

Onofrei, M., Gray, M., Coons, W.E.., and S.R. Alcorn, 1992, "High Performance Cement Based Grout for Use in a Nuclear Waste Disposal Facility, " Waste Management, v.12, pp. 133-154.

Popielak, R.S., Beauheim, R.L., Black, S.B., Coons, W.E., Ellingston, C.T., and R.L. Olsen. 1983. Brine Reservoirs in the Castile Formation, Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico. Project TME-3153. Westinghouse Electric Corporation, Carlsbad, N.M.

Popp, T., Minkley, W., Fillinger, E., and Boettge, V. 2018. "Closure of the Teutschenthal backfill mine – About the challenge to elaborate a geomechanical safety concept in salt formations". In: *The Mechanical Behavior of Salt IX.* Ed. by S. Fahland, J. Hammer, F. D. Hansen, S. Heusermann, K.-H. Lux, and W. M. Minkley, pp. 84–99.

Reedlunn, B. 2017. Joint Project III on the Comparison of Constitutive Models for the Mechanical Behavior of Rock Salt: Reinvestigation into Isothermal Room Closure Predictions at the Waste Isolation Pilot Plant, Proc. 9th Conference on the Mechanical Behavior of Salt

Reedlunn, B., Argüello, J.G., and Hansen F.D. 2022. A reinvestigation into Munson's model for room closure in bedded rock salt, International Journal of Rock Mechanics and Mining Sciences, Volume 151, ISSN 1365-1609, https://doi.org/10.1016/j.ijrmms.2021.105007.

Reedlunn, B.2022. Personal communication.

Roselle, G. T. 2013. Determination of Corrosion Rates from Iron/Lead Corrosion Experiments to be used for Gas Generation Calculations (Revision 1). Analysis Report, January 23, 2013. Sandia National Laboratories, Carlsbad, NM.ERMS 559077

Saiyouri, N., Alaiwa, A.A. and Hicker, P.Y. 2011. Permeability and porosity improvement of grouted sand, European Journal of Environmental and Civil Engineering, Taylor & Francis, Vol. 15, No. 3, pp. 77-97.

Sandia National Laboratories (SNL). 1992. Preliminary Performance Assessment for the Waste Isolation Pilot Plant, December 1992, Volume 1: Third Comparison with 40 CFR 191, Subpart B, SAND92-0700/1.

Sandia National Laboratories (SNL). 1997. Final, Supplemental Summary of EPA-Mandated Performance Assessment Verification Test (All Replicates) and Comparison with the Compliance Certification Application Calculations. ERMS 414879.

Stormont, J.C., Fernandez, S.G. Taha, M.R and Matteo, E.N. 2018. Gas flow through cement-casing microannuli under varying stress conditions, Geomechanics for Energy and Environment, Vol 13, pp. 1-13, DOI: 10.1016/j.gete.2017.12.001

TAPRBI (Tri-Agency Permeable Reactive Barrier Initiative). 2002. United States Department of Defense, U.S. Department of Energy and U.S. Environmental Protection Agency and Interstate Technology and Regulatory Council. Report prepared for Federal Remediation Technologies Roundtable (FRTR). https://www.epa.gov/sites/default/files/2015-04/documents/2-prbperformance_web.pdf

Thompson, T.W., Coons, W.E., Krumhansl, J.L. and Hansen, F.D. 1996. Inadvertent Intrusion Borehole Permeability, Final Draft. May 20, 1996. Sandia National Laboratories. Albuquerque, NM. Sandia WIPP Central Files ERMS # 241131.

U.S. Department of Agriculture Soil Conservation Service (USDA). 1991. Measurement and Estimation of Permeability of Soils for Animal Waste Storage Facility Design, Technical Note 717 prepared by South National Technical Center.

U.S. Department of Energy (DOE). 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant (October). 21 vols. DOE/CAO 1996-2184. Carlsbad, NM: Carlsbad Area Office.

U.S. Department of Energy (DOE). 2004. Title 40 CFR Part 191: Compliance Recertification Application for the Waste Isolation Pilot Plant (March). 10 vols. DOE/WIPP 2004-3231. Carlsbad, NM: U.S. Department of Energy, Carlsbad Field Office.

U.S. Department of Energy (DOE). 2014. Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application for the Waste Isolation Pilot Plant, Appendix TFIELD-2014 Transmissivity Fields. DOE/WIP-14-3503. Carlsbad, NM: U.S. Department of Energy, Carlsbad Field Office.

U.S. Department of Energy (DOE). 2019. Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application for the Waste Isolation Pilot Plant (March 26, 2019, and December 18, 2019). DOE/WIPP 2019-3609. Carlsbad, NM: U.S. Department of Energy, Carlsbad Field Office.

U.S. Department of Energy (DOE). 2022. Delaware Basin Monitoring Annual Report – Plugging Information. Draft report prepared by Regulatory Environmental Services (RES), October 11, 2022.

U.S. Environmental Protection Agency (EPA). 1998. Technical Support Document for Section 194.23: Potential Effects of Mining on Ground Water Flow and Radionuclide Transport at the WIPP Site, Docket No: A-93-02 V-B-8, May 1998.

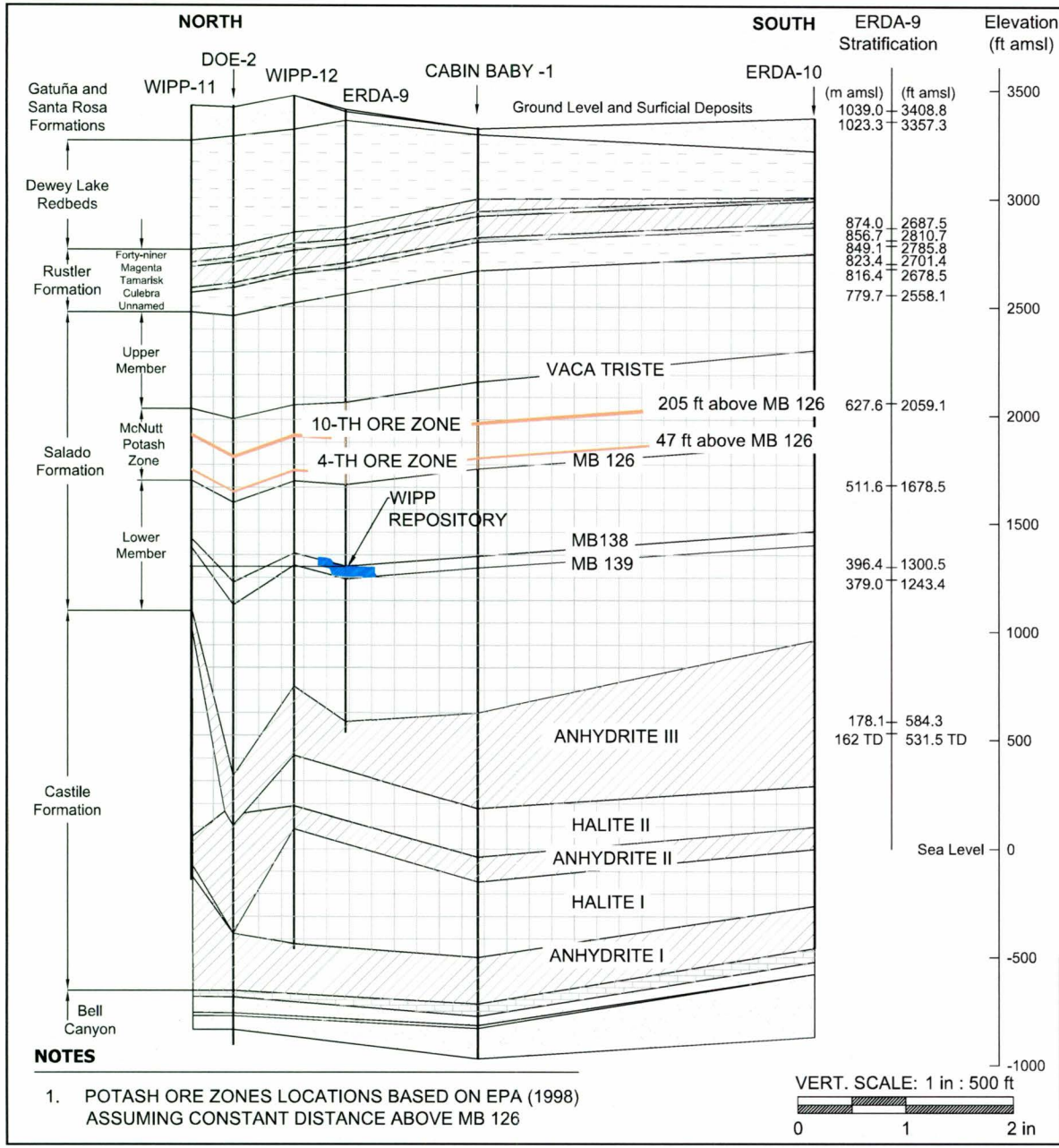
Wagner, S. and Hillesheim, M. 2009. Sandia National Laboratory Compliance Monitoring Parameter Assessment for 2009. Report No. WIPP:1.3.1:CO:QA-L:pkg 510062 prepared for the United States Department of Energy, November 2009.

Zeitler, T.R. 2018a. Cumulative Distribution for STEEL:CORRMCO2 for the CRA-2019 PA. Carlsbad, NM: Sandia National Laboratories. December 12, 2018, ERMS 570869

Zeitler, T.R. 2018b. Bounding Calculation of the Cumulative Distribution for STEEL:HUMCORR. Carlsbad, NM: Sandia National Laboratories. April 30, 3028, ERMS 569807

Zhang, Z. and Wang, H. 2015. Analyzing the relation between pore structure and permeability of alkali-activated concrete binders, in Handbook of Alkali-Activated Cements, Mortars and Concretes, F. Pacheco-Torgal, J.A. Labrincha, C. Leonelli, A. Palomo, P. Chindaprasirt Eds., Woodhead Publishing, pp. 235-264.

DRAWINGS

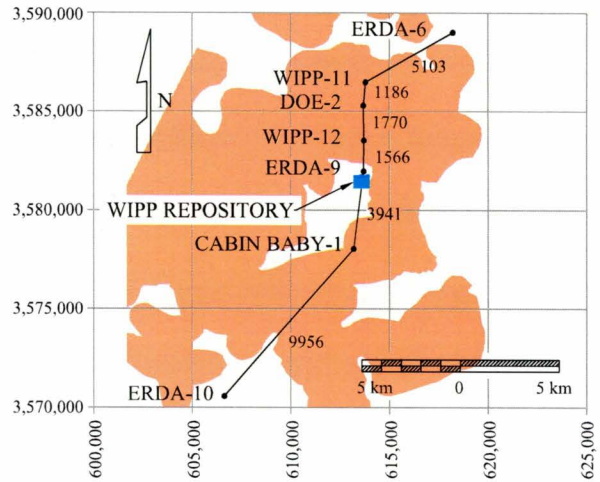


NOTES

1. POTASH ORE ZONES LOCATIONS BASED ON EPA (1998) ASSUMING CONSTANT DISTANCE ABOVE MB 126

LEGEND

- ANHYDRITE
- HALITE
- SANDSTONE
- MUDSTONE AND SILTSTONE
- DOLOMITE
- LIMESTONE
- PABC-2009 MINING AFFECTED AREAS WITHIN MODEL BOUNDARY



Note: distance between wells in meters

REFERENCES

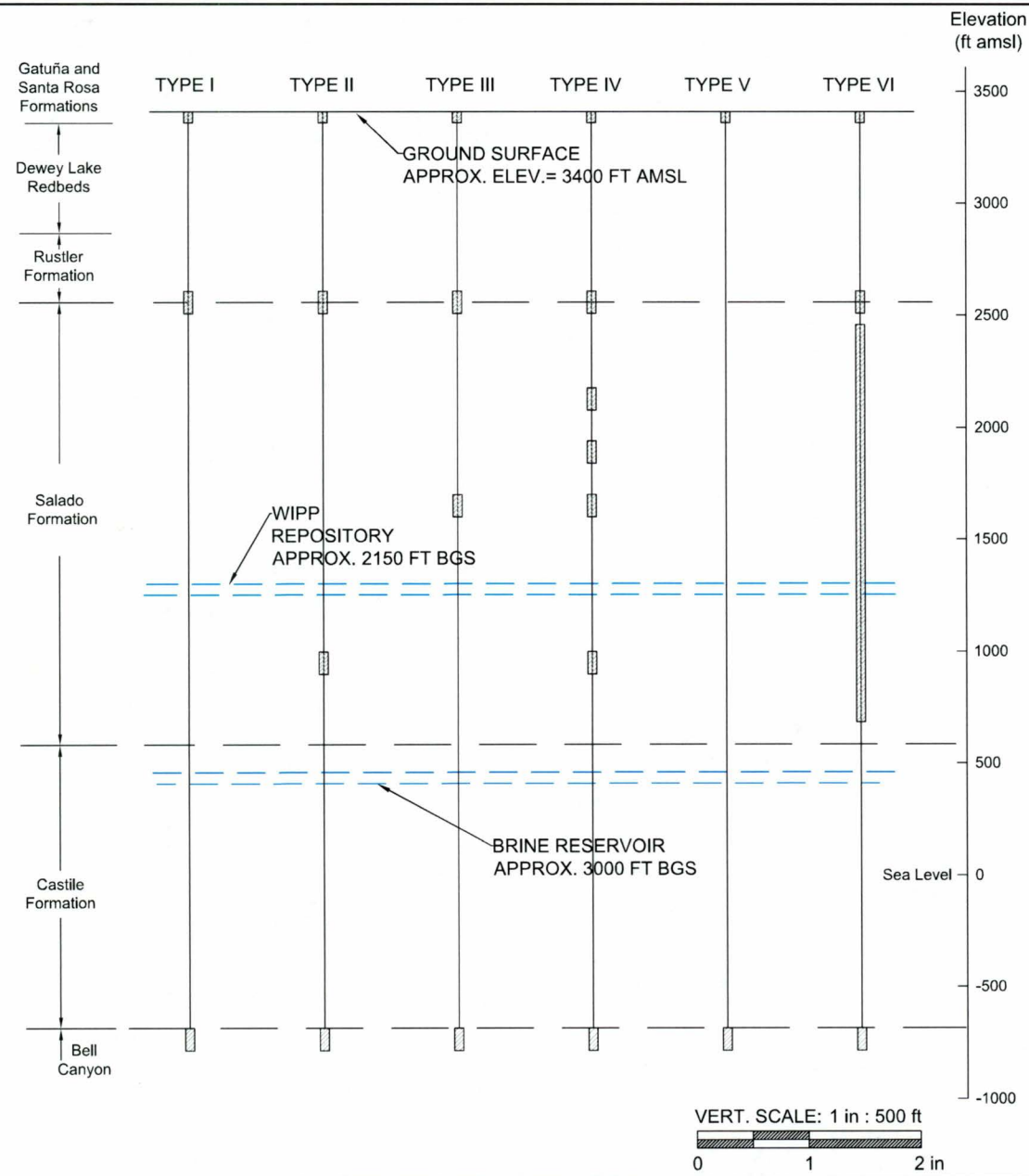
1. INFORMATION COMPILED BASED ON DATA IN EPA (1998), SNL (1992) AND CRA (2014)

ZG-GEO

TITLE: **WIPP STRATIGRAPHY AND POTASH ZONES**

PROJECT: **BOREHOLE PERMEABILITY**

PROJECT NO.	023-1001		
DRAWN	GG	CHECKED	MG
DATE	03/27/2023	REV.	0
SCALE	AS SHOWN	DRAWING NO.	1



LEGEND

- CONCRETE PLUG
- WIPP REPOSITORY (APPROX.)
- BRINE RESERVOIR (EST.)

NOTES

1. ALL DIMENSIONS ARE APPROXIMATE
2. HORIZONTAL PLUG THICKNESS IS EXAGGERATED APPROXIMATELY 27 TO 40 TIMES
3. SURFACE PLUG LENGTH - 50 FEET (15 METERS)
4. TOP, BOTTOM AND INTERMEDIATE PLUG LENGTHS - 100 FEET (30 METERS)

REFERENCES

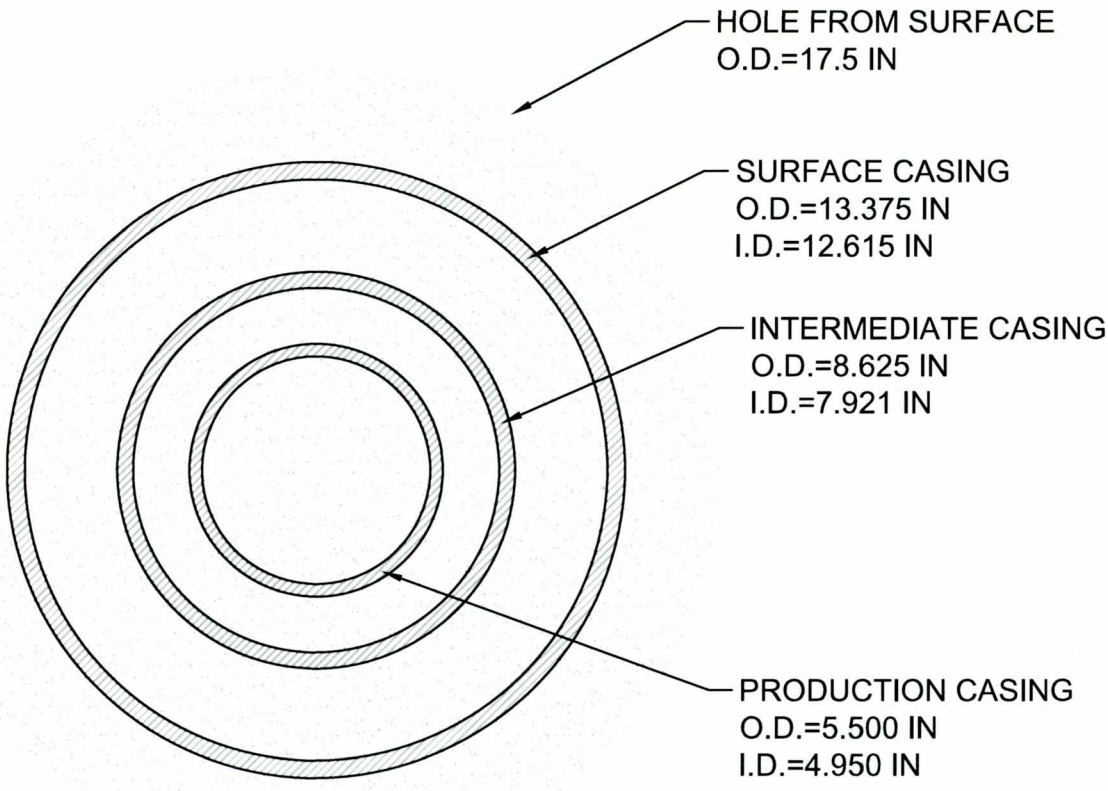
1. INFORMATION COMPILED BASED ON DATA IN BLM (1988), THOMPSON ET AL. (1996), EPA (1998), SNL (1992) AND CRA (2014).

ZG-GEO

TITLE: **BOREHOLE PLUGGING PATTERNS**

PROJECT: **BOREHOLE PERMEABILITY**

PROJECT NO.	023-1001		
DRAWN	GG	CHECKED	MG
DATE	03/28/2023	REV.	0
SCALE	AS SHOWN	DRAWING NO.	2



LEGEND

STEEL CASING

HYDRATED CEMENT

SCALE: 1 in : 4 in

REFERENCES

1. INFORMATION COMPILED BASED ON DATA IN THOMPSON ET AL. (1996)

ZG-GEO		TITLE: **PLUGGED BOREHOLE CROSS SECTION**	
PROJECT: **BOREHOLE PERMEABILITY**		PROJECT NO.	023-1001
		DRAWN GG	CHECKED MG
		DATE 04/17/2023	REV. 0
		SCALE AS SHOWN	DRAWING NO. 3

Appendix A

Description of Geomechanics Calculations for Borehole Closure

Appendix A

Description of Geomechanics Calculations for Borehole Closure

By James L. Bean

Dept. 1554 Solid Mechanics
Sandia National Laboratories

A.1 Overview

This appendix describes numerical modeling of the inadvertent intrusion borehole closure due to creep of the surrounding rock salt. The numerical model used in this analysis is conceptually similar to the one used in Thompson et al. (1996), Appendix D, but utilizes an updated constitutive model for salt creep by Reedlunn et al. (2022). This new creep model, implemented in the Sierra/SolidMechanics Version 5.4.1 (Sierra/SM) finite element code (SNL 2022), was used in this study to estimate the time dependent closure of a borehole at several depths and borehole pressure conditions. Using the closure results, along with the relationship between porosity and permeability adopted from Thompson et al. (1996), the permeability of the intrusion borehole fill material (degraded cement grout and degraded steel casing) was calculated as a function of the initial fill material porosity.

A.2 Model Geometry

The numerical model utilizes a 9-degree wedge with an (initial) inner radius of 6.125 inch (0.15558 m) corresponding to the radius (R_{bh}) of the borehole. The exterior radial boundary of the domain was fixed at 500 times the initial borehole radius, equal to 77.79 m, as shown in Figure A-1. The location of the exterior radial boundary is sufficiently large so that the displacements of the nodes at the borehole wall are not affected by the finite size of the domain.

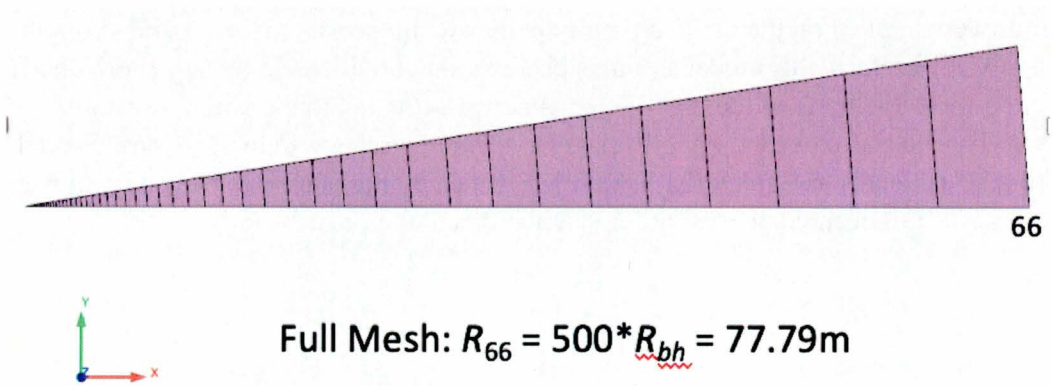


Figure A-1. Top view of the model mesh discretization

A single row of 65 8-node hexahedral elements was used. A growth factor of 1.1 was used so that the radial width of each element (ΔR_i) increases by 10% from the previous element:

$$\frac{\Delta R_{i+1}}{\Delta R_i} = 1.10 \text{ for } i = 1 \text{ to } 64. \quad \text{(A-1)}$$

The growth of element size for the first 31 elements of the domain is illustrated in Figure A-2.

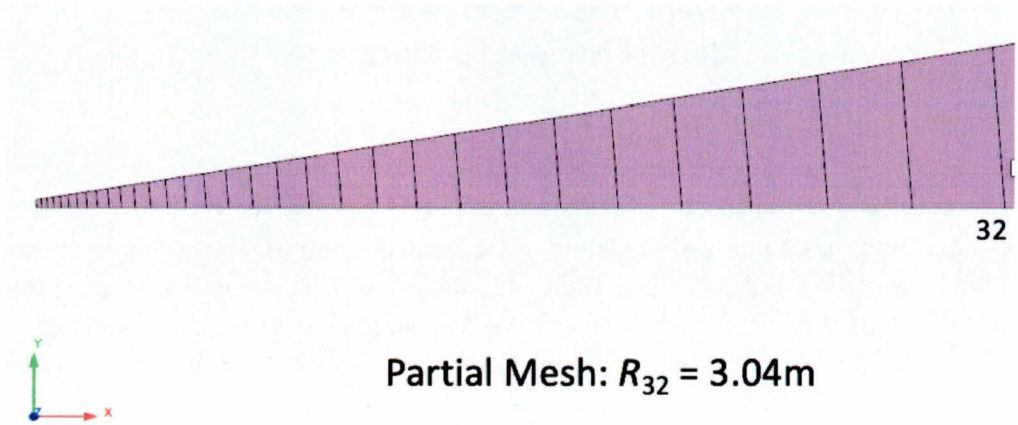


Figure A-2. Top view of the partial Sierra/SM finite element mesh

Figure A-2 shows that the first 31 elements occupy approximately 4% of the total radial distance of the domain. A relatively fine discretization near the borehole wall was used to improve the accuracy and capture the stress gradients near the borehole. All simulations used the selective deviatoric element formulation in Sierra/SM.

A.3 Boundary Conditions

A "roller" boundary condition preventing normal displacements was applied on all exterior surfaces of the model domain except the inner radius where a depth-dependent well pressure was applied. Figure A-3 shows the kinematic boundary conditions used to restrict the displacements in the normal direction to the boundaries. The same no normal displacement kinematic boundary conditions were applied on the top and bottom planes with normals in the +z and -z directions, respectively. Therefore, this model assumes plane strain conditions in the x-y (horizontal) plane. The z-dimension thickness of the row of elements was set equal to the borehole radius. Alternatively, one could expand the model in the vertical direction to include various geologic layers (e.g., clay seams and anhydrite layers) penetrated by the borehole. However, this level of complexity was not deemed necessary for calculations in the present study.

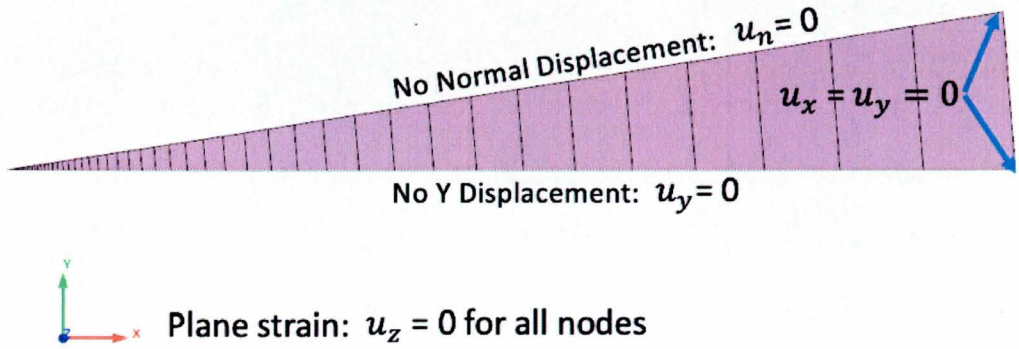


Figure A-3. Kinematic boundary conditions

A.4 Initial Stress Conditions and Borehole Pressure Conditions

The initial stress in the salt depends on the depth below the ground surface. For these simulations, the depths considered were 250 m, 450 m, 650 m and 850 m below the ground surface. The lithostatic stress gradient was assumed to be 1 psi/ft (22620.6 Pa/m). A constant temperature of 300 K (26.8°C) was used for all simulations. The adopted range of stresses and brine backpressures were selected based on previous calculations (Thompson et al. 1996, Appendix D) and reported field conditions (Popielak et al. 1983).

Three different borehole pressures were considered:

- Case 1 – dry borehole scenario
- Case 2 – hydrostatic scenario. This model assumes hydrostatic backpressure inside the borehole based on a brine density of 1200 kg/m^3 and a gravity acceleration g=9.81 m/s^2.
- Case 3 – WIPP-12 scenario. This model assumes backpressure based on the initial WIPP-12 wellhead pressure reported by Popielak et al. (1983).

Initial stresses and borehole backpressures used for borehole closure simulations at different depths are summarized in Table A-1. The initial stress state was assumed to be isotropic.

Table A-1. Boundary Conditions for Creep Calculations

Depth (m)	Location	Initial Stress (MPa)	Case 1 Backpressure (MPa)	Case 2 Backpressure (MPa)	Case 3 Backpressure (MPa)
250	Top of Salado	5.64	0.00	2.94	4.38
450	Salado	10.15	0.00	5.30	6.73
650	Repository elevation	14.70	0.00	7.65	9.09
850	Bottom of Salado	19.18	0.00	10.01	11.44

A.5 Munson-Dawson (MD) Viscoplastic Constitutive Model

The steady state or secondary creep rates of the rock salt for the legacy and the updated Munson-Dawson (MD) models can be estimated based on information from Reedlunn et al. (2022).

$$\dot{\varepsilon}^{ss} = \sum_{i=0}^{i=3} \dot{\varepsilon}_i^{ss} \tag{A-2}$$

$$\dot{\varepsilon}_i^{ss} = A_i \exp\left(-\frac{Q_i}{RT}\right)\left(\frac{\bar{\sigma}}{G}\right)^{n_i} \text{ for i } = 0, 1, \text{ and } 2 \tag{A-3}$$

$$\dot{\varepsilon}_3^{ss} = H(\bar{\sigma} - \bar{\sigma}_g)\sum_{i=0}^{i=2} B_i \exp\left(-\frac{Q_i}{RT}\right) \sinh\left[q\frac{(\bar{\sigma} - \bar{\sigma}_g)}{G}\right] \tag{A-4}$$

The updated MD model includes an additional term $\dot{\varepsilon}_0^{ss}$ to account for the low stress steady state creep behavior but the term has the same form as $\dot{\varepsilon}_1^{ss}$ and $\dot{\varepsilon}_2^{ss}$ in the legacy MD model. This additional mechanism is believed to be governed by pressure solution redeposition along grain boundaries and is dependent on grain size and moisture content. For dry salt (moisture content equal to zero) this creep mechanism is not observed. Mechanism 1 ($\dot{\varepsilon}_1^{ss}$) dominates at high temperaures and low equivalent stresses. Mechanism 2 ($\dot{\varepsilon}_2^{ss}$) dominates at low temperatures and medium equivalent stresses. Mechanism 3 ($\dot{\varepsilon}_3^{ss}$) models dislocation glide, which is only activated when $\bar{\sigma}$ exceeds $\bar{\sigma}_g$, as reflected in the use of the Heaviside function. For simulations in this study, it can be shown that mechanisms 1 and 3 are not significant due to the low temperature (300K) and relatively low equivalent stresses, i.e. $\bar{\sigma} < \bar{\sigma}_g$. While both the updated and legacy MD models include the influence of primary or transient creep, these effects are often negligible in comparison to the steady-state creep deformation. Hence, while the Sierra/SM simulations utilized the MD model with all three deformation mechanisms, only the relevant steady-state creep parameters and their values are listed in Table A-2. A more complete description of the updated MD model can be found in Reedlunn et al. (2022).

Table A-2. MD Viscoplastic Model Parameters for Legacy and Updated Calibration of WIPP Salt (after Reedlunn et al. 2022)

Parameter	Units	Legacy MD Clean Salt	Legacy MD Argillaceous Salt	Updated Model (Cal. 3B)
G	GPa	12.4	12.4	12.4
A_0	s^{-1}	0	0	5.617×10^{1}
Q_0/R	K	0	0	5,123
n_0	-	0	0	1.595
A_1	s^{-1}	8.386×10^{22}	1.407×10^{23}	8.386×10^{22}
Q_1/R	K	12,580.5	12,580.5	12,580.5

Parameter	Units	Legacy MD Clean Salt	Legacy MD Argillaceous Salt	Updated Model (Cal. 3B)
n_1	-	5.5	5.5	5.5
A_2	s^{-1}	9.672×10^{12}	1.314×10^{13}	4.415×10^{16}
Q_2/R	K	5,032.2	5,032.2	5,123
n_2	-	5.0	5.0	6.279
$\overline{\sigma}_g$	MPa	20.57	20.57	20.57
B_0	s^{-1}	0	0	0
B_1	s^{-1}	6.086×10^{6}	8.998×10^{6}	6.086×10^{6}
B_2	s^{-1}	3.034×10^{-2}	4.289×10^{-2}	3.034×10^{-2}
q	-	5,335	5,335	5,335

The parameter values in Table A-2 were used to calculate the steady-state creep strain rates as a function of the equivalent stress, as shown in Figure A-4.

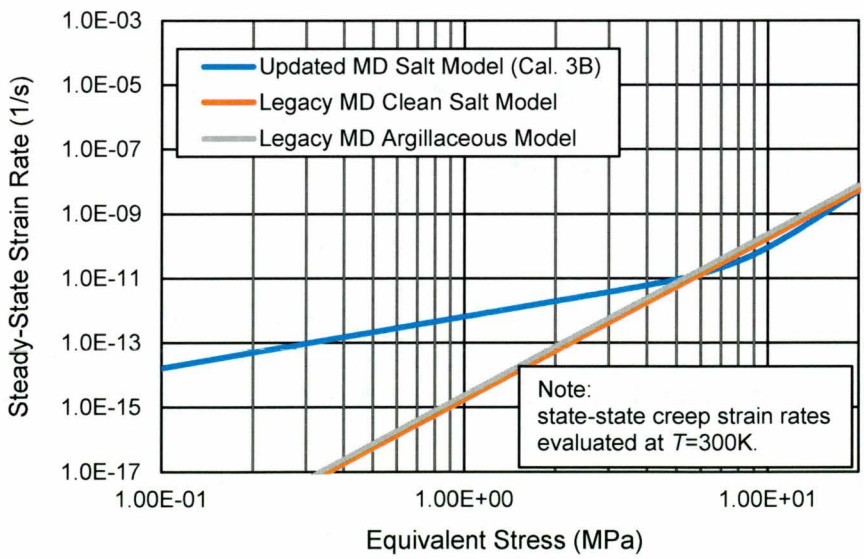


Figure A-4. Steady state creep strain rates estimates for WIPP rock salt

Note that the more recent calibration (Cal. 3B) does not distinguish between clean and argillaceous salt as discussed in more detail in Reedlunn et al. (2022). The creep strain rates in the updated model are similar to those in the legacy Munson-Dawson model for equivalent stresses above 6 MPa (see e.g., Munson and Dawson 1979, 1982) while the lower equivalent stress creep rates are significantly different. The legacy MD model would be expected to

underestimate the creep closure of boreholes when the equivalent stresses are below ~6 MPa, i.e., for scenarios where the pressure solution is the dominant creep mechanism.

The MD model is evaluated at 8 gauss points within each Sierra/SM element to determine the stiffness contribution to the nodal internal force vector. These internal forces balance with the applied external forces to satisfy the quasi-static equilibrium conditions.

A.6 Simulation Results - Borehole Closure

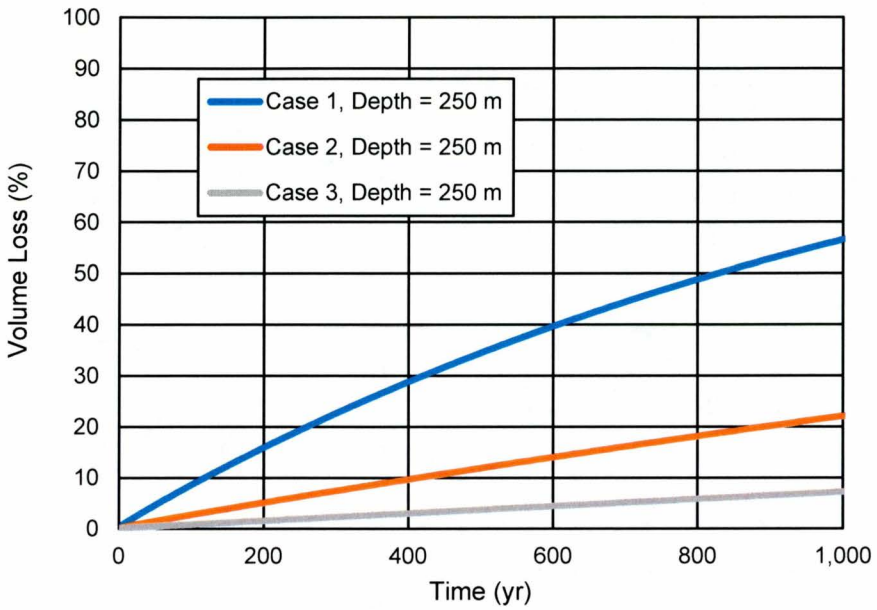
The borehole closure results in this section are based on the updated MD model. An estimate of the maximum amount of borehole closure can be made by assuming an initial borehole diameter (D_{bh}) of 12.25 inch (0.31115 m) and inside diameter of the internal casing (D_c) of 7.921 inch (0.20119 m). The maximum allowable area reduction is assumed to correspond to the area inside the inner casing (A_c). Expressed as a fraction of the initial bore area(A_{bh}), the area loss (A_L) can be expressed as:

$$A_L = \left({}^{A_c}/_{A_{bh}}\right) = \left({}^{D_c^2}/_{D_{bh}^2}\right) = 0.418 \tag{A-5}$$

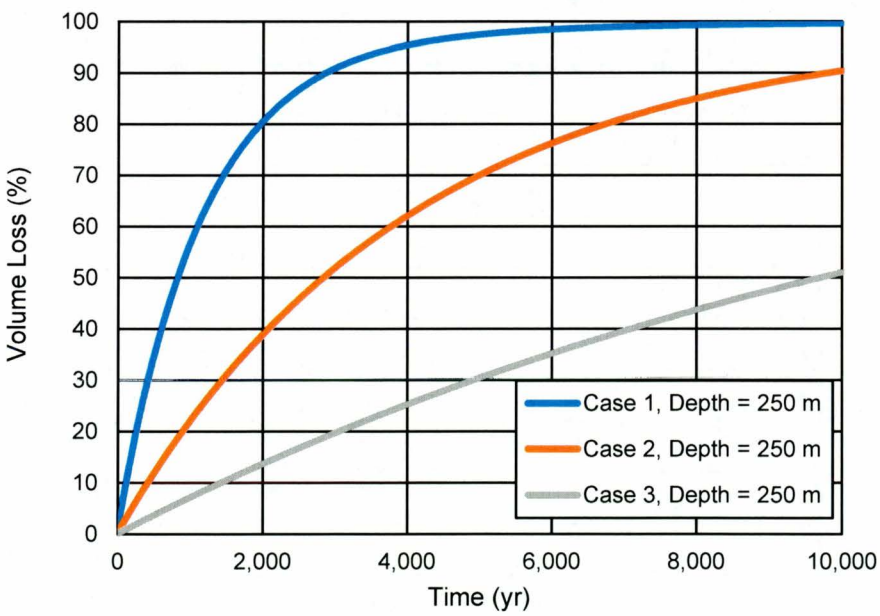
We define the volume loss due to borehole closure as a function of time (t) using the following equation:

$$Volume\ Loss(t) \ = \ V_L(t) = \left(\frac{V_{bh}(0)-V_{bh}(t)}{V_{bh}(0)}\right) \tag{A-6}$$

As noted earlier, the simulations are performed in plane strain mode; therefore, volume loss and area loss are equivalent ($A_L = V_L$). Since the performed simulations are not accounting for the stiffness of borehole fill materials (cement and casing), given enough time, the 12.25-inch diameter borehole is allowed to close completely. From a practical standpoint, it is reasonable to limit the volume loss to 41.8% because at that point the cement and casing would be completely filling the borehole. Figures A-5 to A-8 show the borehole volume loss at four selected depths for three backpressure case scenarios (i.e. for zero pressure, hydrostatic brine pressure and brine pressures encountered at the WIPP-12 well). The graphical presentation of the borehole volume loss with time is provided using two different time scales: a) 0-1,000 years and b) 0-10,000 years. As a reminder, the volume loss is limited to 41.8% which will truncate any predicted response with a volume loss greater than 41.8%.

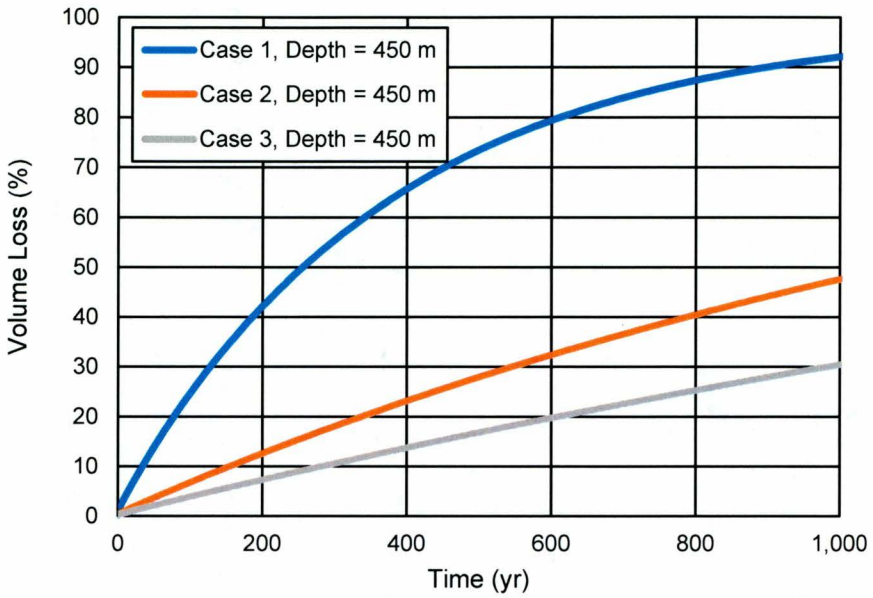


(a) Time range of 0-1,000 years

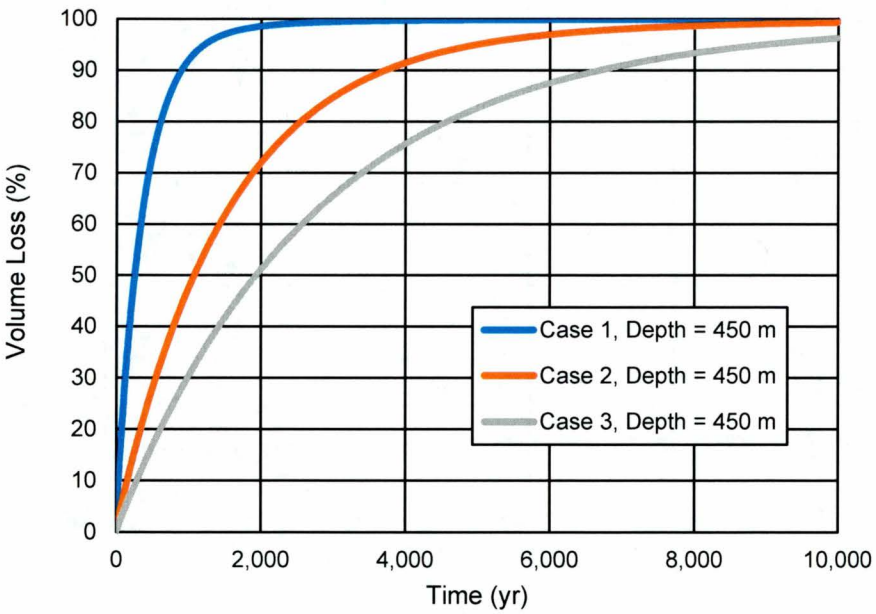


(b) Time range of 0-10,000 years

Figure A-5. Borehole volume loss at depth of 250 meters

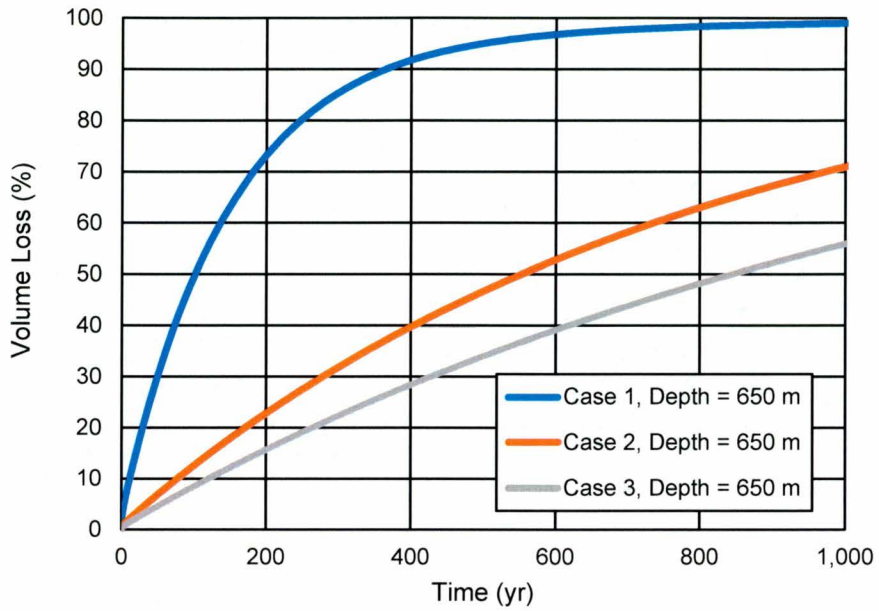


(a) Time range of 0-1,000 years

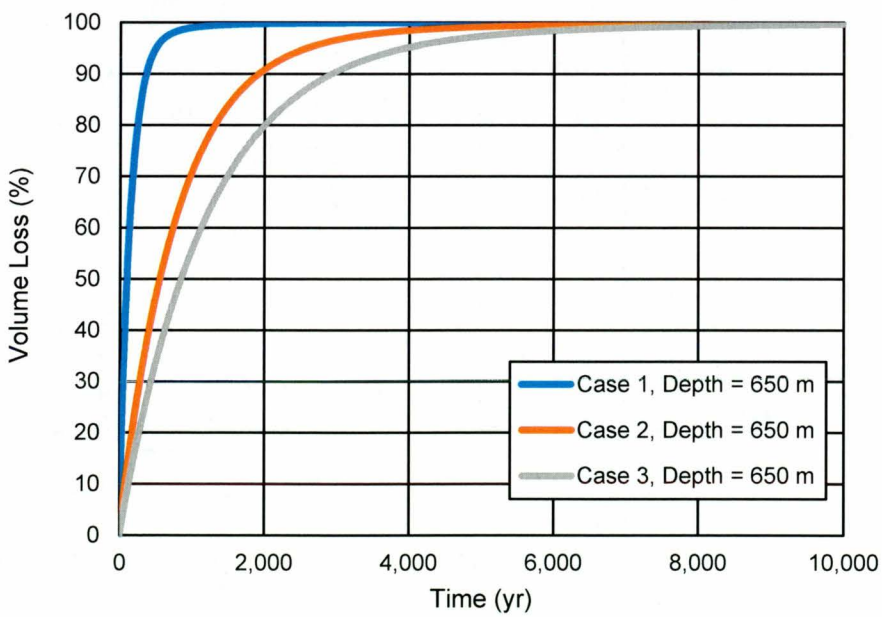


(b) Time range 0-10,000 years

Figure A-6. Borehole volume loss at depth of 450 meters

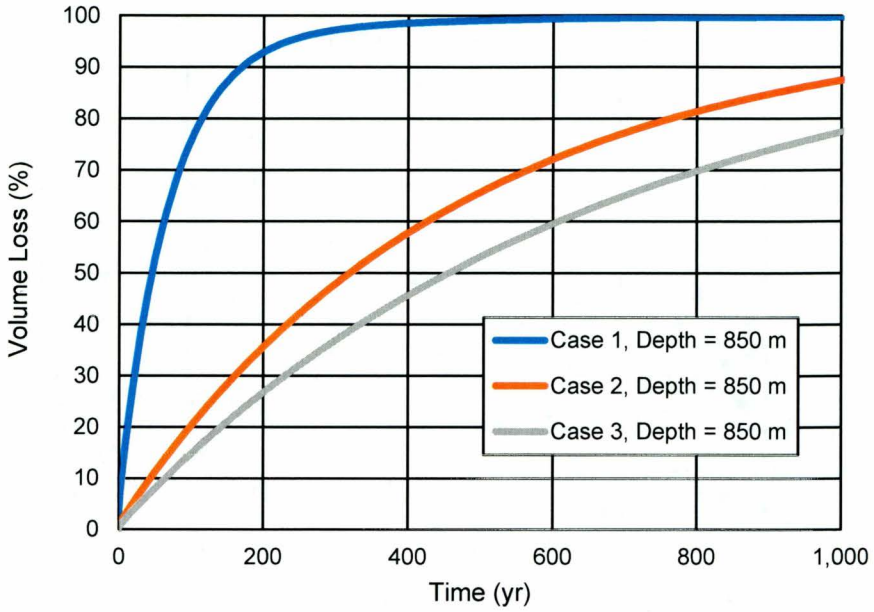


(a) Time range 0-1,000 years

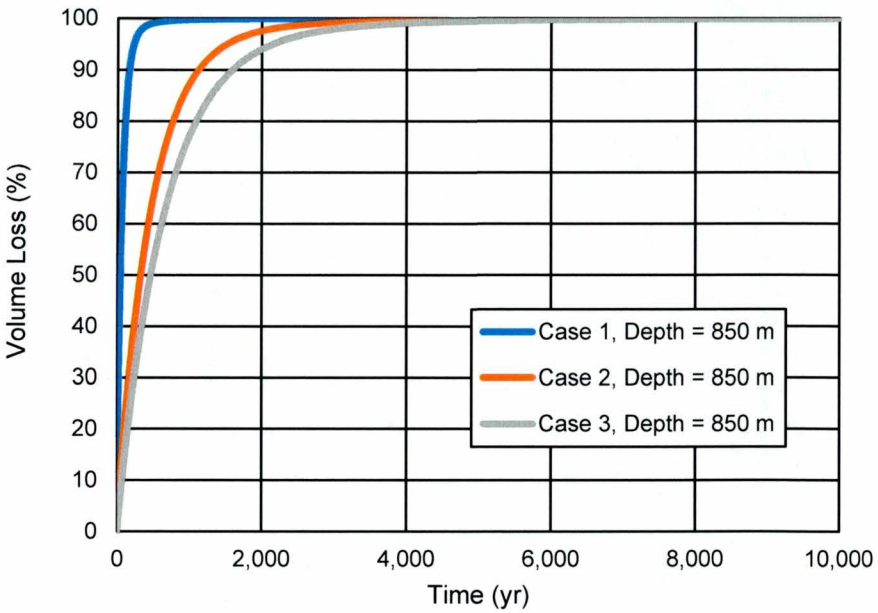


(b) Time range 0-10,000 years

Figure A-7. Borehole volume loss at depth of 650 meters



(a) Time range 0-1,000 years

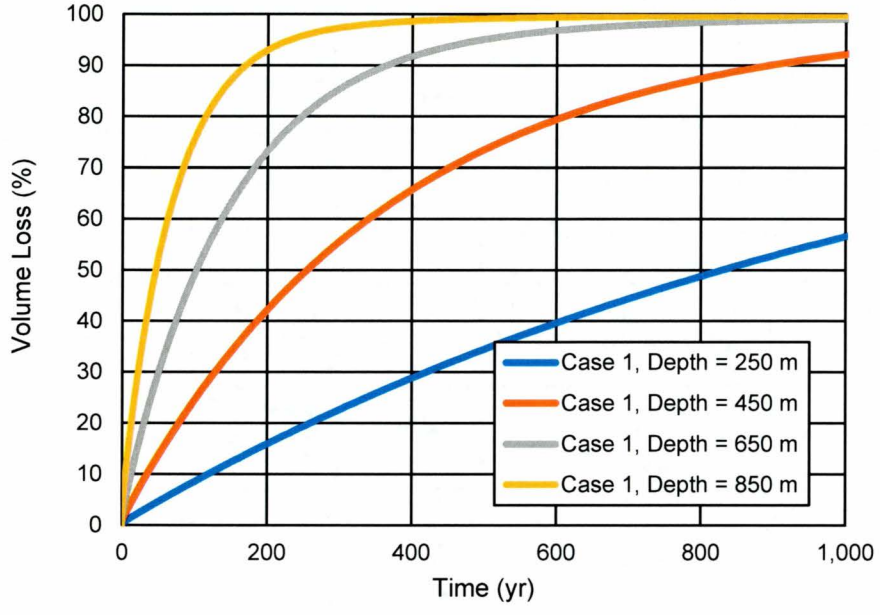


(b) Time range 0-10,000 years

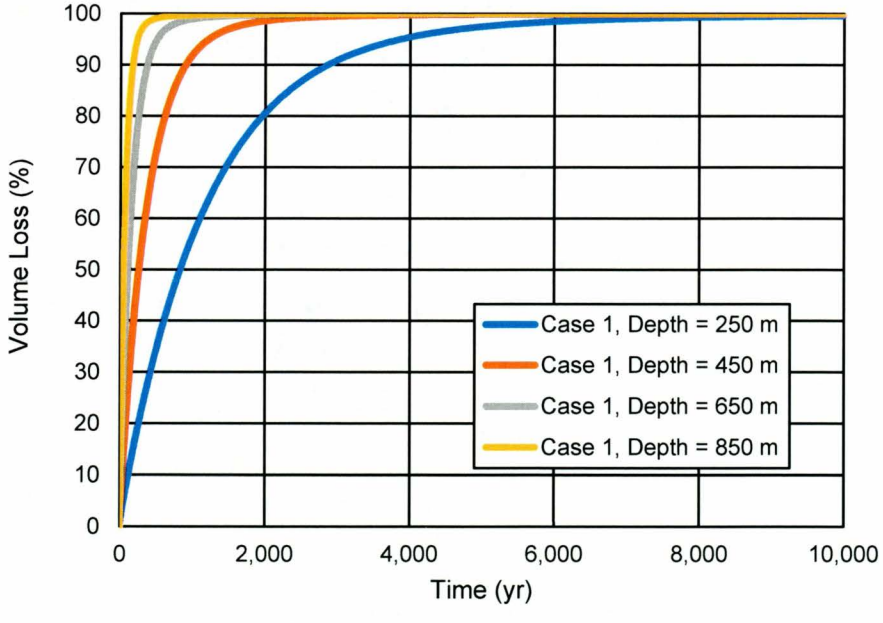
Figure A-8. Borehole volume loss at depth of 850 meters

As expected, the case scenarios with larger backpressures exhibit slower creep resulting in slower volume loss at all depths because the brine pressure in the borehole resists the inward

creep of the surrounding salt. The creep closure results comparing the volume loss at different depths for individual backpressure scenarios are presented in Figures A-9 to A-11.

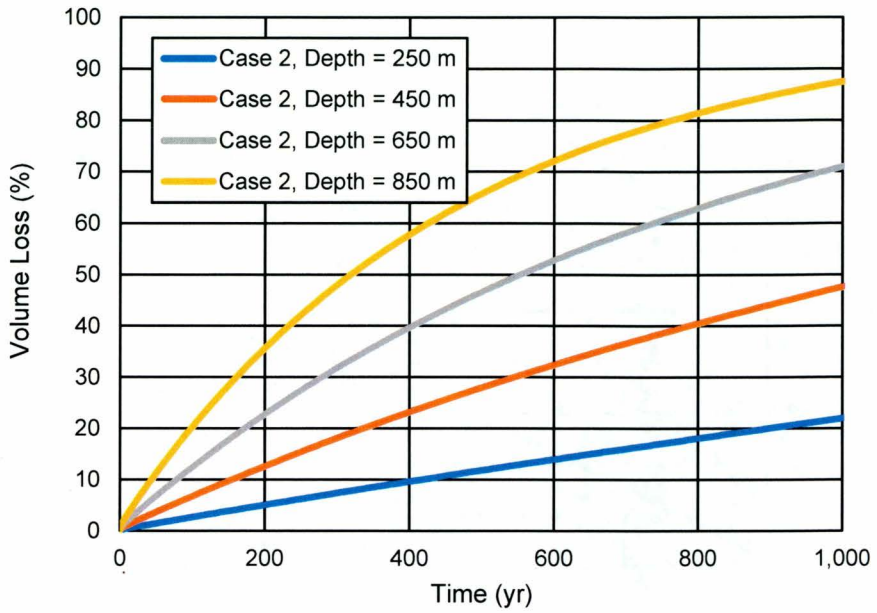


a) Time range 0-1,000 years

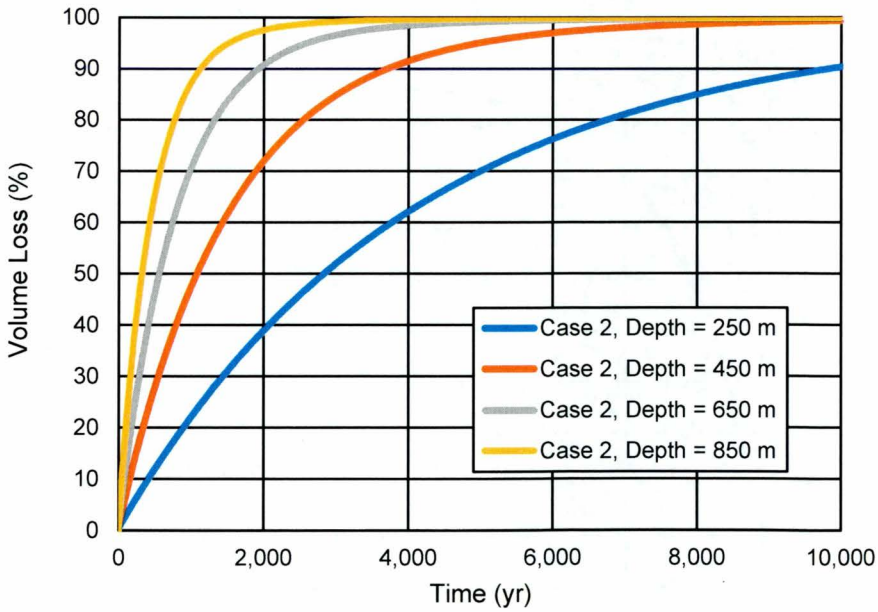


b) Time range 0-10,000 years

Figure A-9. Borehole volume loss - Case 1 scenario

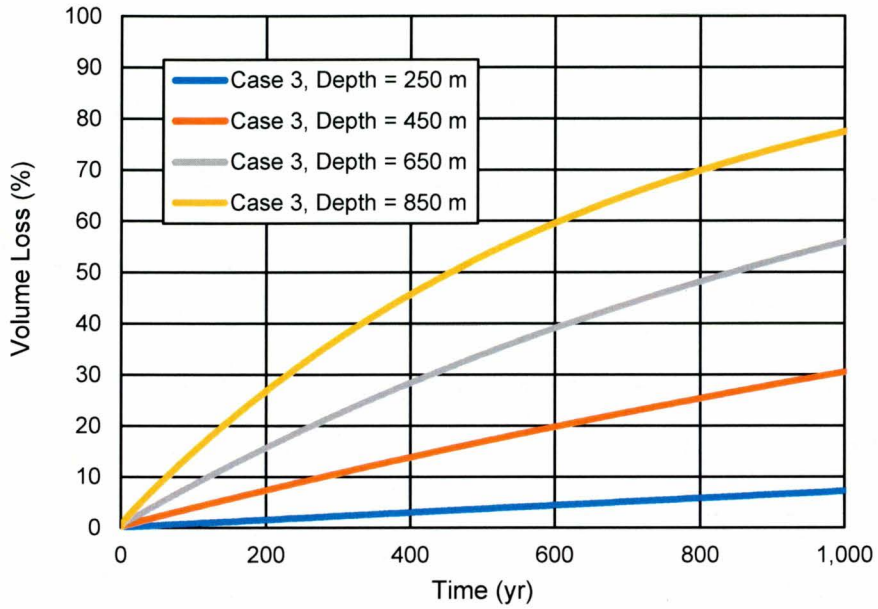


(a) Time range 0-1,000 years

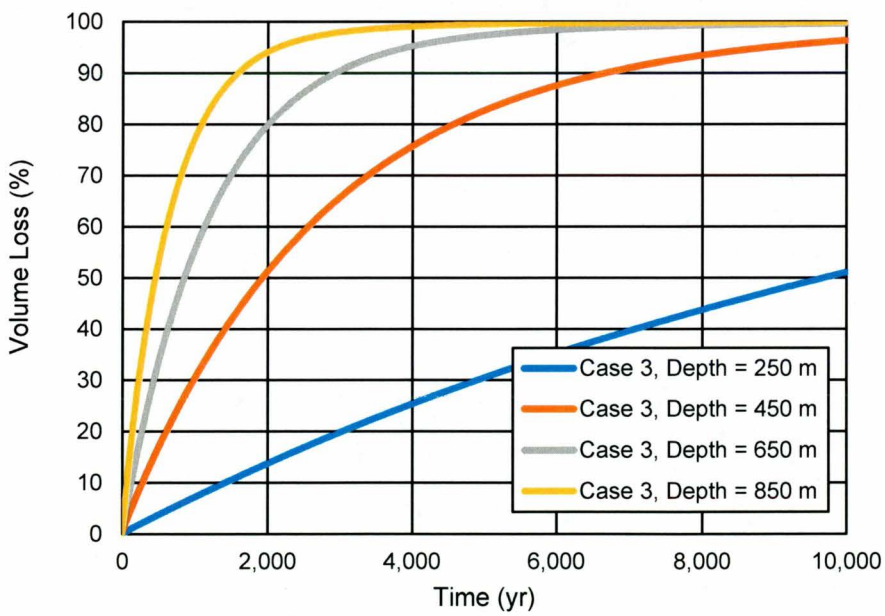


(b) Time range 0-10,000 years

Figure A-10. Borehole volume loss - Case 2 scenario



(a) Time range 0-1,000 years



(b) Time range 0-10,000 years

Figure A-11. Borehole volume loss - Case 3 scenario

For all depths considered and for each of the borehole (back)pressure cases, the volume loss exceeds 41.8% within the 10,000-year simulation period. The times when the volume loss reaches 41.8% are summarized in Table A-3.

Table A-3. Time (Years) to Reach Volume Loss of 41.8%

Depth (m)	Case 1	Case 2	Case 3
250	643	2,207	7,523
450	198	836	1,500
650	78.3	429	656
850	35.1	248	354

A.7 Simulation Results – Borehole Fill Permeability

The porosity (ϕ) is defined as

$$\phi = \frac{volume\ of\ voids}{volume\ of\ solids + volume\ of\ voids} = \frac{V_v}{V_s+V_v} = \frac{V - V_s}{V} \tag{A-7}$$

leading to the following relationships between the volume of solids (V_s) and porosity:

$$\frac{V_s}{V} = 1 - \phi = 1 - \frac{V_v}{V} \tag{A-8}$$

If we assume that the volume of solids is constant (assume that solids are incompressible), one can express the ratio between the current volume, $V(t)$, and the initial volume, V_0, as:

$$\frac{V(t)}{V_0} = 1 - V_L(t) = \frac{1-\phi_0}{1-\phi} \tag{A-9}$$

where ϕ_0 is the initial porosity, i.e. the porosity value at time equal to zero and $V_L(t)$ is the volume loss as a function of time. The borehole fill permeability can be estimated using the Kozeny-Carman relationship (see e.g., Thompson et al. 1996, Appendix D):

$$\mathrm{k} = \alpha\frac{\phi^3}{(1-\phi)^2} \tag{A-10}$$

resulting in the following relationship for the ratio between the current permeability (k) and the initial permeability (k_0) values:

$$\frac{k}{k_0} = \left(\frac{\phi}{\phi_0}\right)^3\left(\frac{1-\phi_0}{1-\phi}\right)^2 = \left(\frac{\phi}{\phi_0}\right)^3[1 - V_L(t)]^2 \tag{A-11}$$

For the initial porosity value, $\phi_0 = 0.418$, and the initial permeability, $k_0 = 1 \times 10^{-10}\ m^2$ (conservatively assumed to correspond to the permeability of intact/uncorroded granular iron), one can utilize Equation (A-11) to calculate the borehole fill permeability as a function of the borehole volume loss. The results of the borehole fill permeability calculations are shown in Figures A-12 through A-15.

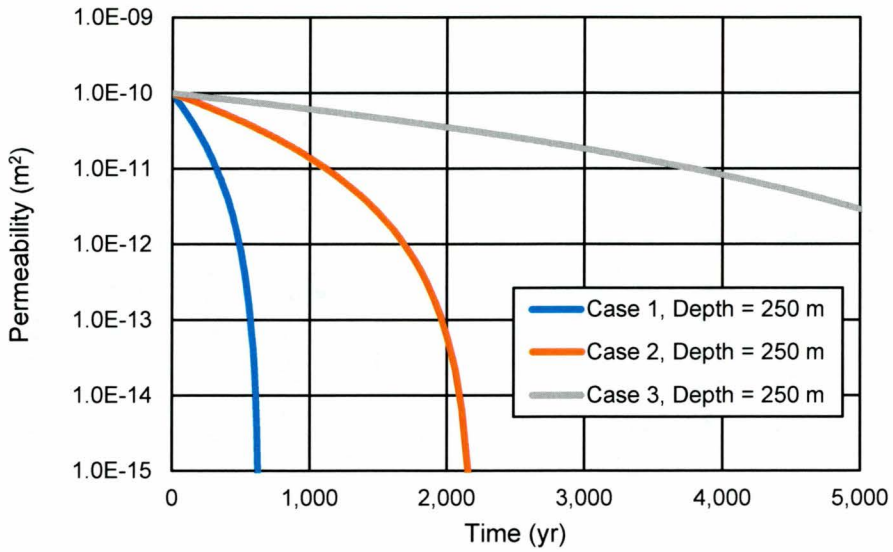


Figure A-12. Permeability for depth = 250 m

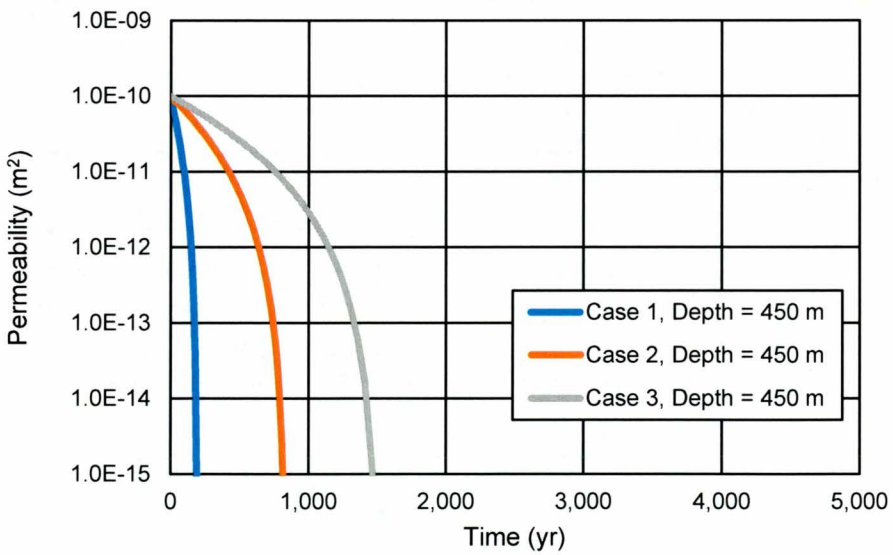


Figure A-13. Permeability for depth = 450 m

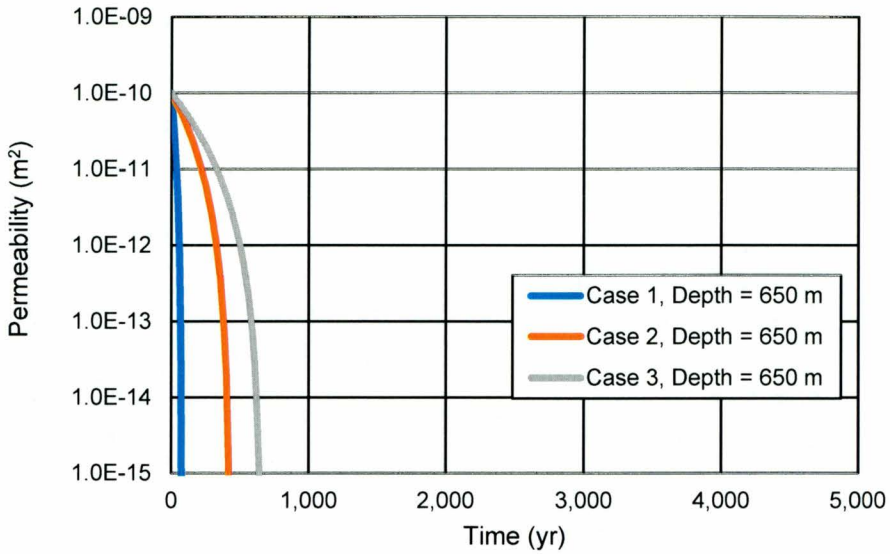


Figure A-14. Permeability for depth = 650 m

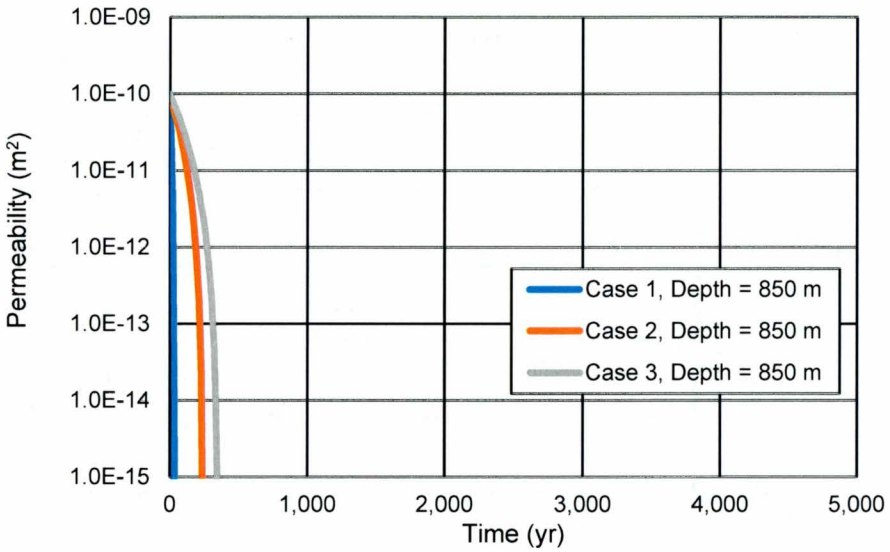


Figure A-15. Permeability for depth = 850 m

The times to reduce the initial borehole permeability by different orders of magnitude are provided in Tables A-4 to A-7. As an example, at a depth of 250 meters (Table A-4), the time to reduce the permeability by one order of magnitude varies from 323 years for the case without backpressure (Case 1) to over 3,700 years when the brine pressure simulating the WIPP-12 well scenario is applied. At the WIPP repository depth of 650 meters (Table A-6), the time required to reduce the initial permeability by one order of magnitude varies from 37 years to 329 years. The additional time required for the borehole fill permeability to exhibit further permeability

reduction (i.e., to reach the permeability reduction by two, three or more orders of magnitude) is significantly reduced.

Table A-4. Time (Years) to Reach Various Permeability Reductions for 250-meter Depth

Depth = 250 m: Years to reach k/k_0			
k/k_0	Case 1	Case 2	Case 3
1×10^{-1}	323	1,112	3,779
1×10^{-2}	490	1,684	5,732
1×10^{-3}	571	1,962	6,681
1×10^{-4}	610	2,091	7,130
1×10^{-5}	628	2,153	7,341
1×10^{-6}	639	2,209	7,409

Table A-5. Time (Years) to Reach Various Permeability Reductions for 450-meter Depth

Depth = 450 m: Years to reach k/k_0			
k/k_0	Case 1	Case 2	Case 3
1×10^{-1}	98	420	756
1×10^{-2}	150	638	1,144
1×10^{-3}	175	743	1,331
1×10^{-4}	186	793	1,419
1×10^{-5}	193	816	1,466
1×10^{-6}	201	829	1,509

Table A-6. Time (Years) to Reach Various Permeability Reductions for 650-meter Depth (at the repository horizon)

Depth = 650 m: Years to reach k/k_0			
k/k_0	Case 1	Case 2	Case 3
1×10^{-1}	37	215	329
1×10^{-2}	58	327	500
1×10^{-3}	69	381	583
1×10^{-4}	73	406	622
1×10^{-5}	77	419	640
1×10^{-6}	81	426	649

Table A-7. Time (Years) to Reach Various Permeability Reductions for 850-meter Depth (at the bottom of the Salado

Depth = 850 m: Years to reach k/k_0			
k/k_0	Case 1	Case 2	Case 3
1×10^{-1}	15	123	176
1×10^{-2}	24	188	269
1×10^{-3}	31	220	314
1×10^{-4}	34	233	335
1×10^{-5}	37	239	346
1×10^{-6}	40	245	356

Appendix B

Calculation of Borehole Debris Volumes and Permeabilities
Supporting Information

Appendix B

Calculation of Borehole Debris Volumes and Permeabilities – Supporting Information

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B.1 Overview

This appendix documents inputs and assumptions used to evaluate the volume of the degraded borehole fill materials (cement and steel casing) and provides additional information on the borehole fill permeability estimates.

B.2 Borehole Fill Volume

An estimate for the degraded borehole fill volume was determined assuming the cement grout bulking factor of 30 percent and an increase in the steel volume of approximately 3.5 times, based on Thompson et al. (1996, Appendices C and D), and assuming that the iron hydroxide will be the main product of the corrosion process.

The predicted volume of the degraded borehole fill is summarized in Table B-1.

Table B-1. Degraded Borehole Fill Volumes

Scenario	Degraded Cement Volume (m^3)	Corroded Steel Volume (m^3)	Borehole Debris Volume (m^3)	$V_{Debris}/V_{Borehole}$† (m^3)
Condition No. 1 – without annulus grouting	85.5	34.8	120.3	1.04
Condition No. 2 – with annulus grouting	112.1	47.6	159.7	1.38

† The ratio between the borehole debris fill and the clear borehole volumes was calculated assuming no spalling during the borehole development. The clear borehole volume (w/out plugs), $V_{Borehole}$, is 115.3 m^3.

Details of the borehole fill calculations are presented in Attachment B-1.

B.3 Borehole Fill Permeability Estimates

Estimates for the borehole fill and cement plug permeability were developed based on the available information including:

- Documented historical performance – see e.g., Bonen (1996)
- Field-testing data – see e.g., Christensen and Hunter (1980) and Popielak et al. (1983)
- Laboratory testing – see e.g., Onofrei et al. (1992) and Stormont et al. (2018)

- Updated literature data on cement materials and numerical models – see e.g. Matteo and Scherer (2012), Reedlunn et al. (2022)

To develop an estimate for the upper bound permeability for a borehole filled with degraded cement and steel casing materials (and capped with the cement plugs with the initial permeability from 10^{-19} to 10^{-17} m^2, see e.g., DOE 2019), one should recognize the complexity of chemical and hydro-geo-mechanical processes affecting both the cement and steel casing long-term performance. Considering the complexity of the problem, available laboratory and numerical estimates were scrutinized against data collected for the WIPP-specific conditions with an emphasis placed on the long-term geo-mechanical and hydrological performance. Based on the nature of the WIPP rock salt, case studies on the geological formations containing potash minerals (Popp et al. 2018, Reedlunn 2022), as well as the WIPP-specific monitoring data (Wagner and Hillesheim 2009), it is reasonable to expect for the cement plugs in the Salado formation to exhibit significantly larger confinement than originally predicted by Thompson et al. (1996). Consequently, degraded cement and steel casing is likely to exhibit larger normal and shear stresses than originally anticipated resulting in a more favorable hydrological performance than predicted by Thompson et al. (1996). These findings are also supported by recent data for the halite behavior under lower deviatoric stresses (Reedlunn et al. 2017, 2022) and the accompanying numerical analyses.

After considering the available information collected since the Thompson et al. (1996) report, one may expect the borehole cement and steel materials to maintain hydraulic performance within the range attained shortly after installation (or even to exhibit performance improvements as the hydraulic conductivity decreases due to the increased borehole confinement with time). The worst-case scenario for the borehole fill materials, in terms of the chemical degradation under expected stresses, is to assume that the "equivalent" borehole fill resembles the granular soil behavior with the grain-size distribution approximating the particle size distribution of cement powders (i.e. to assume that the degraded cement grout behaves as a material before inception of the hydration process). In this case, the hydraulic conductivity can be estimated based on the corresponding particle size distribution (PSD) relationship, e.g. using Hazen's equation (see e.g. Hazen 1892, 1911 and Carrier 2003):

$$K = \mathrm{C} \times d_{10}^2 \qquad \text{(B-1)}$$

where

K = hydraulic conductivity (cm/s)

C = Hazen's coefficient, typically set to unity if d_{10} is in (mm) and K is in (cm/s)

d_{10} = particle size representing 10^{th}-percentile value on the grain size distribution curve (mm)

Other formulations, such as the Kozeny-Carman relationship (see e.g. Carrier 2003, Odong 2007) are based on the capillary tube model considering additional soil parameters (e.g., porosity, void ratio, specific surface area and tortuosity), as well as permeating fluid parameters

(viscosity and unit weight), to determine the value of the hydraulic conductivity (see e.g. Carrier 2003):

$$K = \frac{\gamma_w}{\mu}\frac{1}{C_{KC}}\frac{1}{S_0^2}\frac{e^3}{1+e} \quad \text{(B-2)}$$

or Odong (2007)

$$K = \frac{\gamma_w}{\mu} \times 8.3 \times 10^{-3}\left[\frac{\phi^3}{(1-\phi)^2}\right] d_{10}^2 \quad \text{(B-3)}$$

where

γ_w = unit weight of the permeating fluid (N/m^3)

μ = dynamic viscosity of the permeating fluid (Pa s)

e = void ratio (-)

ϕ = porosity, $\phi = e/(1+e)$ (-)

S_0 = specific surface area (1/m)

C_{KC} = Kozeny-Carman constant, typically C_{KC}=5 (see e.g. Carrier 2003)

The Hazen's equation defined by Equation (B-1) may be re-written in a dimensionally consistent form (see e.g. Odong 2007) as:

$$K = \frac{\gamma_w}{\mu} \times 6.0 \times 10^{-4}[1 + 10(\phi - 0.26)]d_{10}^2 \quad \text{(B-4)}$$

To estimate the value of hydraulic conductivity for a degraded cement grout, the particle size, d_{10}, in Equations (B-1), (B-3) and (B-4) needs to be determined from the PSD curve.

The range of particle size distribution (PSD) curves for the cement powder, determined during the round-robin testing program by Ferraris et al. (2004), is illustrated in Figure B-1.

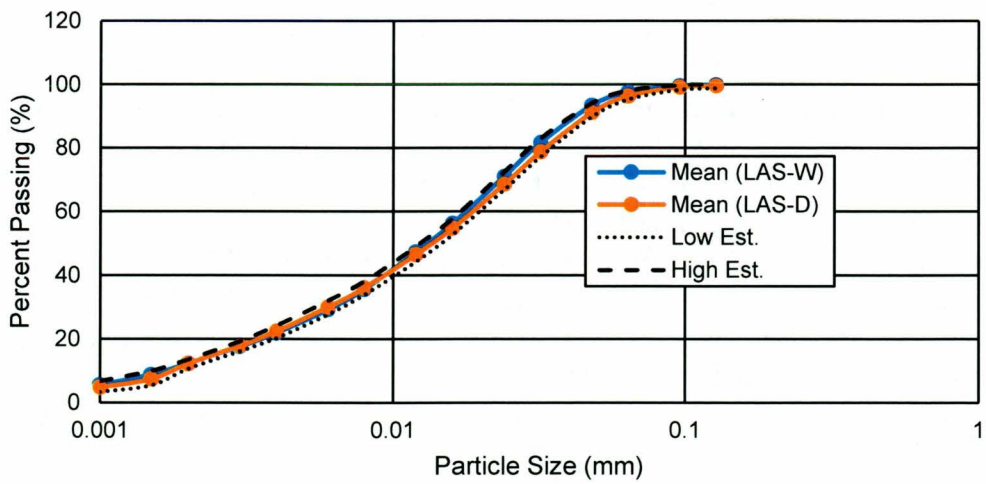


Figure B-1. PSD for cement powder standard reference material (Ferraris et al. 2004)

The reported PSD curve in Figure B-1 indicates favourable agreement between round-robin participants using the laser diffraction method with cement powders dispersed in liquid (LAS-W) or using dry powder methods (LAS-D). Results in Figure B-1 can be used to estimate the upper bound permeability (hydraulic conductivity) assuming that the cement powder behaves as a granular material, i.e., by neglecting the reduction in hydraulic permeability due to hydration of the cement minerals.

Hazen's equation is typically applied to uniformly graded materials with the uniformity coefficient, C_u

$$C_u = \frac{d_{60}}{d_{10}} < 5\,, \tag{B-5}$$

and for particle sizes between 0.1 and 3.0 mm. For materials with $d_{10} < 1\ mm$ and $C_u > 5$ (such as the material in Figure B-1), the Hazen's coefficient in Equation (B-1) is likely smaller than 1.0 due to larger values of the surface area and tortuosity than for uniformly graded sands for which Hazen's equation is directly applicable (see e.g., USDA 1991 and Carrier 2003). Therefore, the upper bound hydraulic conductivity for the cement material with the PSD reported in Figure B-1 can be conservatively estimated as

$$K = 1.0 \times d_{10}^2 \tag{B-6}$$

For the range of d_{10} values in Figure B-1, the upper bound estimates for the cement powder permeability are summarized in Table B-2.

Table B-2. Upper Bound Permeability Estimates for Cement Powder Based on Hazen's Equation

Range	d_{10} (mm)	k (m^2)	k (md)	K (cm/s)
Min	0.0015	2.3×10^{-15}	2.3	2.3×10^{-6}
Max	0.0019	3.6×10^{-15}	3.6	3.6×10^{-6}

During the cement paste degradation process, the reaction zone may become dominated by silica gel materials (Matteo and Scherer, 2012). Assuming that the degraded cement is dominated by compounds consisting of amorphous silica, the upper bound permeability can be estimated from the corresponding PSD curves. Marín et al. (2018) reported the PSDs for the various types of amorphous silica: silica gel (SG), precipitated silica (PS) and fumed silica (FS), also referred to as pyrogenic silica (see Figure B-2). Reported PSD curves in Figure B-2 indicate smaller average pore sizes for materials containing pyrogenic silica as well as the potential for improved hydraulic performance due to the presence of smaller pore sizes when FS materials are added to cement mixtures. In this study, however, it was assumed that the degraded cement performance is dominated by silica gel based on data by Matteo and Scherer (2012).

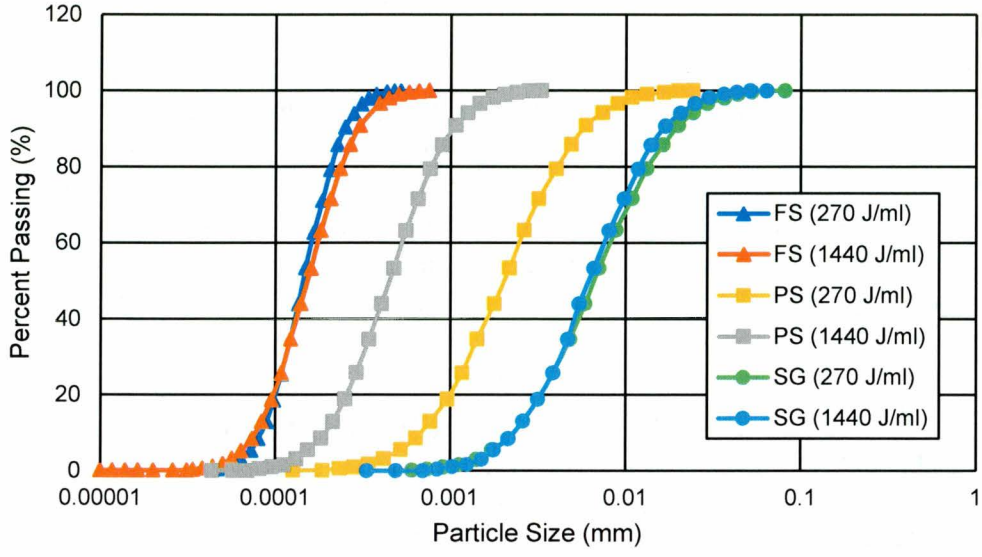


Figure B-2. PSD for amorphous silica materials (after Marín et al. 2018)

Results for the upper bound permeability estimates using Hazen's equation and Marín et al. (2018) PSD data are shown in Table B-3.

Table B-3. Upper Bound Permeability Estimates for Amorphous Silica Based on Hazen's Equation - PSD Data from Marín et al. (2018)

Material	Dispersion Energy (J/ml)	d_{10} (mm)	k (m^2)	k (md)	K (cm/s)
Fumed Silica (FS)	270	8.35×10^{-5}	7.12×10^{-18}	0.007	7.0×10^{-9}
	1,440	7.74×10^{-5}	6.11×10^{-18}	0.006	6.0×10^{-9}
Precipitated Silica (PS)	270	6.81×10^{-4}	4.72×10^{-16}	0.479	4.6×10^{-7}
	1,440	1.92×10^{-4}	3.77×10^{-17}	0.038	3.7×10^{-8}
Silica Gel (SG)	270	2.30×10^{-3}	5.39×10^{-15}	5.461	5.3×10^{-6}
	1,440	2.30×10^{-3}	5.39×10^{-15}	5.461	5.3×10^{-6}

Based on the range of particle sizes in Figure B-2, one can also utilize relationships between the PSD data and hydraulic conductivity values for materials with larger percentage of fines (see e.g., USDA 1991, Figure 6 and Craeger et al. 1947 approach) resulting in the upper bound permeability on the order of 1×10^{-15} m^2.

Based on the permeability estimates for materials with a grain size distribution similar to cement powders or amorphous silica materials, the upper bound permeability estimate for the degraded cement is not likely to exceed 10.0 md (10^{-14} m^2 or 10^{-5} cm/s). This value is considered a reasonable upper bound for the permeability of the borehole debris fill dominated by cement materials as it assumes flow through the granular matrix under limited confinement and the potential presence of larger pore sizes (macro-pores) exposed to WIPP brines. The upper bound permeability for the confined cement grouts, however, is likely to be on the order of 1.0 md (10^{-15} m^2 or 10^{-6} cm/s) or lower based on the available laboratory data (Thompson et al. 1996 based on data from Onofrei et al. 1992) and field data specific for the WIPP environment (Christensen and Hunter 1980).

The laboratory hydraulic conductivity tests on crushed reconsolidated cement grout samples (see e.g., Onofrei et al. 1992 results reported by Thompson et al. 1996) indicate the long-term permeability of about 10^{-15} m^2 or less, i.e. on the order of 10^{-6} cm/s or less, after 200 days as shown in Figure B-3.

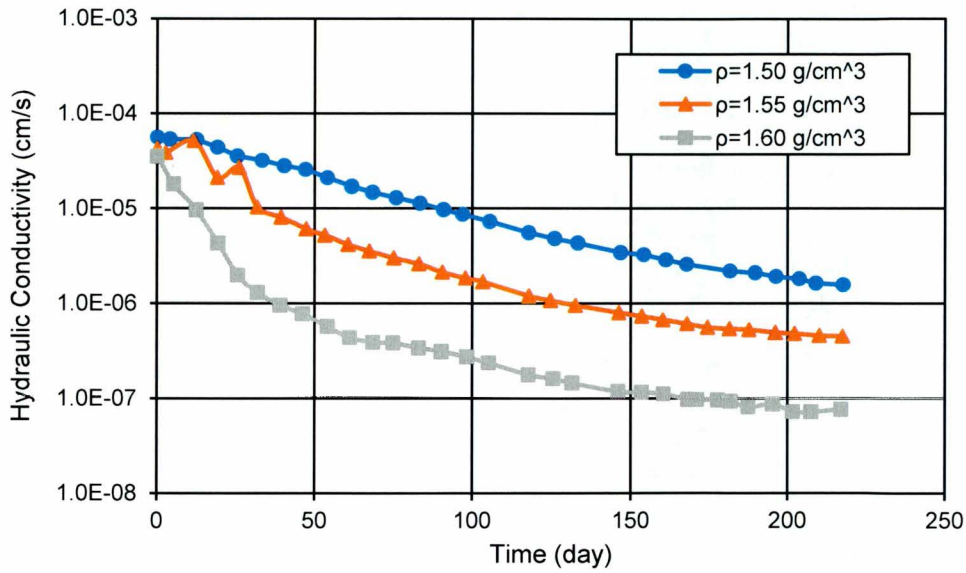


Figure B-3. Hydraulic conductivity measurements on crushed reconsolidated cement grout (digitized data from Thompson et al. 1996 based on data from Onofrei et al. 1992)

The long-term hydraulic conductivity values in Figure B-3 demonstrate the dependence on ρ, the initial grout density and on the elapsed time. The observed trends may be attributed to changes in the associated pore size distribution and the ongoing hydration process of cement minerals. As expected, cement grout samples that are prepared at lower initial densities tend to exhibit larger hydraulic conductivity values (see Figure B-3). These findings are relevant for predictions of the expected field behaviour, because it is expected that the mature cement grouts with lower densities, e.g., due to preparation of cement slurries at higher initial water-cement ratios (W/C ratios), exhibit larger hydraulic conductivities (larger effective pore sizes), see Figure B-4.

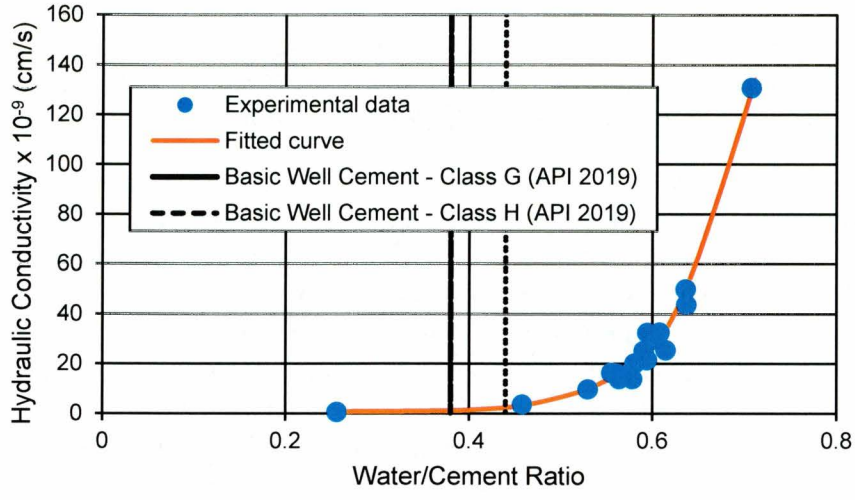


Figure B-4. Hydraulic conductivity dependence on water-cement ratio for mature cement pastes (digitized Neville 1981 data reported by Thompson et al. 1996)

Results in Figure B-4 indicate that the expected hydraulic conductivity of mature cements is not likely to exceed 10^{-8} cm/s (10^{-17} m^2) assuming the range of water/cement ratios for basic well cements (defined by vertical dotted and vertical dashed lines in Figure B-4) specified by API (2019). Thompson et al. (1996) reports the findings by Neville (1981) illustrating the dependence between the hydraulic conductivity and the capillary porosity of the cement grout (mature cement paste) matrix as shown in Figure B-5.

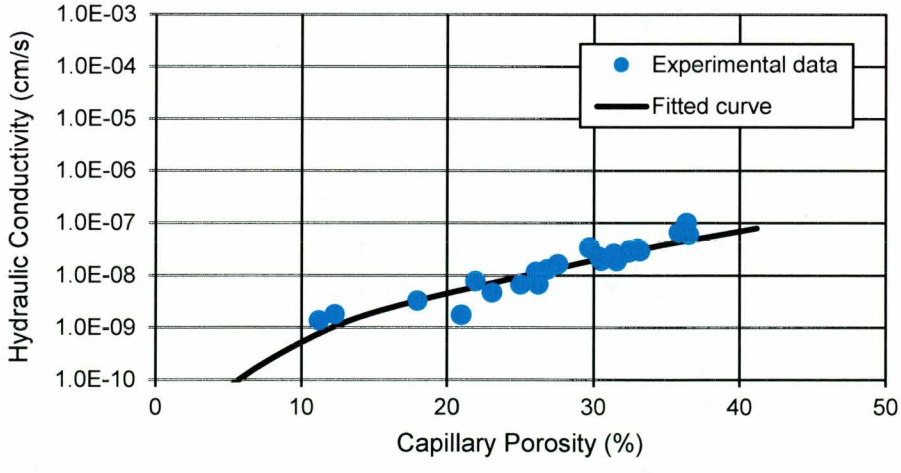


Figure B-5. Hydraulic conductivity dependence on capillary porosity of cement pastes (digitized Neville 1981 data as reported by Thompson et al. 1996)

Figure B-5 demonstrates that the cement grout with a relatively large percentage of pores may still exhibit hydraulic conductivity values below approximately 0.1 md (10^{-16} m^2 or 10^{-7} cm/s) as long as the capillary radii of the interconnected pore matrix are relatively small, i.e., without the presence of macro-pores. Onofrei et al. (1992) considered the cement grout dissolution

mechanism at the underground nuclear waste repository in Canada and concluded that the initial hydraulic conductivity of mature grout is below approximately 10^{-10} to 10^{-13} cm/s (~ 10^{-19} to 10^{-22} m^2) and may degrade over time resulting in long-term hydraulic conductivity values below approximately 10^{-7} cm/s (10^{-16} m^2) for a period of at least 300,000 years.

For numerical analyses required to determine seepage flows through degraded plug samples at WIPP, one can estimate the equivalent hydraulic conductivity for the upper borehole (i.e., the portion of the borehole located from the bottom of the Rustler formation to the WIPP underground repository) by considering a 40-meter long cement plug and the open section of the borehole with the length of approximately 360 to 380 meters that provides no hydraulic resistance to flow. The equivalent upper borehole permeability (i.e., the permeability assuming homogeneous borehole parameters used in PA calculations) can be determined from the continuity equation (i.e., based on the requirement that the flow through the equivalent borehole fill and the flow through the actual borehole, consisting of a cement plug and an open section, remains the same) as follows:

$$K_{eq}\frac{dH}{L_{eq}} = K_{plug}\frac{dH}{L_{plug}} \tag{B-7}$$

Equation (B-7) can be used to determine the equivalent borehole fill permeability as:

$$K_{eq} = K_{plug}\frac{L_{eq}}{L_{plug}}, \tag{B-8}$$

where dH = change in the hydraulic head across the length of equivalent borehole fill (assumed to be equal to the hydraulic head loss across the installed cement plug), in meters (m),
L_{eq} = length of the upper borehole (from the bottom of the Rustler to the WIPP waste repository), approximately 400 meters, in meters (m), and
L_{plug} = length of the borehole plug, in meters (m), assumed to be equal to 40 meters.

One can now utilize Equation (B-8) to calculate the equivalent borehole fill permeability as K_{eq}= 10^{-14} m^2 based on the borehole plug permeability K_{plug}= 10^{-15} m^2 and assuming that the length of the borehole fill is approximately 10 times larger than the cement plug thickness.

The upper bound permeability estimates may also be evaluated by considering the flow along the cement-steel casing interface gaps (micro-annuli) or through potential micro-fractures developed in the hydrated cement. From the laboratory data by Stormont et al. (2018), after considering the preferential flow due to thermal de-bonding or corrosion of steel, the following permeability data were reported using relatively short (203-mm long) laboratory specimens (see Table B-4).

Table B-4: Upper Bound Permeability Estimates – Laboratory Data (Stormont et al. 2018)

Specimen ID	Method to Create Micro-Annulus	Confining Pressure (MPa)	Casing Pressure (MPa)	Range of Permeabilities (m^2)	Range of Hydraulic Apertures (μm)
T1	Thermally de-bond	4.1 - 29.0	0	5.9×10^{-16} to 6.7×10^{-15}	5 - 12
T2	Thermally de-bond	4.1 - 12.4	0 - 21.0	6.5×10^{-16} to 9.6×10^{-15}	5 - 14

Specimen ID	Method to Create Micro-Annulus	Confining Pressure (MPa)	Casing Pressure (MPa)	Range of Permeabilities (m^2)	Range of Hydraulic Apertures (μm)
C1	Corroded casing	2.1 - 9.7	0	3.2×10^{-15} to 6×10^{-15}	10 - 12
C2	Corroded casing	0.7 - 20.7	0	1.6×10^{-16} to 4.3×10^{-15}	4 - 11

Attachment B-1

Borehole Debris Fill Calculations

Attachment B-1.1

Condition No. 1 Calculations
Borehole Geometry w/out Annulus Grouting

Condition No. 1 calculations - borehole geometry w/out plugs and w/out annulus grouting

	Surface Casing	Intermediate Casing Above Repository (Above MB 138)	Intermediate Casing Below Repository (Below MB 138)
Borehole length (m)	259.3	385.3	602.3
Borehole diameter (inch)	17.5	12.25	12.25
Borehole diameter (m)	0.4445	0.3112	0.3112
Surface Casing OD (inch)	13.375	n/a	n/a
Surface Casing OD (m)	0.3397	n/a	n/a
Surface Casing ID (inch)	12.615	n/a	n/a
Surface Casing ID (m)	0.3204	n/a	n/a
Intermediate Casing OD (inch)	8.625	8.625	8.625
Intermediate Casing OD (m)	0.2191	0.2191	0.2191
Intermediate Casing ID (inch)	7.921	7.921	7.921
Intermediate Casing ID (m)	0.2012	0.2012	0.2012
Production Casing OD (inch)	5.5	5.5	5.5
Production Casing OD (m)	0.1397	0.1397	0.1397
Production Casing ID (inch)	4.95	4.95	4.95
Production Casing ID (m)	0.1257	0.1257	0.1257
Surface Casing (SC) steel area (m^2)	1.00E-02	n/a	n/a
Surface Casing (SC) steel volume (m^3)	2.595	n/a	n/a
Intermediate Casing (IC) steel area (m^2)	5.90E-03	5.90E-03	5.90E-03
Intermediate Casing (IC) steel volume (m^3)	1.530	2.274	3.555
Production Casing (PC) steel area (m^2)	2.91E-03	2.91E-03	2.91E-03
Production Casing (PC) steel volume (m^3)	0.755	1.122	1.754
Contact cement grout area (m^2)	6.45E-02	3.83E-02	3.83E-02
Contact cement grout volume (m^3)	16.734	14.774	23.096
Annulus area between SC and IC (m^2)	4.29E-02	n/a	n/a
Annulus volume between SC and IC (m^3)	11.135	n/a	n/a
Annulus area between IC and PC (m^2)	1.65E-02	1.65E-02	1.65E-02
Annulus volume between IC and PC (m^3)	n/a	n/a	0.247
Corroded steel volume (m^3) (3.5x initial_vol)	14.44	7.96	12.44
Disaggregated cement grout volume (m^3)	36.23	19.21	30.02
Borehole volume w/out spalling (m^3)	40.24	29.30	45.80

Attachment B-1.2

Condition No. 2 Calculations
Borehole Geometry w/ Annulus Grouting

Condition No. 2 calculations - borehole geometry w/out plugs and w/ annulus grouting (no pipe stubbing)

	Surface Casing	Intermediate Casing Above Repository (Above MB 138)	Intermediate Casing Below Repository (Below MB 138)
Borehole length (m)	259.3	385.3	602.3
Borehole diameter (inch)	17.5	12.25	12.25
Borehole diameter (m)	0.4445	0.3112	0.3112
Surface Casing OD (inch)	13.375	n/a	n/a
Surface Casing OD (m)	0.3397	n/a	n/a
Surface Casing ID (inch)	12.615	n/a	n/a
Surface Casing ID (m)	0.3204	n/a	n/a
Intermediate Casing OD (inch)	8.625	8.625	8.625
Intermediate Casing OD (m)	0.2191	0.2191	0.2191
Intermediate Casing ID (inch)	7.921	7.921	7.921
Intermediate Casing ID (m)	0.2012	0.2012	0.2012
Production Casing OD (inch)	5.5	5.5	5.5
Production Casing OD (m)	0.1397	0.1397	0.1397
Production Casing ID (inch)	4.95	4.95	4.95
Production Casing ID (m)	0.1257	0.1257	0.1257
Surface Casing (SC) steel area (m^2)	1.00E-02	n/a	n/a
Surface Casing (SC) steel volume (m^3)	2.595	n/a	n/a
Intermediate Casing (IC) steel area (m^2)	5.90E-03	5.90E-03	5.90E-03
Intermediate Casing (IC) steel volume (m^3)	1.530	2.274	3.555
Production Casing (PC) steel area (m^2)	2.91E-03	2.91E-03	2.91E-03
Production Casing (PC) steel volume (m^3)	0.755	1.122	1.754
Contact cement grout area (m^2)	6.45E-02	3.83E-02	3.83E-02
Contact cement grout volume (m^3)	16.734	14.774	23.096
Annulus area between SC and IC (m^2)	4.29E-02	n/a	n/a
Annulus volume between SC and IC (m^3)	11.135		
Annulus area between IC and PC (m^2)	1.65E-02	1.65E-02	1.65E-02
Annulus volume between IC and PC (m^3)	4.269	6.344	9.917
Corroded steel volume (m^3) (3.5 x initial_vol)	17.08	11.89	18.58
Disaggregated cement grout volume (m^3)	41.78	27.45	42.92
Borehole volume w/out spalling (m^3)	40.24	29.30	45.80

Attachment B-2

BLM Drilling Performance Requirements

BUREAU OF LAND MANAGEMENT
43 CFR 3160

Federal Register / Vol. 53, No. 223
Friday, November 18, 1988
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Onshore Oil and Gas Operations; Federal and Indian Oil and Gas Leases; Onshore Oil and Gas Order No. 2, Drilling Operations

Onshore Oil and Gas Order No. 2
Drilling Operations on Federal and Indian Oil and Gas Leases

I. Introduction

A. Authority

This order is established pursuant to the authority granted to the Secretary of the Interior pursuant to various Federal and Indian mineral leasing statutes and the Federal Oil and Gas Royalty Management Act of 1982. This authority has been delegated to the Bureau of Land Management and is implemented by the onshore oil and gas operating regulations contained in 43 CFR Part 3160. Section 3164.1 thereof specially authorizes the Director, Bureau of Land Management, to issue Onshore Oil and Gas Orders when necessary to implement and supplement the operating regulations and provides that all such Orders shall be binding on the lessees and operators of Federal and restricted Indian (except Osage tribe) oil and gas leases that have been, or may hereafter be issued.

Specific authority for the provisions contained in this Order is found at: 3162.3-1 Drilling Applications and Plans; 3162.3-4 Well Abandonment; 3162.4-1 Well Records and Reports; 3162.4-2 Samples, Tests, and Surveys; 3162.5-1 Environmental Obligations; 3162.5-2 Control of Wells; 3162.5-2(a) Drilling Wells; 3162.5-3 Safety Precautions; and Subpart 3163 Noncompliance, Assessments, and Penalties.

B. Purpose

This Order details the Bureau's uniform national standards for the minimum levels of performance expected from lessees and operators when conducting drilling operations on Federal and Indian lands (except Osage Tribe) and for abandonment immediately following drilling. The purpose also is to identify the enforcement actions that will result when violations of the minimum standards are found, and when those violations are not abated in a timely manner.

C. Scope

This Order is applicable to all onshore Federal and Indian (except Osage Tribe) oil and gas leases.

D. General

1. If an operator chooses to use higher rated equipment than that authorized in the Application for Permit to Drill (APD), testing procedures shall apply to the approved working pressures, not the upgraded higher working pressures.

2. Some situations may exist either on a well-by-well or field-wide basis whereby it is commonly accepted practice to vary a particular minimum standard(s) established in this Order. This situation may be resolved by requesting a variance (See section IV of this Order), by the inclusion of a stipulation to the APD, or by the issuance of Notice to Lessees and Operators (NTL) by the appropriate BLM office.

3. When a violation is discovered and if it does not cause or threaten immediate substantial and adverse impact on public health and safety, the environment, production accountability or royalty, it will be reissued as a major violation if not corrected during the abatement period and continued

drilling has changed the adverse impact of the violation so that it meets the specific definition of a major violation.

4. This Onshore Order is not intended to circumvent the reporting requirements or compliance aspects that may be stated elsewhere in Existing NTL's, Onshore Orders, etc. A lessee's compliance with the requirements of the regulations in this Part shall not relieve the lessee of the obligation to comply with other applicable laws and regulations in accordance with 43 CFR 3162.5-1(c). Lessee's should give special attention to the automatic assessment provisions in 43 CFR 3163.1(b).

5. This Order is based upon the assumption that operations have been approved in accordance with 43 CFR Part 3160 and Onshore Oil and Gas Order No.1. Failure to obtain approval prior to commencement of drilling or related operations shall subject the operator to immediate assessment under 43 CFR 3163.1(b)(2).

II. Definitions.

A. Abnormal Pressure Zone means a zone that has either pressure above or below the normal gradient for an area and/or depth.

B. Bleed Line means the vent line that bypasses the chokes in the choke manifold system; also referred to as Panic Line.

C. Blooie Line means a discharge line used in conjunction with a rotating head. D. Drilling Spool means a connection component with both ends either flanged or hubbed with an internal diameter at least equal to the bore of the casing, and with smaller side outlets for connecting auxiliary lines.

E. Exploratory Well means any well drilled beyond the known producing limits of a pool.

F. Filled-up Line means the line used to fill the hole when the drill pipe is being removed from the well. It is usually connected to a 2-inch collar that is welded into a drilling nipple.

G. Flare Line means a line used to carry gas from the rig to be burned at a safer location. The gas comes from the degasser, gas buster, separator, or when drill stem testing, directly from the drill pipe.

H. Functionally Operated means activating equipment without subjecting it to well-bore pressure.

I. Isolating means using cement to protect, separate, or segregate usable water and mineral resources.

J. Lease means any contact, profit-share agreement, joint venture, or other agreement issued or approved by the United States under a mineral leasing law that authorizes exploration for, extraction of, or removal of oil or gas (See 43 CFR 3160.0-5).

K. Lessee means a person holding record title in a lease issued by the United States (See 43 CFR 3160.0-5).

L. Make-up Water means water that is used in mixing slurry for cement jobs and plugging operations, and is compatible with cement constituents being used.

M. Manual Locking Device means any manually activated device, such as a hand wheel, etc., that is used for the purpose of locking the preventer in the closed position.

N. Mud for Plugging Purposes means a slurry of bentonite of similar flocculent/viscosfer, water, and additive needed to achieve the desired weight and consistency to stabilize the hole.

O. Mudding Up means adding materials and chemicals to water to control the viscosity, weight, and filtrate loss of the circulating system.

P. Operating Rights Owner (or Owner) means a person or entity holding operating rights in a lease issued by the United States. A lessee also may be an operating rights owner if the operating rights in a lease or portion thereof have not been severed from record title.

Q. Operational means capable of functioning as designed and installed without undue force or further modification.

R. Operator means any person or entity , including but not limited to the lessee or operating rights owner, who has stated in writing to the authorized officer his/her responsibility for the operations conducted in the leased lands or a portion thereof.

S. Precharge Pressure means the nitrogen pressure remaining in the accumulator after all the hydraulic fluid has been expelled from beneath the movable barrier.

T. Prompt Correction means immediate correction of violations, with drilling suspended if required in the discretion of the authorized officer.

U. Prospectively Valuable Deposit of Minerals means any deposit of minerals that the authorized officer determines to have characteristics of quantity and quality that warrant its protection.

V. Tagging the Plug means running in the hole with a string of tubing or drill pipe and placing sufficient weight on the plug to insure its integrity. Other methods of tagging the plug may be approved by the authorized officer.

W. Targeted Tee or Turn means a fitting used in pressure piping in which a bull plug or blind flange of the same pressure rating as the rest of the approved system is installed at the end of a tee or cross, opposite the fluid entry arm, to change the direction of flow and to reduce erosion.

X. 2M, 3M, 5M, 10M, and 15M mean the pressure ratings used for equipment with a working pressure rating of the equivalent thousand pounds per square inch (psi) (2M=2,000 psi, 3M=3,000 psi, etc.)

Y. Usable Water means generally those waters containing up to 10,000 ppm of total dissolved solids.

Z. Weep Hole means a small hole that allows pressure to bleed off through the metal plate, used in covering well bores after abandonment operations.

[57 FR 3025, Jan. 27, 1992]

III. Requirements

A. Well Control Requirements

1. Blowout preventer (BOP) and related equipment (BOPE) shall be installed, used, maintained, and tested in manner necessary to assure well control and shall be in place and operational prior to drilling the surface casing shoe unless otherwise approved by the APD. Commencement of drilling without the approved BOPE installed, unless otherwise approved, shall subject the operator to immediate assessment under 43 CFR 3163.1(b)(1). The BOP and related control equipment shall be suitable for operations in those areas which are subject to sub-freezing conditions. The BOPE shall be based on known or anticipated sub-surface pressures, geologic conditions, accepted engineering practice, and surface environment. The working pressure of all BOPE shall exceed the anticipated surface pressure to which it may be subjected, assuming a partially evacuated hole with a pressure gradient of 0.22 psi/ft.

2. The gravity of the violations for many of the well control minimum standards listed below are shown as minor. However, very short abatement periods in this Order are often specified in recognition that by continuing to drill, the violation which was originally determined to be of a minor nature may cause or threaten immediate, substantial and adverse impact on public health and safety, the environment, production accountability, or royalty income, which would require it reclassification as a major violation.

a. Minimum standards and enforcement provisions for well control equipment.

i. A well control device shall be installed at the surface that is capable of complete closure of the well bore. This device shall be closed whenever the well is unattended.

Violation: Major.
Corrective Action: Install the equipment as specified.
Normal Abatement Period: Prompt correction required.

ii. 2M system:

- Annular preventer, or double ram, or two rams with one being blind and onebeing a pipe ram *
- kill line (2 inch minimum)
- 1 kill line valve (2 inch minimum)
- 1 choke line valve
- 2 chokes (refer to diagram in Attachment 1)
- Upper kelly cock valve with handle available
- Safety valve and subs to fit all drill strings in use
- Pressure gauge on choke manifold
- 2 inch minimum choke line
- Fill-up line above the uppermost preventer.

Violation: Minor (all items unless marked by asterisk).
Corrective Action: Install the equipment as specified.
Normal Abatement Period: 24 hours.

*Violation: Major.
Corrective Action: Install the equipment as specified.
Normal Abatement Period: Prompt correction required.

iii. 3M system:

- Annular preventers*
- Double ram with blind rams and pipe rams*
- Drilling spool, or blowout preventer with 2 side outlets (choke side shall be a 3-inch minimum diameter, kill side shall be at least 2-inch diameter)*

- Kill line (2 inch minimum)
- A minimum of 2 choke line valves (3 inch minimum)*
- 3 inch diameter choke line
- 2 kill line valves, one of which shall be a check valve (2 inch minimum)*

- 2 chokes (refer to diagram in Attachment 1)
- Pressure gauge on choke manifold
- Upper kelly cock valve with handle available
- Safety valve and subs to fit all drill string connections in use
- All BOPE connections subjected to well pressure shall be flanged, welded, or clamped*
- Fill-up line above the uppermost preventer.

Violation: Minor (all items unless marked by asterisk).
Corrective Action: Install the equipment as specified.
Normal Abatement Period: 24 hours.

*Violation: Major.
Corrective Action: Install the equipment as specified.
Normal Abatement Period: Prompt correction required.

iv. 5M system:

- Annular preventer*
- Pipe ram, blind ram, and, if conditions warrant, as specified by the authorized officer, another pipe ram shall also be required*
- A second pipe ram preventer shall be used with a tapered drill string
- Drilling spool, or blowout preventer with 2 side outlets (choke side shall be a 3-inch minimum diameter, kill side shall be at least 2-inch diameter)*
- 3 inch diameter choke line
- 2 choke line valves (3 inch minimum)*
- Kill line (2 inch minimum)
- 2 chokes with 1 remotely controlled from rig floor (refer to diagram in Attachment 1)
- 2 kill line valves and a check valve (2 inch minimum)*
- Upper kelly cock valve with handle available
- When the expected pressures approach working pressure of the system, 1 remote kill line tested to stack pressure (which shall run to the outer edge of the substructure and be unobstructed)
- Lower kelly cock valve with handle available
- Safety valve(s) and subs to fit all drill string connections in use
- Inside BOP or float sub available

- Pressure gauge on choke manifold
- All BOPE connections subjected to well pressure shall be flanged, welded, orclamped*
- Fill-up line above the uppermost preventer.

Violation: Minor (all items unless marked by asterisk).
Corrective Action: Install the equipment as specified.
Normal Abatement Period: 24 hours

*Violation: Major.
Corrective Action: Install the equipment as specified.
Normal Abatement Period: Prompt correction required.

v. 10M & 15M system:
- Annular preventer*
- 2 pipe rams*
- Blind rams*
- Drilling spool, or blowout preventer with 2 side outlets (choke side shall be a 3-inch minimum diameter, kill side shall be at least 2-inch diameter)*
- 3 inch choke line*
- 2 kill line valves (2 inch minimum) and check valve*
- Remote kill line (2 inch minimum) shall run to the outer edge of the substructure and be unobstructed
- Manual and hydraulic choke line valve (3 inch minimum)*
- 3 chokes, 1 being remotely controlled (refer to diagram in Attachment 1)
- Pressure gauge on choke manifold
- Upper kelly cock valve with handle available
- Lower kelly cock valve with handle available
- Safety valves and subs to fit all drill string connections in use
- Inside BOP or float sub available
- Wearing ring in casing head
- All BOPE connections subjected to well pressure shall be flanged, welded, or clamped*
- Fill-up line installed above the uppermost preventer.

Violation: Minor (all items unless marked by asterisk).
Corrective Action: Install the equipment as specified.
Normal Abatement Period: 24 hours.

*Violation: Major. Corrective Action:
Install the equipment as specified.
Normal Abatement Period: Prompt correction required.

vi. If repair or replacement of the BOPE is required after testing, this work shall be performed prior to drilling out the casing shoe.

Violation: Major.
Corrective Action: Install the equipment as specified.
Normal Abatement Period: Prompt correction required.

vii. When the BOPE cannot function to secure the hole, the hole shall be secured using cement, retrievable packer or a bridge plug packer, bridgeplug, or other acceptable approved method to assure safe well conditions.

Violation: Major.
Corrective Action: Install the equipment as specified.
Normal Abatement Period: Prompt correction required.

[54 FR 39528, Sept. 27, 1989]

b. Minimum standards and enforcement provisions for choke manifold equipment.

i. All choke lines shall be straight lines unless turns use tee blocks or are targeted with running tees, and shall be anchored to prevent whip and reduce vibration.

Violation: Minor.
Corrective Action: Install the equipment as specified.
Normal Abatement Period: 24 hours.

ii. Choke manifold equipment configuration shall be functionally equivalent to the appropriate example diagram shown in Attachment 1 of this Order. The configuration of the chokes may vary.

Violation: Minor.
Corrective Action: Install the equipment as specified.
Normal Abatement Period: Prompt correction required.

iii. All valves (except chokes) in the kill line choke manifold, and choke line shall be a type that does not restrict the flow (full opening) and that allows a straight through flow (same enforcement as item ii).
iv. Pressure gauges in the well control system shall be a type designed for drilling fluid service (same enforcement as above).

[57 FR 3025, Jan. 27, 1992]

c. Minimum standards and enforcement provisions for pressure accumulator system.

i. 2M system accumulator shall have sufficient capacity to close all BOP's and retain 200 psi above precharge. Nitrogen bottles that meet manufacturer's specifications may be used as the backup to the required independent power source.
Violation: Minor.
Corrective Action: Install the equipment as specified.
Normal Abatement Period: 24 hours.
ii. 3M system accumulator shall have sufficient capacity to open the hydraulically-controlled choke line valve(if so equipped), close all rams plus the annual preventer, and retain a minimum of 200 psi above precharge on the closing manifold without the use of the closing pumps. this is a minimum requirement. The fluid reservoir capacity shall be double the usable fluid volume of the accumulator system capacity and the fluid level shall be maintained at the manufacturer's recommendations. The 3M system shall have 2 independent power sources to close the preventers. Nitrogen bottles (3 minimum) may be 1 of the independent power sources and, if so, shall maintain a charge equal to the manufacturer's specifications.

Violation: Minor
Corrective Action: Install the equipment as specified.
Normal Abatement Period: 24 hours.

iii. 5M and higher system accumulator shall have sufficient capacity to open the hydraulically-controlled gate valve (if so equipped) and close all rams plus the annular preventer (for 3 ram systems add a 50 percent safety factor to compensate for any fluid loss in the control system or preventers) and retain a minimum pressure of 200 psi above precharge on the closing manifold without use of the closing unit pumps. The fluid reservoir capacity shall be double the usable fluid volume of the accumulator system capacity and the fluid level of the reservoir shall be maintained at the manufacturer's recommendations. Two independent sources of power shall be available for powering the closing unit pumps. Sufficient nitrogen bottles are suitable as a backup power source only, and shall be recharged when the pressure falls below manufacturer's specifications.

Violation: Minor.
Corrective Action: Install the equipment as specified.
Normal Abatement Period: 24 hours.

[57 FR 3025, Jan. 27, 1992]

d. Minimum standards and enforcement provisions for accumulator precharge pressuretest. This test shall be conducted prior to connecting the closing unit to the BOP stack and at least once every 6 months. The accumulator pressure shall be corrected if the measured precharge pressure is found to be above or below the maximum or minimum limit specified below (only nitrogen gas may be used to precharge):

Accumulator working pressure rating	Minimum acceptable operating pressure	Desired precharge pressure	Maximum acceptable precharge pressure	Minimum acceptable precharge pressure
1,500 psi	1,500 psi	750 psi	800 psi	700 psi
2,000 psi	2,000 psi	1,000 psi	1,100 psi	900 psi
3,000 psi	3,000 psi	1,000 psi	1,100 psi	900 psi

Violation: Minor.
Correction Action: Perform test.
Normal Abatement Period: 24 hours.

e. Minimum standards and enforcement provisions for power availability. Power for the closing unit pumps shall be available to the unit at all times so that the pumps shall automatically start when the closing valve manifold pressure has decreased to the pre-set level.

Violation: Major.
Corrective Action: Install the equipment as specified.
Normal Abatement Period: Prompt correction required.

f. Minimum standards and enforcement provisions for accumulator pump capacity. Each BOP closing unit shall be equipped with sufficient number and sizes of pumps so that, with the accumulator system isolated from service, the pumps shall be capable of opening the hydraulically-operated gate valve (if so equipped), plus closing the annular preventer on the smallest size drill pipe to be used within 2 minutes, and obtain a minimum of 200 psi above specified accumulator precharge pressure.

g. Minimum standards and enforcement provisions for locking devices. A manual locking device (i.e., hand wheels) or automatic locking devices shall be installed on all systems of 2M or greater. A valve shall be installed in the closing line as close as possible to the annular preventer to act as a locking device. This valve shall be maintained in the open position and shall be closed only when the power source for the accumulator system is inoperative.

Violation: Minor.
Corrective Action: Install the equipment as specified.
Normal Abatement Period: 24 hours.

h. Minimum standards and enforcement provisions for remote controls. Remote controls shall be readily accessible to the driller. Remote controls for all 3M or greater systems shall be capable of closing all preventers. Remote controls for 5M or greater systems shall be capable of both opening and closing all preventers. Master controls shall be at the accumulator and shall be capable of opening and closing all preventers and the choke line valve (if so equipped). No remote control for a 2M system is required.

Violation: Minor.
Correction Action: Install the equipment as specified.
Normal Abatement Period: 24 hours.

i. Minimum standards and enforcement provisions for well control equipment testing.

i. Perform all tests described below using clear water or an appropriate clear liquid for subfreezing temperatures with a viscosity similar to water.
ii. Ram type preventers and associated equipment shall be tested to approved (see item I.D.1. of this order) stack working pressure if isolated by test plug or to 70 percent of internal yield pressure of casing if BOP stack is not isolated from casing. Pressure shall be maintained for at least 10 minutes or until requirements of test are met, whichever is longer. If a test plug is utilized, no bleed-off of pressure is acceptable. For a test not utilizing a test plug, if a decline in pressure of more than 10 percent in 30 minutes occurs, the test shall be considered to have failed. Valve on casing head below test plug shall be open during test of BOP stack.

iii. Annular type preventers shall be tested to 50 percent of rated working pressure. Pressure shall be maintained at least 10 minutes or until provisions of test are met, whichever is longer.

iv. As a minimum, the above test shall be performed:

A. when initially installed:
B. whenever any seal subject to test pressure is broken:
C. following related repairs: and
D. at 30-day intervals.

v. Valves shall be tested from working pressure side during BOPE tests with all down stream valves open.

vi. When testing the kill line valve(s), the check valve shall be held open or the ball removed.

vii. Annular preventers shall be functionally operated at least weekly.
viii. Pipe and blind rams shall be activated each trip, however, this function need not be performed more than once a day.

ix. A BOPE pit level drill shall be conducted weekly for each drilling crew.

x. Pressure tests shall apply to all related well control equipment.

xi. All of the above described tests and/or drills shall be recorded in the drilling log.

Violation: Minor.
Corrective action: Perform the necessary test or provide documentation.
Normal Abatement Period: 24 hours or next trip, as most appropriate.

[54 FR 39528, Sept. 27, 1989]

B. Casing and Cementing Requirements

The proposed casing and cementing programs shall be conducted as approved to protect and/or isolate all usable water zones, lost circulation zones, abnormally pressured zones, and any prospectively valuable deposits of minerals. Any isolating medium other than cement shall receive approval prior to use. The casing setting depth shall be calculated to position the casing seat opposite a competent formation which will contain the maximum pressure to which it will be exposed during normal drilling operations. Determination of casing setting depth shall be based on all relevant factors, including: presence/absence of hydrocarbons; fracture gradients; usable water zones; formation pressures; lost circulation zones; other minerals; or other unusual characteristics. All indications of usable water shall be reported.

- Minimum design factors for tensions, collapse, and burst that are incorporated into the casing design by an operator/lessee shall be submitted to the authorized operator for his review and approval along with the APD for all exploratory wells or as otherwise specified by the authorized officer.

- Casing design shall assume formation pressure gradients of 0.44 to 0.50 psi per foot for exploratory wells (lacking better data).

- Casing design shall assume fracture gradients from 0.70 to 1.00 psi per foot for exploratory wells (lacking better data).

- Casing collars shall have a minimum clearance of 0.422 inches on all sides in the hole/casing annulus, with recognition that variances can be granted for justified exceptions.

- All waiting on cement times shall be adequate to achieve a minimum of 500 psi compressive strength at the casing shoe prior to drilling out.

1. Minimum Standards and Enforcement Provisions for Casing and Cementing.

a. All casing, except the conductor casing, shall be new or reconditioned and tested casing. All casing shall meet or exceed API standards for new casing. The use of reconditioned and tested used casing shall be subject to approval by the authorized officer: approval will be contingent upon the wall thickness of any such casing being verified to be at least 87 1/2 percent of the nominal wall thickness of new casing.

Violation: Major.
Corrective Action: Perform remedial action as specified by the authorized officer.
Normal Abatement Period: Prompt correction required.

[57 FR 3025, Jan. 27, 1992]

b. For liners, a minimum of 100 feet of overlap between a string of casing and the next larger casing is required. The interval of overlap shall be sealed and tested. The liner shall be tested by a fluid entry or pressure test to determine whether a seal between the liner top and next larger string has been achieved. The test pressure shall be the maximum anticipated pressure to which the seal will be exposed. No test shall be required for liners that do not incorporate or need a seal mechanism.

Violation: Minor.
Corrective Action: Perform remedial action as specified by the authorized officer.
Normal Abatement Period: Upon determination of corrective action.

c. The surface casing shall be cemented back to surface either during the primary cement job or by remedial cementing

Corrective Action: Perform remedial cementing.
Normal Abatement Period: Prompt correction required.

d. All of the above described tests shall be recorded in the drilling log.

Violation: Minor.
Corrective Action: Perform the necessary test or provide documentation.
Normal Abatement Period: 24 hours.

e. All indications of usable water shall be reported to the authorized officer prior to running the next string of casing or before plugging orders are requested, whichever occurs first.

Violation: Major.
Corrective Action: Report information as required.
Normal Abatement Period: Prompt correction required.

f. Surface casing shall have centralizers on the bottom 3 joints of the casing (a

minimum of 1 centralizer per joint, starting with the shoe joint).

Violations: Major.
Corrective Action: Logging/testing may be required to determine the quality of the job. Recementing may then be specified.
Normal Abatement Period: Prompt correction upon determination of corrective action.

[57 FR 3025, Jan. 27, 1992]

g. Top plugs shall be used to reduce contamination of cement by displacement fluid. A bottom plug or other acceptable technique, such as a preflush fluid, inner string cement method, etc., shall be utilized to help isolate the cement from contamination by the mud fluid being displaced ahead of the cement slurry.

Violation: Major.
Correction Action: Logging may be required to determine the quality of the cement job. Recementing or further recementing may then be specified.
Normal Abatement Period: Based upon determination of corrective action.

h. All casing strings below the conductor shall be pressure tested to 0.22 psi per foot of casing string length or 1500 psi, whichever is greater, but not to exceed 70 percent of the minimum internal yield. If pressure declines more than 10 percent in 30 minutes, corrective action shall be taken.

Violation: Minor.
Corrective Action: Perform the test and/or remedial action as specified by the authorized officer.
Normal Abatement Period: 24 hours.

i. On all exploratory wells, and on that portion of any well approved for a 5M BOPE system or greater, a pressure integrity test of each casing shoe shall be performed. Formation at the shoe shall be tested to a minimum of the mud weight equivalent anticipated to control the formation pressure to the next casing depth or at total depth of the well. This test shall be performed before drilling more than 20 feet of new hole.

Violation: Minor.
Corrective Action: Perform the specified test.
Normal Abatement Period: 24 hours.

C. Mud Program Requirements

The characteristics, use, and testing of drilling mud and the implementation of related drilling procedures shall be designed to prevent the loss of well control. Sufficient quantities of mud materials shall be maintained or readily accessible for the purpose of assuring well control.

Minimum Standards and Enforcement Provisions for Mud Program and Equipment

1. Record slow pump speed on daily drilling report after mudding up.

Violation: Minor.
Corrective Action: Record required information.
Normal Abatement Period: 24 hours.

2. Visual mud monitoring equipment shall be in place to detect volume changes indicating loss or gain of circulating fluid volume.

Violation: Minor.
Corrective Action: Install necessary equipment.
Normal Abatement Period: 24 hours.

3. When abnormal pressures are anticipated, electronic/mechanical mud monitoring equipment shall be required, which shall include as a minimum; pit volume totalizer (PVT); stroke counter; and flow sensor.

Violation: Minor.
Corrective Action: Install necessary instrumentation.
Normal Abatement Period: 24 hours.

4. A mud test shall be performed every 24 hours after mudding up to determine, as applicable: density, viscosity, gel strength, filtration, and pH.

Violation: Minor.
Correction Action: Perform necessary tests.
Normal Abatement Period: 24 hours.

5. A trip tank shall be used on 10M and 15M systems and on upgraded 5M systems as determined by the authorized officer.

Violation: Minor.
Corrective Action: Install necessary equipment.
Normal Abatement Period: 24 hours.

6. a. Gas detecting equipment shall be installed in the mud return system for exploratory wells or wells where abnormal pressure is anticipated, and hydrocarbon gas shall be monitored for pore pressure changes.

b. Hydrogen sulfide safety and monitoring equipment requirements may be found in Onshore Oil and Gas Order No. 6 - Hydrogen Sulfide Operations.

Violation: Minor.
Corrective Action: Install necessary equipment.
Normal Abatement Period: 24 hours.

7. All flare systems shall be designed to gather and burn all gas. The flare line(s) discharge shall be located not less than 100 feet from the well head, having straight lines unless turns are targeted with running tees, and shall be positioned downwind of the prevailing wind direction and shall be anchored. The flare system shall have an effective method for ignition. Where noncombustible gas is likely or expected to be vented, the system shall be provided

supplemental fuel for ignition and to maintain a continuous flare.

Violation: Major.
Corrective Action: Install equipment as specified.
Normal Abatement Period: 24 Hours.

8. A mud-gas separator (gas buster) shall be installed and operable for all systems of 10M or greater and for any system where abnormal pressure is anticipated beginning at a point at least 500 feet above any anticipated hydrocarbon zone of interest.

Violation: Minor.
Corrective Action: Install required equipment.
Normal Abatement Period: Prompt correction required.

[54 FR 39528, Sept. 27, 1989, further amended at 57 FR 3026, Jan.27, 1992]

D. Drill Stem Testing Requirements

Initial opening of drill stem test tools shall be restricted to daylight hours unless specific approval to start during other hours is obtained from the authorized officer. However, DSTs may be allowed to continue at night if the test was initiated during daylight hours and the rate of flow is stabilized and if adequate lighting is available (i.e., lighting which is adequate for visibility and vapor-proof for safe operations). Packers can be released, but tripping shall not begin before daylight, unless prior approval is obtained from the authorized officer. Closed chamber DSTs may be accomplished day or night.

Minimum Standards for Drill Stem Testing.

1. A DST that flows to the surface with evidence of hydrocarbons shall be eitherreversed out of the testing string under controlled surface conditions or displaced into the formation prior to pulling the test tool. This would involve providing some means forreserve circulation.

Violation: Major.
Corrective Action: Contingent on circumstances and as specified by the authorizedofficer.
Normal Abatement Period: Prompt correction required.

2. Separation equipment required for the anticipated recovery shall be properly installed before a test starts.

Violation: Major.
Corrective Action: Install required equipment.
Normal Abatement Period: Prompt correction required.

3. All engines within 100 feet of the wellbore that are required to "run" during the test shall have spark arresters or water cooled exhausts.

Violation: Major.
Corrective Action: Contingent on circumstances and as specified by the authorized officer.
Normal Abatement Period: Prompt correction required.

E. Special Drilling Operations

1. In addition to the equipment already specified elsewhere in this onshore order, the following equipment shall be in place and operational during air/gas drilling:

- Properly lubricated and maintained rotating head*
- Spark arresters on engines or water cooled exhaust*
- Blooie line discharge 100 feet from well bore and securely anchored
- Straight run on blooie line unless otherwise approved
- Deduster equipment*
- All cuttings and circulating medium shall be directed into a reserve or blooie pit*
- Float valve above bit*
- Automatic igniter or continuous pilot light on the blooie line*
- Compressors located in the opposite direction from the blooie line a minimum of 100 feet from the well bore
- Mud circulating equipment, water, and mud materials (does not have to be premixed) sufficient to maintain the capacity of the hole and circulating tanks or pits

Violation: Minor (unless marked by an asterisk).
Corrective Action: Install the equipment as specified.
Normal Abatement Period: 24 hours.
*Violation: Major.
Corrective Action: Install the equipment as specified.
Normal Abatement Period: Prompt correction required.

2. Hydrogen sulphide operation is specifically addressed under Onshore Oil and Gas Order No. 6.

F. Surface Use

Onshore Oil and Gas Order No. 1 specifically addresses surface use. That Order provides for safe operations, adequate protection of surface resources and uses, and other environmental components. The operator/lessee is responsible for, and liable for, all building, construction, and operating activities and subcontracting activies conducted in association with the APD. Requirements and special stipulations for surface use are contained in or attached to the approved APD.

Minimum Standards and Enforcement Provisions for Surface Use.

The requirements and stipulations of approval shall be strictly adhered to by the operator/lessee and any contractors. Violation: If a violation is identified by the authorized officer he shall dtermine wherther it is major or minor, considering the definitions in 43 CFR 3160.0-5, and shall specify the appropriate corrective action and abatement period.

G. Drilling Abandonment Requirements

The following standards apply to the abandonment of newly drilled dry or non- productive wells in accordance with 43 CFR 3162.3-4 and section V of Onshore Oil and Gas Order No. 1. Approval shall be obtained prior to the commencement of abandonment. All formations bearing usable-quality water, oil, gas, or geothermal resources, and/or a prospectively valuable deposit of minerals shall be protected. Approval may be given orally by the authorized officer before abandonment operations are initiated. This oral request and approval shall be followed by a written notice of intent to abandon filed not later than the fifth business day following oral approval. Failure to obtain approval prior to commencement of abandonment operations shall result in

immediate assessment of under 43 CFR 3163.1(b)(3). The hole shall be in static condition at the time any plugs are placed (this does not pertain to plugging lost circulation zones). Within 30 days of completion of abandonment, a subsequent report of a abandonment shall be filed. Plugging design for an abandonment hole shall include the following:

1. Open Hole.

i. A cement plug shall be placed to extend at least 50 feet below the bottom (except as limited by total depth (TD) or plugged back total depth (PBTD)), to 50 feet above the top of:

a. Any zone encountered during which contains fluid or gas with a potential to migrate;

b. Any prospectively valuable deposit of minerals.

ii. All cement plugs, except the surface plug, shall have sufficient slurry volume to fill 100 feet of the hole, plus an additional 10 percent of slurry for each 1,000 feet of depth.

iii. No plug, except the surface plug, shall be less than 25 sacks without receiving specific approval from the authorized officer.

iv. Extremely thick sections of single formation may be secured by placing 100-foot plugs across the top and bottom of the formation, and in accordance with item ii hereof. v. In the absence of productive zones or prospectively valuable deposits of minerals which otherwise require placemnt of cement plugs, long sections of open hole shall be plugged at least every 3,000 feet. Such plugs shall be placed across in-gauge sections of the hole, unless otherwise approved by the authoriuzed officer.

2. Cased Hole. A cement plug shall be placed opposite all open perforation and extend to a minimum of 50 feet below (except as limited by TD or PBTD) to 50 feet above the perforated interval. All cement plugs, except the surface plug, shall have sufficient slurry volume to fill 100 feet of hole, plus an additional 10 percent of slurry for each 1,000 feet of depth. In lieu of the cement plug, a bridge plug is acceptable, provided:

i. The bridge plug is set within 50 feet to 100 feet above the open perforations;

ii. The perforations are isolated from any open hole below; and

iii. The bridge plug is capped with 50 feet of coment. If a bailer is used to cap this plug, 35 feet of cement shall be sufficient.

3. Casing Removed from Hole. If any casing is cut and recovered, a cement plug shall be placed to extend at least 50 feet above and below the stub. The exposed hole resulting from the casing removal shall be secured as required in items 1i and 1ii hereof.

4. An additional cement plug placed to extend a minimum of 50 feet above and below the shoe of the surface casing for intermediate string, as appropriate).

5. Annular Space. No annular space that extends to the surface shall be left open to the drilled hole below. If this condition exists, a minimum of the top 50 feet of annulus shall be plugged with cement.

6. Isolating Medium. Any cement plug which is the only isolating medium for a usable water interval or a zone containg a prspectively valuable deposit of minerals shall be testedby tagging with the drill string. Any plugs placed where the fluid level will not remain static also shall be tested by either tagging the plug with the working pipe string, or pressuring to a minimum pump (surface) pressure of 1,000 psi, with no more than a 10 percent drop during a 15-minute period (cased hole only). If the integrity of any other plug is questionable, or if the authorized officer has specific concerns for which he/she orders a plug to be tested, it shall be tested in the same manner.

7. Silica Sand or Silica Flour. Silica sand or silica flour shall be added to cement exposed to bottom hole static temperatures above 230 øF to prevent heat degradation of the cement.

8. Surface Plug. A cement plug of at least 50 feet shall be placed across all annuluses. The top of this plug shall be placed as near the eventual casing cutoff point as possible.

9. Mud. Each of the intervals between plugs shall be filled with mud of suffcient density to exert hydrostatic pressure exceeding the greatest formation pressure encountered while drilling such interval. In the absense of other information at the time plugging is approved, a minimum mud weight of 9 pounds per gallon shall be specified.

10. Surface Cap. All casing shall be cut-off at the base of the cellar or 3 feet below final restored ground level (whichever is deeper). The well bore shall then be covered with a metal plate at least 1/4 inch thick and welded in place, or a 4-inch pipe, 10-feet in length, 4 feet above ground and embedded in cement as specified by the authorizedofficer. The well location and identity shall be permanently inscribed. A weep hole shall be left if a metal plate is welded in place.

11. The cellar shall be filled with suitable material as specified by the authorized officer and the surface restored in accordancxe with the instructions of the authorized officer.

Minimum Standard

All plugging orders shall be strictly adhered to.

Violation: Major.
Corrective Action: Contingent upon circumstances.
Normal Abatement Period: Prompt correction required.

[54 FR 39528, Sept. 27, 1989]

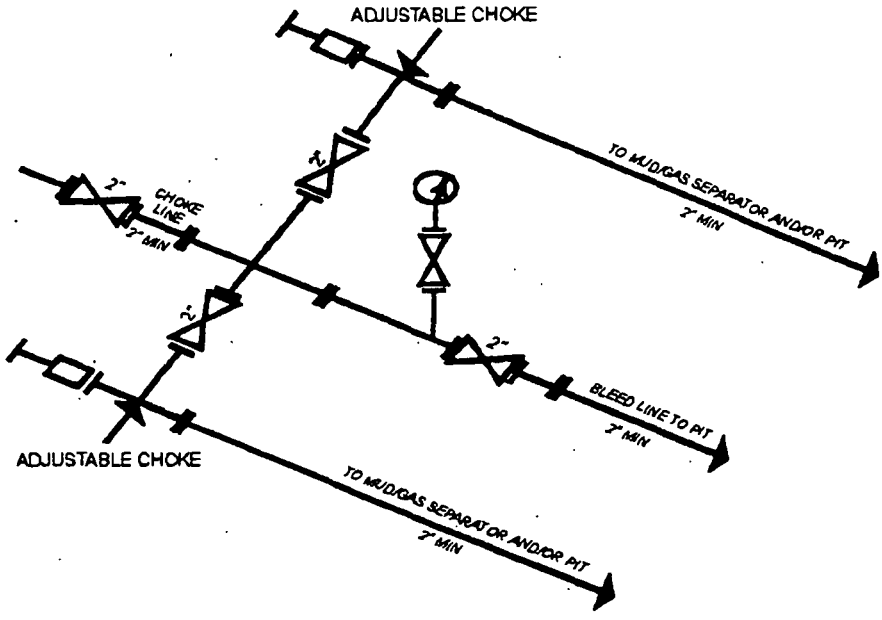
IV. Variances From Minimum Standard

An operator may request the authorized officer to approve a variance from any ofthe minimum standards prescribed in section III hereof. All such request shall be submitted in writing to the appropriate authorized officer and provide information as to the circumstances which warrant approval of the variance(s) requested and the proposed alternative methods by which the related minimum standard(s) are to be satisfied. The authorized officer, afterconsidering all relevant factors, if appropriate, may approve the requested variance(s) if it is determined that the proposed alternative(s) meet or exceed the objectives of the applicable minimum standard(s).

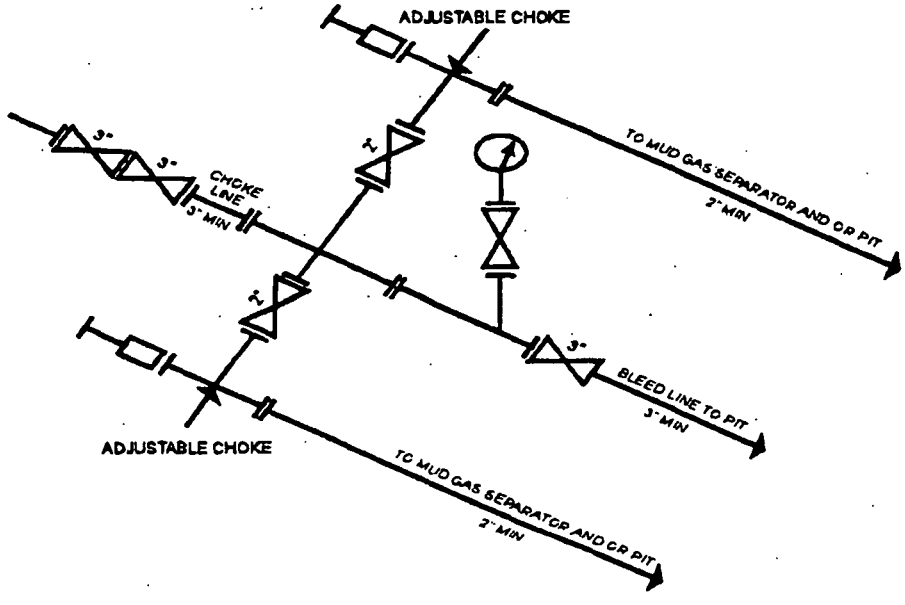
Emergency or other situations of an immediate nature that could not be reasonably forseen at the time of APD approval may recieve oral approval. However, such requests shall be followed up by a written notice filed not later than the fifth business day following oral approval.

ATTACHMENTS

I. Diagrams of Choke Manifold Equipment
II. Sections from 43 Subparts 3163 and 3165 (Not included in Federal Register Publication)

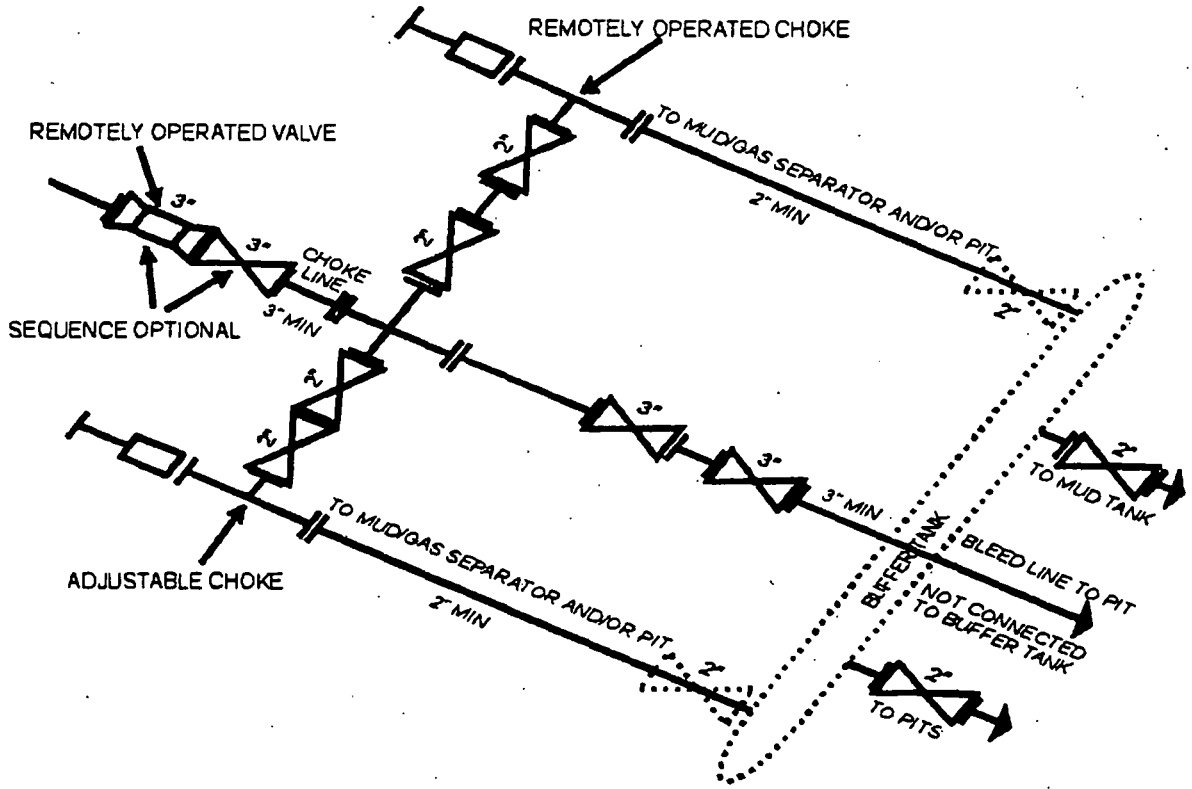


2M CHOKE MANIFOLD EQUIPMENT - CONFIGURATION OF CHOKES MAY VARY



3M CHOKE MANIFOLD EQUIPMENT - CONFIGURATION OF CHOKES MAY VARY

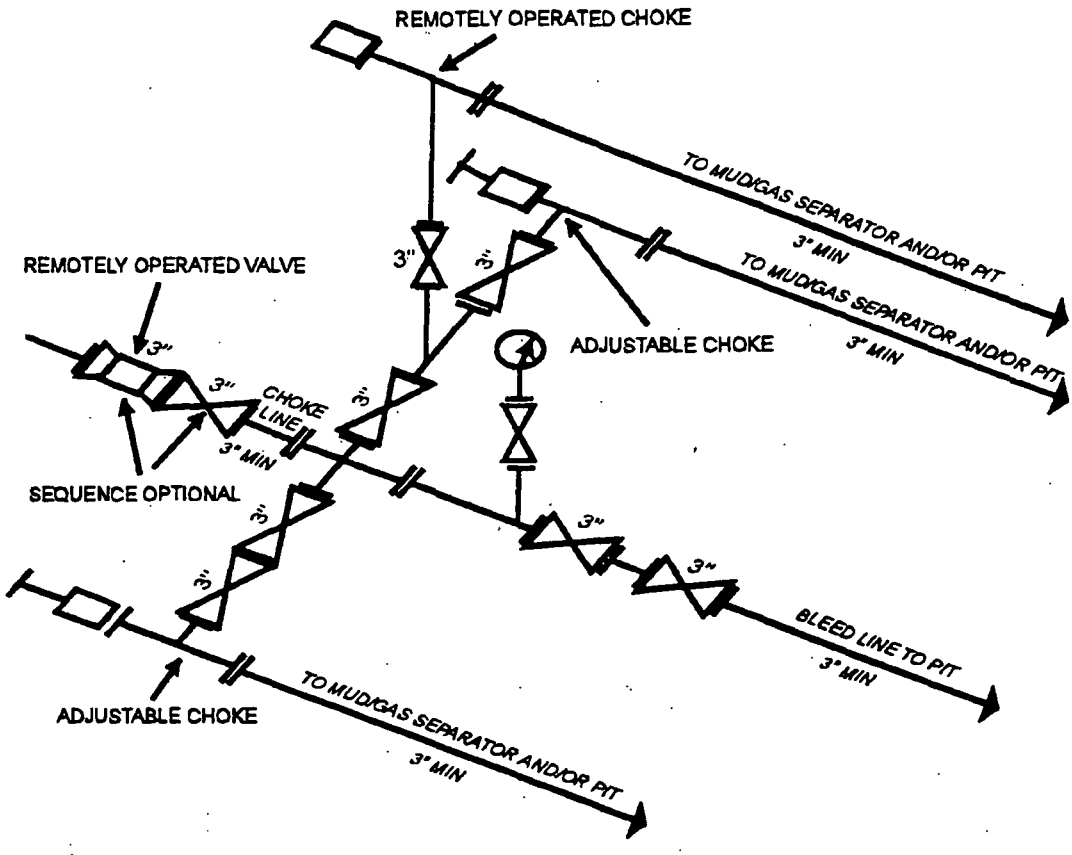
[54 FR 39528, Sept. 27, 1989]



5M CHOKE MANIFOLD EQUIPMENT - CONFIGURATION OF CHOKES MAY VARY

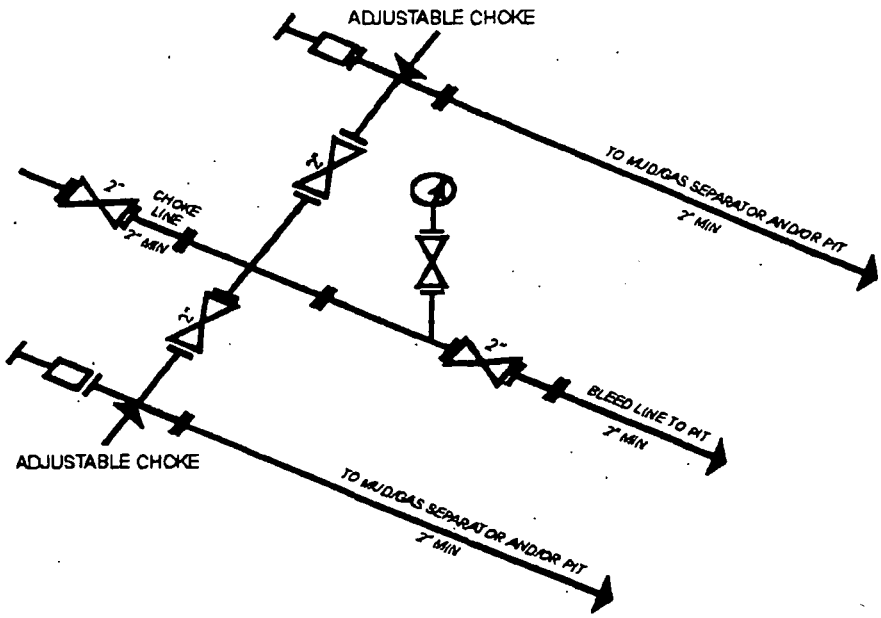
Although not required for any of the choke manifold systems, buffer tanks are sometimes installed downstream of the choke assemblies for the purpose of manifolding the bleed lines together. When buffer tanks are employed, valves shall be installed upstream to isolate a failure or malfunction without interrupting flow control. Though not shown on 2M, 3M, 10M, OR 15M drawings, it would also be applicable to those situations.

[54 FR 39528, Sept. 27, 1989]

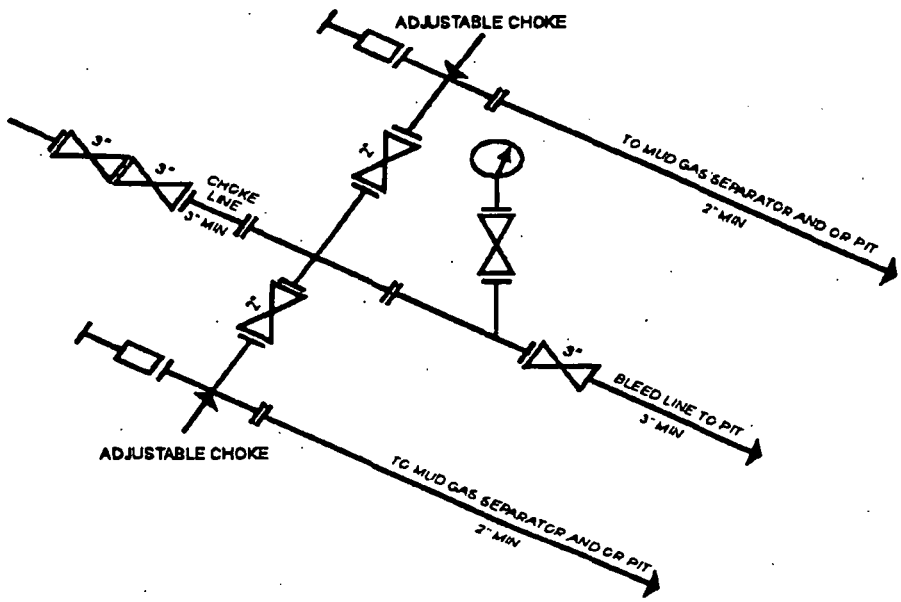


10M AND 15M CHOKE MANIFOLD EQUIPMENT - CONFIGURATION OF CHOKES MAY VARY

[53 FR 49661, Dec. 9, 1988 and 54 FR 39528, Sept. 27, 1989]

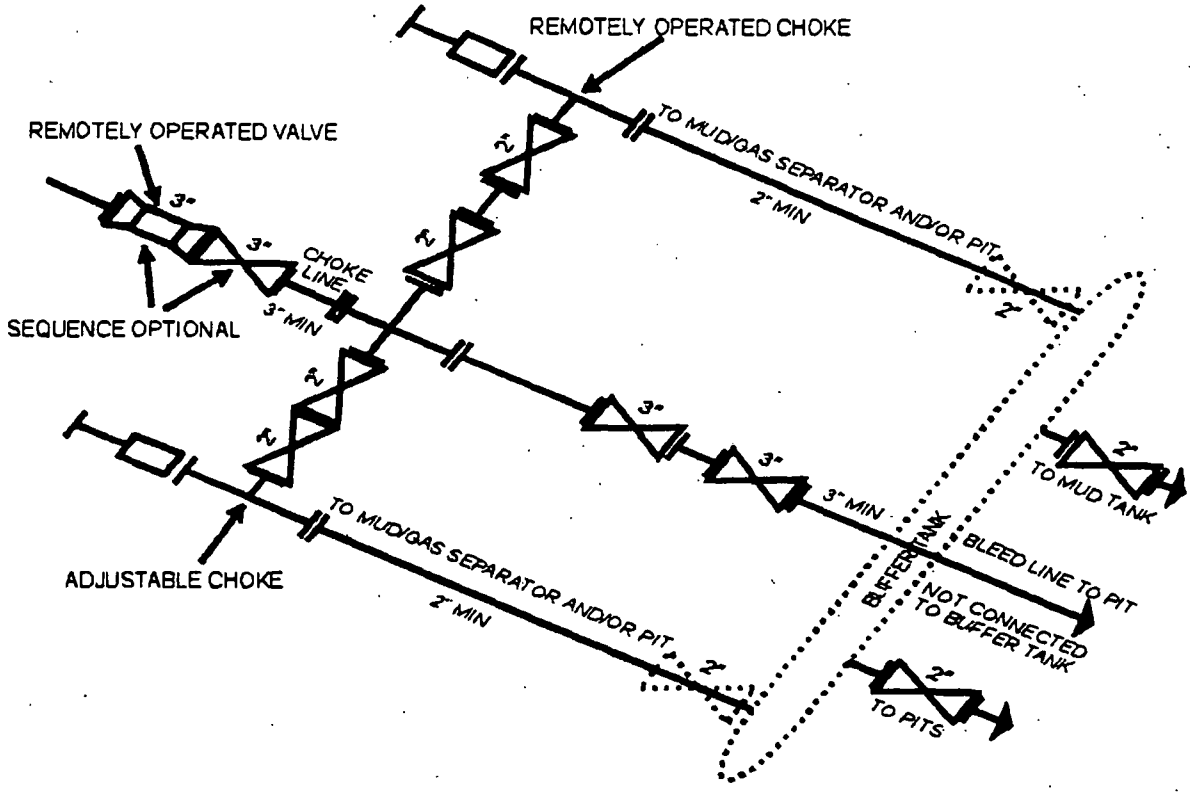


2M CHOKE MANIFOLD EQUIPMENT - CONFIGURATION OF CHOKES MAY VARY



3M CHOKE MANIFOLD EQUIPMENT - CONFIGURATION OF CHOKES MAY VARY

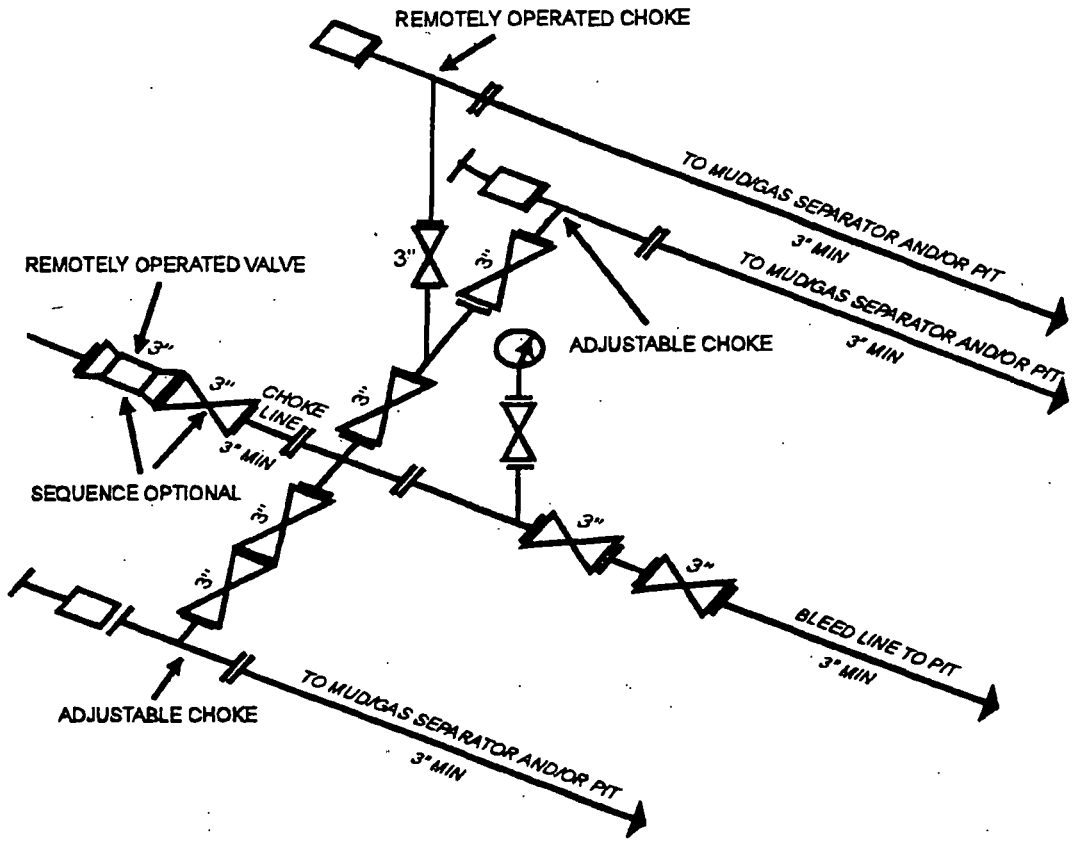
[54 FR 39528, Sept. 27, 1989]



5M CHOKE MANIFOLD EQUIPMENT - CONFIGURATION OF CHOKES MAY VARY

Although not required for any of the choke manifold systems, buffer tanks are sometimes installed downstream of the choke assemblies for the purpose of manifolding the bleed lines together. When buffer tanks are employed, valves shall be installed upstream to isolate a failure or malfunction without interrupting flow control. Though not shown on 2M, 3M, 10M, OR 15M drawings, it would also be applicable to those situations.

[54 FR 39528, Sept. 27, 1989]



10M AND 15M CHOKE MANIFOLD EQUIPMENT - CONFIGURATION OF CHOKES MAY VARY

[53 FR 49661, Dec. 9, 1988 and 54 FR 39528, Sept. 27, 1989]

which it is subject, along with the location of the plan.

[47 FR 47765, Oct. 27, 1982. Redesignated at 48 FR 36583-36586, Aug. 12, 1983, and amended at 52 FR 5392, Feb. 20, 1987. Redesignated at 53 FR 1218, Jan. 15, 1988; 53 FR 24688, June 30, 1988]

Subpart 3163—Noncompliance, Assessments, and Penalties

§3163.1 Remedies for acts of noncompliance.

(a) Whenever an operating rights owner or operator fails or refuses to comply with the regulations in this part, the terms of any lease or permit, or the requirements of any notice or order, the authorized officer shall notify the operating rights owner or operator, as appropriate, in writing of the violation or default. Such notice shall also set forth a reasonable abatement period:

(1) If the violation or default is not corrected within the time allowed, the authorized officer may subject the operating rights owner or operator, as appropriate, to an assessment of not more than $500 per day for each day nonabatement continues where the violation or default is deemed a major violation;

(2) Where noncompliance involves a minor violation, the authorized officer may subject the operating rights owner or operator, as appropriate, to an assessment of $250 for failure to abate the violation or correct the default within the time allowed;

(3) When necessary for compliance, or where operations have been commenced without approval, or where continued operations could result in immediate, substantial, and adverse impacts on public health and safety, the environment, production accountability, or royalty income, the authorized officer may shut down operations. Immediate shut-in action may be taken where operations are initiated and conducted without prior approval, or where continued operations could result in immediate, substantial, and adverse impacts on public health and safety, the environment, production accountability, or royalty income. Shut-in actions for other situations may be taken only after due notice, in writing, has been given;

(4) When necessary for compliance, the authorized officer may enter upon a lease and perform, or have performed, at the sole risk and expense of the operator, operations that the operator fails to perform when directed in writing by the authorized officer. Appropriate charges shall include the actual cost of performance, plus an additional 25 percent of such amount to compensate the United States for administrative costs. The operator shall be provided with a reasonable period of time either to take corrective action or to show why the lease should not be entered;

(5) Continued noncompliance may subject the lease to cancellation and forfeiture under the bond. The operator shall be provided with a reasonable period of time either to take corrective action or to show why the lease should not be recommended for cancellation;

(6) Where actual loss or damage has occurred as a result of the operator's noncompliance, the actual amount of such loss or damage shall be charged to the operator.

(b) Certain instances of noncompliance are violations of such a serious nature as to warrant the imposition of immediate assessments upon discovery. Upon discovery the following violations shall result in immediate assessments, which may be retroactive, in the following specified amounts per violation:

(1) For failure to install blowout preventer or other equivalent well control equipment, as required by the approved drilling plan, $500 per day for each day that the violation existed, including days the violation existed prior to discovery, not to exceed $5,000;

(2) For drilling without approval or for causing surface disturbance on Federal or Indian surface preliminary to drilling without approval, $500 per day for each day that the violation existed, including days the violation existed prior to discovery, not to exceed $5,000;

(3) For failure to obtain approval of a plan for well abandonment prior to commencement of such operations, $500.

(c) Assessments under paragraph (a)(1) of this section shall not exceed

$1,000 per day, per operating rights owner or operator, per lease. Assessments under paragraph (a)(2) of this section shall not exceed a total of $500 per operating rights owner or operator, per lease, per inspection.

(d) Continued noncompliance shall subject the operating rights owner or operator, as appropriate, to penalties described in § 3163.2 of this title.

(e) On a case-by-case basis, the State Director may compromise or reduce assessments under this section. In compromising or reducing the amount of the assessment, the State Director shall state in the record the reasons for such determination.

[52 FR 5393, Feb. 20, 1987; 52 FR 10225, Mar. 31, 1987, as amended at 53 FR 17364, May 16, 1988; 53 FR 22847, June 17, 1988]

§ 3163.2 Civil penalties.

(a) Whenever an operating rights owner or operator, as appropriate, fails or refuses to comply with any applicable requirements of the Federal Oil and Gas Royalty Management Act, any mineral leasing law, any regulation thereunder, or the terms of any lease or permit issued thereunder, the authorized officer shall notify the operating rights owner or operator, as appropriate, in writing of the violation, unless the violation was discovered and reported to the authorized officer by the liable person or the notice was previously issued under § 3163.1 of this title. If the violation is not corrected within 20 days of such notice or report, or such longer time as the authorized officer may agree to in writing, the operating rights owner or operator, as appropriate, shall be liable for a civil penalty of up to $500 per violation for each day such violation continues, dating from the date of such notice or report. Any amount imposed and paid as assessments under the provisions of § 3163.1(a)(1) of this title shall be deducted from penalties under this section.

(b) If the violation specified in paragraph (a) of this section is not corrected within 40 days of such notice or report, or a longer period as the authorized officer may agree to in writing, the operating rights owner or operator, as appropriate, shall be liable for a civil penalty of up to $5,000 per violation for each day the violation continues, not to exceed a maximum of 60 days, dating from the date of such notice or report. Any amount imposed and paid as assessments under the provisions of § 3163.1(a)(1) of this title shall be deducted from penalties under this section.

(c) In the event the authorized officer agrees to an abatement period of more than 20 days, the date of notice shall be deemed to be 20 days prior to the end of such longer abatement period for the purpose of civil penalty calculation.

(d) Whenever a transporter fails to permit inspection for proper documentation by any authorized representative, as provided in § 3162.7–1(c) of this title, the transporter shall be liable for a civil penalty of up to $500 per day for the violation, not to exceed a maximum of 20 days, dating from the date of notice of the failure to permit inspection and continuing until the proper documentation is provided.

(e) Any person shall be liable for a civil penalty of up to $10,000 per violation for each day such violation continues, not to exceed a maximum of 20 days if he/she:

(1) Fails or refuses to permit lawful entry or inspection authorized by § 3162.1(b) of this title; or

(2) Knowingly or willfully fails to notify the authorized officer by letter or Sundry Notice, Form 3160–5 or orally to be followed by a letter or Sundry Notice, not later than the 5th business day after any well begins production on which royalty is due, or resumes production in the case of a well which has been off of production for more than 90 days, from a well located on a lease site, or allocated to a lease site, of the date on which such production began or resumed.

(f) Any person shall be liable for a civil penalty of up to $25,000 per violation for each day such violation continues, not to exceed a maximum of 20 days if he/she:

(1) Knowingly or willfully prepares, maintains or submits false, inaccurate or misleading reports, notices, affidavits, records, data or other written information required by this part; or

(2) Knowingly or willfully takes or removes, transports, uses or diverts

any oil or gas from any Federal or Indian lease site without having valid legal authority to do so; or

(3) Purchases, accepts, sells, transports or conveys to another any oil or gas knowing or having reason to know that such oil or gas was stolen or unlawfully removed or diverted from a Federal or Indian lease site.

(g) Determinations of Penalty Amounts for this section are as follows:

(1) For major violations, all initial proposed penalties shall be at the maximum rate provided in paragraphs (a), (b), and (d) through (f) of this section, i.e., in paragraph (a) of this section, the initial proposed penalty for a major violation shall be at the rate of $500 per day through the 40th day of a noncompliance beginning after service of notice, and in paragraph (b) of this section, $5,000 per day for each day the violation remains uncorrected after the date of notice or report of the violation. Such penalties shall not exceed a rate of $1,000 per day, per operating rights owner or operator, per lease under paragraph (a) of this section or $10,000 per day, per operating rights owner or operator, per lease under paragraph (b) of this section. For paragraphs (d) through (f) of this section, the rate shall be $500, $10,000, and $25,000, respectively.

(2) For minor violations, no penalty under paragraph (a) of this section shall be assessed unless:

(i) The operating rights owner or operator, as appropriate, has been notified of the violation in writing and did not correct the violation within the time allowed; and

(ii) The operating rights owner or operator, as appropriate, has been assessed $250 under §3163.1 of this title and a second notice has been issued giving an abatement period of not less than 20 days; and

(iii) The noncompliance was not abated within the time allowed by the second notice. The initial proposed penalty for a minor violation under paragraph (a) of this section shall be at the rate of $50 per day beginning with the date of the second notice. Under paragraph (b) of this section, the penalty shall be at a daily rate of $500. Such penalties shall not exceed a rate of $100 per day, per operating rights owner or operator, per lease under paragraph (a) of this section, of $1,000 per day, per operating rights owner or operator, per lease under paragraph (b) of this section.

(h) On a case-by-case basis, the Secretary may compromise or reduce civil penalties under this section. In compromising or reducing the amount of a civil penalty, the Secretary shall state on the record the reasons for such determination.

(i) Civil penalties provided by this section shall be supplemental to, and not in derogation of, any other penalties or assessments for noncompliance in any other provision of law, except as provided in paragraphs (a) and (b) of this section.

(j) If the violation continues beyond the 60-day maximum specified in paragraph (b) of this section or beyond the 20 day maximum specified in paragraphs (e) and (f) of this section, lease cancellation proceedings shall be initiated under either Title 43 or Title 25 of the Code of Federal Regulations.

(k) If the violation continues beyond the 20-day maximum specified in paragraph (d) of this section, the authorized officer shall revoke the transporter's authority to remove crude oil or other liquid hydrocarbons from any Federal or Indian lease under the authority of that authorized officer or to remove any crude oil or liquid hydrocarbons allocation to such lease site. This revocation of the transporter's authority shall continue until compliance is achieved and related penalty paid.

[52 FR 5393, Feb. 20, 1987; 52 FR 10225, Mar. 31, 1987, as amended at 53 FR 17364, May 16, 1988]

§3163.3 Criminal penalties.

Any person who commits an act for which a civil penalty is provided in §3163.4-1(b)(6) of this title shall, upon conviction, be punished by a fine of not more than $50,000 or by imprisonment for not more than 2 years or both.

[49 FR 37367, Sept. 21, 1984. Redesignated at 52 FR 5394, Feb 20, 1987]

§3163.4 Failure to pay.

If any person fails to pay an assessment or a civil penalty under §3163.1 or §3163.2 of this title after the order

making the assessment or penalty becomes a final order, and if such person does not file a petition for judicial review in accordance with this subpart, or, after a court in an action brought under this subpart has entered a final judgment in favor of the Secretary, the court shall have jurisdiction to award the amount assessed plus interest from the date of the expiration of the 90-day period provided by §3165.4(e) of this title. The Federal Oil and Gas Royalty Management Act requires that any judgment by the court shall include an order to pay.

[52 FR 5394, Feb. 20, 1987; 52 FR 10225, Mar. 31, 1987]

§3163.5 Assessments and civil penalties.

(a) Assessments made under §3163.1 of this title are due upon issuance and shall be paid within 30 days of receipt of certified mail written notice or personal service, as directed by the authorized officer in the notice. Failure to pay assessed damages timely will be subject to late payment charges as prescribed under Title 30 CFR Group 202.

(b) Civil penalties under §3163.2 of this title shall be paid within 30 days of completion of any final order of the Secretary or the final order of the Court.

(c) Payments made pursuant to this section shall not relieve the responsible party of compliance with the regulations in this part or from liability for waste or any other damage. A waiver of any particular assessment shall not be construed as precluding an assessment pursuant to §3163.1 of this title for any other act of noncompliance occurring at the same time or at any other time. The amount of any civil penalty under §3163.2 of this title, as finally determined, may be deducted from any sums owing by the United States to the person charged.

[47 FR 47765, Oct. 27, 1982. Redesignated and amended at 48 FR 36583-36586, Aug. 12, 1983; 49 FR 37368, Sept. 21, 1984; 52 FR 5394, Feb. 20, 1987; 52 FR 10225, Mar. 31, 1987; 53 FR 17364, May 16, 1988]

§3163.6 Injunction and specific performance.

(a) In addition to any other remedy under this part or any mineral leasing law, the Attorney General of the United States or his designee may bring a civil action in a district court of the United States to:

(1) Restrain any violation of the Federal Oil and Gas Royalty and Management Act or any mineral leasing law of the United States; or

(2) Compel the taking of any action required by or under the Act or any mineral leasing law of the United States.

(b) A civil action described in paragraph (a) may be brought only in the United States district court of the judicial district wherein the act, omission or transaction constituting a violation under the Act or any other mineral leasing law occurred, or wherein the defendant is found or transacts business.

[49 FR 37368, Sept. 21, 1984]

Subpart 3164—Special Provisions

§3164.1 Onshore Oil and Gas Orders.

(a) The Director is authorized to issue Onshore Oil and Gas Orders when necessary to implement and supplement the regulations in this part. All orders will be published in the FEDERAL REGISTER both for public comment and in final form.

(b) These Orders are binding on operating rights owners and operators, as appropriate, of Federal and restricted Indian oil and gas leases which have been, or may hereafter be, issued. The Onshore Oil and Gas Orders listed below are currently in effect:

Order No.	Subject	Effective date	FEDERAL REGISTER reference	Supersedes
1.	Approval of operations	Nov. 21, 1983	48 FR 48916 and 48 FR 56226	NTL–6.
2.	Drilling	Dec. 19, 1988	53 FR 46790	None.

Order No.	Subject	Effective date	FEDERAL REGISTER reference	Supersedes
3.	Site security	Mar. 27, 1989	54 FR 8056	NTL-7.
4.	Measurement of oil	Aug. 23, 1989	54 FR 8086	None.
5.	Measurement of gas	Mar. 27, 1989, new facilities greater than 200 MCF production; Aug. 23, 1989, existing facility greater than 200 MCF production; Feb. 26, 1990, existing facility less than 200 MCF production.	54 FR 8100	None.
6.	Hydrogen sulfide operations	Jan. 22, 1991	55 FR 48958	None.
7.	Disposal of produced water	October 8, 1993	58 FR 47354	NTL-2B

Note: Numbers to be assigned sequentially by the Washington Office as proposed Orders are prepared for publication.

[47 FR 47765, Oct. 27, 1982. Redesignated at 48 FR 36583-36586, Aug. 12, 1983, and amended at 48 FR 48921, Oct. 21, 1983; 48 FR 56226, Dec. 20, 1983; 53 FR 17364, May 16, 1988; 54 FR 8060, Feb. 24, 1989; 54 FR 8092, Feb. 24, 1989; 54 FR 8106, Feb. 24, 1989; 54 FR 39527, 39529, Sept. 27, 1989; 56 FR 48967, Nov. 23, 1991; 57 FR 3025, Jan. 27, 1992; 58 FR 47361, Sept. 8, 1993; 58 FR 58505, Nov. 2, 1993]

§3164.2 NTL's and other implementing procedures.

(a) The authorized officer is authorized to issue NTL's when necessary to implement the onshore oil and gas orders and the regulations in this part. All NTL's will be issued after notice and opportunity for comment.

(b) All NTL's issued prior to the promulgation of these regulations shall remain in effect until modified, superseded by an Onshore Oil and Gas Order, or otherwise terminated.

(c) A manual and other written instructions will be used to provide policy and procedures for internal guidance of the Bureau of Land Management.

§3164.3 Surface rights.

(a) Operators shall have the right of surface use only to the extent specifically granted by the lease. With respect to restricted Indian lands, additional surface rights may be exercised when granted by a written agreement with the Indian surface owner and approved by the Superintendent of the Indian agency having jurisdiction.

(b) Except for the National Forest System lands, the authorized officer is responsible for approving and supervising the surface use of all drilling, development, and production activities on the leasehold. This includes storage tanks and processing facilities, sales facilities, all pipelines upstream from such facilities, and other facilities to aid production such as water disposal pits and lines, and gas or water injection lines.

(c) On National Forest System lands, the Forest Service shall regulate all surface disturbing activities in accordance with Forest Service regulations, including providing to the authorized officer appropriate approvals of such activities.

[47 FR 47765, Oct. 27, 1982. Redesignated and amended at 48 FR 36583-36586, Aug. 12, 1983, further amended at 53 FR 17364, May 16, 1988; 53 FR 22847, June 17, 1988]

§3164.4 Damages on restricted Indian lands.

Assessments for damages to lands, crops, buildings, and to other improvements on restricted Indian lands shall be made by the Superintendent and be payable in the manner prescribed by said official.

Subpart 3165—Relief, Conflicts, and Appeals

§3165.1 Relief from operating and producing requirements.

(a) Applications for relief from either the operating or the producing requirements of a lease, or both, shall be filed with the authorized officer, and shall include a full statement of the circumstances that render such relief necessary.

(b) The authorized officer shall act on applications submitted for a suspension

of operations or production, or both, filed pursuant to § 3103.4–4 of this title. The application for suspension shall be filed with the authorized officer prior to the expiration date of the lease; shall be executed by all operating rights owners or, in the case of a Federal unit approved under part 3180 of this title, by the unit operator on behalf of the committed tracts or by all operating rights owners of such tracts; and shall include a full statement of the circumstances that makes such relief necessary.

(c) If approved, a suspension of operations and production will be effective on the first of the month in which the completed application was filed or the date specified by the authorized officer. Suspensions will terminate when they are no longer justified in the interest of conservation, when such action is in the interest of the lessor, or as otherwise stated by the authorized officer in the approval letter.

[47 FR 47765, Oct. 27, 1982. Redesignated and amended at 48 FR 36583–36586, Aug. 12, 1983, further amended at 53 FR 17364, May 16, 1988; 61 FR 4752, Feb. 8, 1996]

§ 3165.1–1 Relief from royalty and rental requirements.

Applications for any modification authorized by law of the royalty or rental requirements of a lease for lands of the United States shall be filed in the office of the authorized officer having jurisdiction of the lands. (For other regulations relating to royalty and rental relief, and suspension of operations and production, see part 3103 of this title.)

[48 FR 36586, Aug. 12, 1983, as amended at 53 FR 17365, May 16, 1988]

§ 3165.2 Conflicts between regulations.

In the event of any conflict between the regulations in this part and the regulations in title 25 CFR concerning oil and gas operations on Federal and Indian leaseholds, the regulations in this part shall govern with respect to the obligations in the conduct of oil and gas operations, acts of noncompliance, and the jurisdiction and authority of the authorized officer.

[47 FR 47765, Oct. 27, 1982. Redesignated and amended at 48 FR 36583–36586, Aug. 12, 1983, further amended at 53 FR 17365, May 16, 1988]

§ 3165.3 Notice, State Director review and hearing on the record.

(a) *Notice.* Whenever an operating rights owner or operator, as appropriate, fails to comply with any provisions of the lease, the regulations in this part, applicable orders or notices, or any other appropriate orders of the authorized officer, written notice shall be given the appropriate party and the lessee(s) to remedy any defaults or violations. Written orders or a notice of violation, assessment, or proposed penalty shall be issued and served by personal service by an authorized officer or by certified mail. Service shall be deemed to occur when received or 7 business days after the date it is mailed, whichever is earlier. Any person may designate a representative to receive any notice of violation, assessment, or proposed penalty on his/her behalf. In the case of a major violation, the authorized officer shall make a good faith effort to contact such designated representative by telephone to be followed by a written notice. Receipt of notice shall be deemed to occur at the time of such verbal communication, and the time of notice and the name of the receiving party shall be confirmed in the file. If the good faith effort to contact the designated representative is unsuccessful, notice of the major violation may be given to any person conducting or supervising operations subject to the regulations in this part. In the case of a minor violation, written notice shall be provided as described above. A copy of all orders, notices, or instructions served on any contractor or field employee or designated representative shall also be mailed to the operator. Any notice involving a civil penalty shall be mailed to the operating rights owner.

(b) *State Director review.* Any adversely affected party that contests a notice of violation or assessment or an instruction, order, or decision of the authorized officer issued under the regulations in this part, may request an administrative review, before the State Director, either with or without oral presentation. Such request, including all supporting documentation, shall be filed in writing with the appropriate State Director within 20 business days of the date such notice of violation or

assessment or instruction, order, or decision was received or considered to have been received and shall be filed with the appropriate State Director. Upon request and showing of good cause, an extension for submitting supporting data may be granted by the State Director. Such review shall include all factors or circumstances relevant to the particular case. Any party who is adversely affected by the State Director's decision may appeal that decision to the Interior Board of Land Appeals as provided in §3165.4 of this part.

(c) *Review of proposed penalties.* Any adversely affected party wishing to contest a notice of proposed penalty shall request an administrative review before the State Director under the procedures set out in paragraph (b) of this section. However, no civil penalty shall be assessed under this part until the party charged with the violation has been given the opportunity for a hearing on the record in accordance with section 109(e) of the Federal Oil and Gas Royalty Management Act. Therefore, any party adversely affected by the State Director's decision on the proposed penalty, may request a hearing on the record before an Administrative Law Judge or, in lieu of a hearing, may appeal that decision directly to the Interior Board of Land Appeals as provided in §3165.4(b)(2) of this part. If such party elects to request a hearing on the record, such request shall be filed in the office of the State Director having jurisdiction over the lands covered by the lease within 30 days of receipt of the State Director's decision on the notice of proposed penalty. Where a hearing on the record is requested, the State Director shall refer the complete case file to the Office of Hearings and Appeals for a hearing before an Administrative Law Judge in accordance with part 4 of this title. A decision shall be issued following completion of the hearing and shall be served on the parties. Any party, including the United States, adversely affected by the decision of the Administrative Law Judge may appeal to the Interior Board of Land Appeals as provided in §3163.4 of this title.

(d) *Action on request for State Director review. Action on request for administrative review.* The State Director shall issue a final decision within 10 business days of the receipt of a complete request for administrative review or, where oral presentation has been made, within 10 business days therefrom. Such decision shall represent the final Bureau decision from which further review may be obtained as provided in paragraph (c) of this section for proposed penalties, and in §3165.4 of this title for all decisions.

(e) *Effect of request for State Director review or for hearing on the record.* (1) Any request for review by the State Director under this section shall not result in a suspension of the requirement for compliance with the notice of violation or proposed penalty, or stop the daily accumulation of assessments or penalties, unless the State Director to whom the request is made so determines.

(2) Any request for a hearing on the record before an administrative law judge under this section shall not result in a suspension of the requirement for compliance with the decision, unless the administrative law judge so determines. Any request for hearing on the record shall stop the accumulation of additional daily penalties until such time as a final decision is rendered, except that within 10 days of receipt of a request for a hearing on the record, the State Director may, after review of such request, recommend that the Director reinstate the accumulation of daily civil penalties until the violation is abated. Within 45 days of the filing of the request for a hearing on the record, the Director may reinstate the accumulation of civil penalties if he/she determines that the public interest requires a reinstatement of the accumulation and that the violation is causing or threating immediate, substantial and adverse impacts on public health and safety, the environment, production accountability, or royalty income. If the Director does not reinstate the daily accumulation within 45 days of the filing of the request for a hearing on the record, the suspension shall continue.

[52 FR 5394, Feb. 20, 1987; 52 FR 10225, Mar. 31, 1987, as amended at 53 FR 17365, May 16, 1988; 66 FR 1894, Jan. 10, 2001]

§ 3165.4 Appeals.

(a) *Appeal of decision of State Director.* Any party adversely affected by the decision of the State Director after State Director review, under §3165.3(b) of this title, of a notice of violation or assessment or of an instruction, order, or decision may appeal that decision to the Interior Board of Land Appeals pursuant to the regulations set out in part 4 of this title.

(b) *Appeal from decision on a proposed penalty after a hearing on the record.* (1) Any party adversely affected by the decision of an Administrative Law Judge on a proposed penalty after a hearing on the record under §3165.3(c) of this title may appeal that decision to the Interior Board of Land Appeals pursuant to the regulations in part 4 of this title.

(2) In lieu of a hearing on the record under §3165.3(c) of this title, any party adversely affected by the decision of the State Director on a proposed penalty may waive the opportunity for such a hearing on the record by appealing directly to the Interior Board of Land Appeals under part 4 of this title. However, if the right to a hearing on the record is waived, further appeal to the District Court under section 109(j) of the Federal Oil and Gas Royalty Management Act is precluded.

(c) *Effect of an appeal on an approval/decision by a State Director or Administrative Law Judge.* All decisions and approvals of a State Director or Administrator Law Judge under this part shall remain effective pending appeal unless the Interior Board of Land Appeals determines otherwise upon consideration of the standards stated in this paragraph. The provisions of 43 CFR 4.21(a) shall not apply to any decision or approval of a State Director or Administrative Law Judge under this part. A petition for a stay of a decision or approval of a State Director or Administrative Law Judge shall be filed with the Interior Board of Land Appeals, Office of Hearings and Appeals, Department of the Interior, and shall show sufficient justification based on the following standards:

(1) The relative harm to the parties if the stay is granted or denied,

(2) The likelihood of the appellant's success on the merits,

(3) The likelihood of irreparable harm to the appellant or resources if the stay is not granted, and

(4) Whether the public interest favors granting the stay.

Nothing in this paragraph shall diminish the discretionary authority of a State Director or Administrative Law Judge to stay the effectiveness of a decision subject to appeal pursuant to paragraph (a) or (b) of this section upon a request by an adversely affected party or on the State Director's or Administrative Law Judge's own initiative. If a State Director or Administrative Law Judge denies such a request, the requester can petition for a stay of the denial decision by filing a petition with the Interior Board of Land Appeals that addresses the standards described above in this paragraph.

(d) *Effect of appeal on compliance requirements.* Except as provided in paragraph (d) of this section, any appeal filed pursuant to paragraphs (a) and (b) of this section shall not result in a suspension of the requirement for compliance with the order or decision from which the appeal is taken unless the Interior Board of Land Appeals determines that suspension of the requirements of the order or decision will not be detrimental to the interests of the lessor or upon submission and acceptance of a bond deemed adequate to indemnify the lessor from loss or damage.

(e) *Effect of appeal on assessments and penalties.* (1) Except as provided in paragraph (d)(3) of this section, an appeal filed pursuant to paragraph (a) of this section shall suspend the accumulation of additional daily assessments. However, the pendency of an appeal shall not bar the authorized officer from assessing civil penalties under §3163.2 of this title in the event the operator has failed to abate the violation which resulted in the assessment. The Board of Land Appeals may issue appropriate orders to coordinate the pending appeal and the pending civil penalty proceeding.

(2) Except as provided in paragraph (d)(3) of this section, an appeal filed pursuant to paragraph (b) of this section shall suspend the accumulation of additional daily civil penalties.

(3) When an appeal is filed under paragraph (a) or (b) of this section, the State Director may, within 10 days of receipt of the notice of appeal, recommend that the Director reinstate the accumulation of assessments and daily civil penalties until such time as a final decision is rendered or until the violation is abated. The Director may, if he/she determines that the public interest requires it, reinstate such accumulation(s) upon a finding that the violation is causing or threatening immediate substantial and adverse impacts on public health and safety, the environment, production accountability, or royalty income. If the Director does not act on the recommendation to reinstate the accumulation(s) within 45 days of the filing of the notice of appeal, the suspension shall continue.

(4) When an appeal is filed under paragraph (a) of this section from a decision to require drainage protection, BLM's drainage determination will remain in effect during the appeal, notwithstanding the provisions of 43 CFR 4.21. Compensatory royalty and interest determined under 30 CFR Part 218 will continue to accrue throughout the appeal.

(f) *Judicial review.* Any person who is aggrieved by a final order of the Secretary under this section may seek review of such order in the United States District Court for the judicial district in which the alleged violation occurred. Because section 109 of the Federal Oil and Gas Royalty Management Act provides for judicial review of civil penalty determinations only where a person has requested a hearing on the record, a waiver of such hearing precludes further review by the district court. Review by the district court shall be on the administrative record only and not de novo. Such an action shall be barred unless filed within 90 days after issuance of final decision as provided in §4.21 of this title.

[52 FR 5395, Feb. 20, 1987; 52 FR 10225, Mar. 31, 1987, as amended at 53 FR 17365, May 16, 1988; 57 FR 9013, Mar. 13, 1992; 66 FR 1894, Jan. 10, 2001]

PART 3180—ONSHORE OIL AND GAS UNIT AGREEMENTS: UNPROVEN AREAS

NOTE: Many existing unit agreements currently in effect specifically refer to the United States Geological Survey, USGS, Minerals Management Service, MMS, Supervisor, Conservation Manager, Deputy Conservation Manager, Minerals Manager and Deputy Minerals Manager in the body of the agreements, as well as references to 30 CFR part 221 or specific sections thereof. Those references shall now be read in the context of Secretarial Order 3087 and now mean either the Bureau of Land Management or Minerals Management Service, as appropriate.

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