Sealing Concepts for the Waste Isolation Pilot Plant (WIPP) Site

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SEALING CONCEPTS FOR THE
WASTE ISOLATION PILOT PLANT (WIPP) SITE

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SEALING CONCEPTS FOR THE WIPP SITE

1.0 Introduction

The Waste Isolation Pilot Plant (WIPP) facility is proposed for development in the southeast portion of the State of New Mexico. The proposed horizon is in bedded salt located approximately 2150 ft below the surface. The purpose of the WIPP is to provide an R&D facility to demonstrate the safe disposal of radioactive wastes resulting from defense activities of the United States. As such, it will include a disposal demonstration for transuranic (TRU) wastes and an experimental area to address issues associated with disposal of defense high level wastes (DHLW) in bedded salt. All DHLW used in the experiments are planned for retrieval at the termination of testing; the TRU waste can be permanently disposed of at the site after the pilot phase is complete.

The WIPP R&D program includes several programs relating to waste disposal issues: Thermal/Structural interactions between heat producing waste and the host rock, Plugging and Sealing requirements for long term waste isolation and Waste Package requirements for

containment of heat producing wastes. These programs and the associated in situ testing at the WIPP location are described in Reference 1. This report addresses only the Plugging and Sealing program, which will result in an adequate and acceptable technology for final sealing and decommissioning of the facility at the WIPP site. The actual plugging operations are intended to be conducted on a commercial industrial basis through contracts issued by the DOE. This report is one in a series that is based on a technical program of modeling, laboratory materials testing and field demonstration which will provide a defensible basis for the actual plugging operations to be conducted by the DOE for final closure of the facility. The basic Plugging and Sealing program is contained in Reference 2.

This report furnishes preliminary guidance for plugging and sealing* vertical (boreholes, shafts) and horizontal (tunnels, drifts) penetrations in the Waste Isolation Pilot Plant (WIPP). Issues under current consideration for sealing activities are suggested as a basis for further development. The information presented is not intended as final criteria but as an initial concept allowing for periodic revisions and updates as new data are obtained. The ultimate goal is final plug designs. The report specifically addresses concepts pertinent to the lithology of the WIPP site.

*The terms "plug" and "seal" are considered essentially synonymous in this paper; however, the authors' interpretation of the subtle distinction between the two is contained in Section 2.0.

This report begins with the premise that the primary function of a plug is to limit groundwater intrusion and subsequent egress from the facility and proceeds then to discuss how and where this flow can be controlled in each of the intended plugging formations (Rustler, Salado, Castile) at the site, and the nature of the man-made penetration under consideration (for example, vertical or horizontal) and the required preparation of the penetration for plugging. It ends with a recommended set of plugging criteria which should be considered in designing tests within the Plugging and Sealing technology development program. It is not intended to portray the final plug design at the WIPP site but rather to initiate activities leading to this final design.

2.0 Premise

For purposes of this paper, the primary function of a plug is to limit or reduce the access of groundwater to the facility horizon that could come in contact with the waste material.

It is worthwhile to briefly discuss the basis for this premise. First, at the WIPP site the storage medium is soluble rock salt (halite), which suggests that fluid barriers should be designed that limit the volume of groundwater accessible to this formation. This barrier need not preclude groundwater from reaching the horizon, but it should reduce or limit the amount. The consequences have been calculated for an open unplugged wellbore or shaft conducting

available groundwater at the WIPP site to and through the facility and the subsequent transport of radionuclides into the biosphere. These calculations show that, even in the unplugged case, there would be no significant hazard from the standpoint of public health and safety.³ Nevertheless, prudence dictates that wellbores intercepting the facility should be plugged before abandonment of the WIPP. This will provide greater confidence in waste containment and reduce the public perception of hazard.

Second, the calculational models assume that the flow of groundwater through the storage horizon is a mechanism for transporting radionuclides into the biosphere. Limiting the volume of flow will retard the movement of radionuclides from the site, both in time and quantity. A barrier that prevents all groundwater from reaching the horizon (a "perfect" seal), is an unnecessary constraint; such a "perfect" seal might not be achievable and it would be impossible to demonstrate over the time periods of interest, ie, hundreds to thousands of years. Plugs (or the conceptually more flow-restrictive term "seal"), in this paper, are discussed on the basis that some small leakage is acceptable.

Specific objectives within the Plugging and Sealing program are designed to address the following questions regarding plug performance.

1. Are the candidate materials under consideration for sealing suitable for long term flow restrictions within the intended formations?
2. To what extent do these materials actually limit flow and given these limited flows, what is the magnitude of any potential release of radionuclides to the biosphere and the subsequent effect on public health and safety?
3. How confident can we be in the measured performance of these plugs and for how long?

3.0 Materials for Seals Within the Host-Rock Formations

One condition that enhances the performance of a fluid barrier is the similarity of a material to its host rock. The more nearly a plugging material resembles or replicates its host rock, the greater the likelihood of forming and maintaining a seal. If replication cannot be completely achieved, then the barrier should be compatible thermodynamically and mechanically with the host rock to lessen reactions with the formation in which it is emplaced. Complete compatibility between barrier and host rock may not be necessary (or possible) in all cases, but the sealing goal is selection of materials that most completely satisfy the sealing (ie, restriction of fluid flow) condition. Proposed seals can then be evaluated with respect to facility integrity and public safety.

Plugging materials are proposed to be compatible with the various strata (based on existing drillhole logs) at the WIPP site (Figure 1). The left-hand side of Figure 1 shows the formations; the right-hand side suggests candidate plugging materials which are described in the following paragraphs. The gross lithology⁴ from the surface down to the Rustler Formation (labeled as Dewey Lake Redbeds) consists of the cenozoic alluvium (Gatuna Fur, Santa Rosa SS) and sandstones, siltstones, and mudstones through the Dewey Lake Redbeds. The lithology in the Rustler Formation consists basically of gypsiferous anhydrite which includes the Magenta and Culebra dolomite aquifer marker beds. These are underlain by halitic siltstone down to the Salado Formation. Within the Salado, halite predominates, thinly interbedded with anhydrite, polyhalite, mudstones, and, at some locations, potash minerals. Underlying the Salado is the Castile Formation, which consists of thick layers of laminated anhydrite/carbonate separated by similarly thick halite beds. The Delaware Mountain Group (DMG) is characterized by sandstones interbedded with shales and limestones, and includes the Bell Canyon aquifer (the uppermost sandstone layers about 100' below the Castile-DMG interface).

Sealing activities for the WIPP will address the Rustler, Salado, and Castile Formations only. The upper (from the surface to the Rustler) and lower (below the Castile) sandstone formations will not require plugging for waste isolation, but will be plugged as

FIGURE 1
GENERALIZED STRATIGRAPHY AND WIPP PLUGGING CONCEPTS

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required by existing State of New Mexico statutes. These formations are the more permeable, less competent zones in which a plug adds little to the restriction of fluids, because the zones themselves are relatively permeable.

Rustler:

Within the Rustler Formation (containing an abundance of gypsum/anhydrite rock types, with local interspersing of dolomite crystals (hence the term dolomite beds), a likely plugging material would be a calcium-sulfate based grout suggested by S. J. Lambert. This material ultimately cures to form gypsum and, hence, should be reasonably compatible with the host rock. Any subsequent activity that tends to convert anhydrite to gypsum (or vice versa) should affect the plug material in much the same way as the host rock. This is a first step toward creating a seal, and would lessen the long-term geochemical reactivity because the materials are similar to the host rock. At present, a calcium sulfate-type grout cannot be satisfactorily emplaced because of its short pot life. This restriction may be overcome by the use of retarders. At this writing, from the viewpoint of geochemical stability, the calcium sulfate grout is considered the primary plugging candidate in the Rustler.

An alternate seal material is a freshwater grout mix such as that used in the Bell Canyon Test (BCT),^{5,6} which has been shown to be compatible with anhydrite. The long-term stability of this material (including concretes using CaSO_4 aggregate) is being evaluated in the geochemical program under way at the Pennsylvania State University (PSU) and the US Army Corps of Engineers Waterways Experiment Station (WES). The availability and use of this Portland cement-based grout has been demonstrated in a limited field-test activity.⁵

Salado:

In the Salado Formation, the natural plugging material is halite. While its method of emplacement on a wellbore or shaft scale has not been demonstrated, laboratory scale emplacements by Lambert have been achieved and extension to industrial processes appears feasible. Tests are in progress to address the consolidation of crushed salt.⁸ Reformation and permeability at different states of confinement are being evaluated. Field test designs are in progress to develop the industrial process. The effectiveness of a halite plug on a structural and geochemical basis is obvious; emplacing a halite plug in a halite formation will, in the long-term, permit salt creep and stress redistribution to convert the plug to an in situ stress condition, thus "healing" the wellbore using native materials.

This halite plug would initially be vulnerable to groundwater inflow, requiring protection against dissolution during the reconsolidation phase. Reduction of fluid flow from above and/or below this salt plug could be controlled by bracketing the halite plug with low-permeability grout plugs during the reconsolidation phase. The long-term result of this modular emplacement would leave a long-term reconstructed halite plug in the wellbore penetration zone. The time required for this "healing" process is under investigation;^{1,8} it is expected that the results may lead to an assurance of continuous duration plug, with the grout plugs persisting in the short-term during the formation of a late time natural halite seal in the salt formation. Again, this use of a natural halite material in the formation will enhance geochemical compatibility.

Alternatively, a brine-based grout seal could be considered in the Salado, where using brine would lessen the effects of salt dissolution during emplacement. This seal sets up quickly, providing a low-permeability barrier in the formation that limits the capability of the wellbore to transmit fluids. While this plug could never be fully integrated geochemically within the formation, with proper selection of materials it may form a relatively "inert" geochemical inclusion in the host rock. The addition of a grout plug could reasonably be expected to maintain at least a short-term protective seal; its long term (ie, 500 to 1000's of years) performance is presently less predictable than for natural halite plugs.

The modular concept using both grout and salt plugs should provide the best overall combination.

Castile:

In the Castile Formation, the rock type is largely anhydrite. Thus, as for the Rustler Formation, a calcium sulfate (CaSO_4) grout would be appropriate. The geochemical compatibility of gypsum and anhydrite is known, leading to the expectation of a reconstitution process similar to that described for salt plugs, thus lessening any tendency for geochemical instability. Data on this process are limited, but work in progress at WES is encouraging. Alternatively, the freshwater BCT-1FF mix from the Bell Canyon Test^{5,6} is available to use in this formation if the CaSO_4 based mix cannot be emplaced. As in the Rustler Formation emplacements, the geochemical compatibility of the BCT-1FF mix (including CaSO_4 aggregate mixes) must be evaluated over the long term.

Interbeds:

No attempt was made in the previous discussion to address the departure from a gross bulk-rock type resulting from interlayered clay seams, other minerals, or other formation anomalies. These are considered second-order effects and will be evaluated within the Sandia WIPP Plugging and Sealing Program (P&S) as it proceeds. The attempt here is to consider whether materials can be assembled to replicate the characteristics of the gross formation and, if so, to

assess how well the sealing functions can be achieved. In the vicinity of ERDA 9 and the WIPP site, the availability of groundwater is so low that migration of radionuclides from the storage horizon through unsealed penetrations does not create a public safety hazard.³ Sealing activities in existing man-created penetrations (boreholes, shafts) can further reduce this migration, leaving only natural processes to be considered. Alternatively, one must also consider inadvertent future intrusions when the memory of disposal location is lost. In these cases, one must protect the remaining waste inventory from introduction to the biosphere. Since the facility plugging activities may not be recognized or appreciated at these later times, one must design now to reduce access to this inventory. The preferred technique is to provide room-to-room isolation and is discussed more fully in Section 6. To the extent that man-made effects can be confidently removed, the more nearly the site can be restored to its original state where geologic processes continue to dominate.

4.0 Vertical Penetrations

With the previous concepts in mind, we can consider which boreholes must be plugged and the condition of these boreholes during plugging. As an initial criterion, any borehole that connects an aquifer (fluid-producing zone) with the facility becomes a plugging candidate. Conservative preliminary estimates indicate that a wellbore that merely connects the aquifers above the Salado

with the repository horizon is not a serious candidate for sealing unless the distance of the closest point of approach (CPA) of the wellbore to the underground workings is 1000 feet or less (see Appendix B). If a wellbore penetrates into the lower aquifers (eg, Bell Canyon) as well, then this distance for the closest point of approach should be increased to 5000 feet. Conservative hydrologic calculations^{8,9,10, 11} conducted for the WIPP site suggest that for greater distances dissolution cannot imperil the site. It is important to realize that these suggested distances are subject to change, pending planned specific calculations to refine these CPA criteria within the Sandia Plugging and Sealing Program. Confidence in these distances is based on experience within the oil industry and consequence assessment scenarios developed for the WIPP site.^{3,10,11} Once a penetration qualifies for plugging, the current recommendation is to remove any unsuitable wellbore materials (such as steel casing or old plugging materials) in the section of the hole to be plugged. Evidence exists that casing materials corrode in groundwater environments,^{12,13} potentially creating an unwanted conduit through the formations. This constraint may be relaxed at a later time if warranted by test data, but the present uncertainty of the long-term effects of casing materials on seal performance necessitates at least partial removal prior to final plugging. Appendix A lists the current status of all WIPP site wellbores that meet the 1000-ft/5000-ft CPA conditions.

5.0 Horizontal Penetrations

This section addresses the need for plugging horizontal penetrations (tunnels, drifts) created during development of the storage locations. This task requires less development because the activity will be confined to the halite rock type within the Salado Formation.

The concern here is to provide isolation from panel to panel (a panel is a collection of rooms) and from panels to drifts and tunnels. This will minimize the area of the facility horizon which could be breached through vertical penetrations, either by plug failure or inadvertent intrusion. The current assumption is that individual rooms within a panel need not be isolated from each other, if the panels themselves are isolated. Clearly, however, the option should remain for isolating room from room from the operational viewpoint for fire, smoke, radiation and access control and, also, to reduce effects caused by inadvertent human intrusion over the long term. Design plans for the WIPP require modularization and isolation of waste volumes in approximately $8 \times 10^5 \text{ ft}^3$ increments.

Within a panel, backfill emplacement is suggested in which the storage rooms are backfilled with crushed salt (obtained from the construction operation) to a compaction density on the order of 60

to 70+ percent. This backfill provides bulk material for decreasing the effective volume of the room, thereby reducing the amount of room closure needed to restore the formation to near its original state. The higher the initial compaction of the backfill material, the more nearly the backfilled room resembles its premixed state and the less significant are the effects of subsidence. Preliminary calculations (letter to Ban-Hunter June 1, 1980) have provided estimates which indicate that compaction to about 90 percent density in 300 years can be anticipated. A compacted salt backfill will also be emplaced in the access drifts to the storage panels along with protecting cementitious plugs to serve as short term fluid barriers until recompaction of the halite backfill is achieved. These cementitious plugs will be low-permeability, brine-based grouts (like BCT-1F, concretes, saltcretes, or grouted preplaced aggregate), with an expected lifetime (100 to 300 years during which properties are essentially constant) in excess of the time required to attain natural in situ recompaction in the crushed salt backfill. Similar procedures and material will be introduced into the entire tunnel and drift complex to obtain the greatest degree of separation and isolation of the stored waste. Other materials, such as clays, could also be introduced to sorb and retard radionuclides.³ Activities are underway within the Sandia WIPP Program to address the above issues and provide the required data on crushed-salt consolidation processes,⁸ sealing materials, and

WIPP UNDERGROUND LAYOUT

Planned WIPP Underground Layout Showing Typical Isolation Options for Excavated Regions. (Final Design Dependent on As Built Configurations)

FIGURE 2

selected clays as retardants to the migration of radionuclides. A series of in situ tests¹ have been also imposed to address the emplacement technique and sealing potential of candidate plugs. Figure 2 depicts some suggested panel/drift isolation locations.

Based on the Bell Canyon Test results,⁵ the actual length of the plug does not need to be great to fulfill its sealing function. A reasonable length in any given formation for either vertical or horizontal emplacements may be on the order of 50 to 100 feet separated by similar distances in which other tailored function materials may be emplaced. Other materials for tailored functions such as radionuclide sorption or secondary sealing (such as clays) could be emplaced in the intervening spaces between primary seals. The need for these has not been demonstrated, but they should not be excluded until it can be shown that they are unnecessary. Thus, at least in concept, a modular plug sequence can be envisioned that is tailored to the host formation to provide the combined functions of plugging, sorption, and essentially zero flow sealing. Material configurations must also be evaluated on the basis of geochemical stability to ensure no compromise of the seal because of adverse synergistic effects.

6.0 Proposed WIPP Site Plugging Criteria

The conditions, shown in Table 1, are suggested by the authors as a basis for establishing plugging criteria for existing penetrations at the WIPP site. It should be noted that these conditions

are subject to change pending further testing and evaluation within the Sandia Plugging and Sealing Program. Appendix B provides a basis for establishing the suggested distances.

Two criteria are envisioned for the seal integrity required depending on the wellbore condition:

WIPP Plugging Criterion (WPC): This criterion is suggested for wellbores meeting Condition 1 or 2 and would require methods for plugging those wellbores which relate to facility integrity and/or public safety. Penetration zones within the Rustler, Salado and Castile Formations would be plugged in a manner suggested in this report which will exceed statutory requirements.

State of New Mexico Criterion (SNM): This criterion is mandated by statutory legislation and will be applied to those penetrations not meeting Condition 1 or 2 for which the USDOE is responsible. References 14, 15, and 16 contain the specifications for SNM criterion.

It is anticipated that the USDOE and the State of New Mexico will formally agree to the application of these criteria on a case-by-case basis prior to final plugging and abandonment in accordance with statutory requirements.

Table 1.

<u>Criteria</u>	<u>Wellbore Condition</u>
WPC	1. Terminates in the Salado and in or within 1000 ft horizontally of the Zone 2 boundary.
WPC	2. Terminates below the Salado/Castile interface within Zone 3.
SNM	3. Those wellbores drilled by DOE and not included within Conditions 1 or 2 inside the Zone 4 boundary.

Conditions 1 and 2 address those penetrations which must be considered in light of the 1000-ft or 5000-ft rule relating to facility integrity and/or public safety. Application of the WPC to these penetrations will ensure that minimum statutory requirements are met and will provide for enhanced isolation in the immediate vicinity of the waste storage horizon. Condition 3 ensures that the minimum statutory requirements are met for those penetrations which do not constitute a threat to either the facility or public safety. It is reiterated that the application of the appropriate criteria will be coordinated between the USDOE and the State of New Mexico prior to permanent abandonment of any penetration as required by statute.

Candidate wellbores to which these criteria have been applied are listed in Appendix A. Figure 3 depicts those wellbores within Zone 4 which were considered; Figure 4 depicts a planar vertical projection of those wellbores to indicate depths and distances from the center of the facility horizon.

These conditions were based on the following assumptions:

- o The Rustler/Salado contact is assumed to be at 850 ft and the facility is developed throughout Zone 2 between 2000 and 2300 ft. However, plugging operations will be governed by the actual formation depth determined from wellbore logs.
- o Delaware Mountain Group (DMG): The Castile/DMG interface is assumed to be at 4000 ft within Zones 1, 2, 3, and 4. However, plugging operations will be governed by the actual formation depth determined from the wellbore logs.

7.0 Summary

This report presents the current intentions and directions of the WIPP Plugging and Sealing Program and provides a basic structure for the engineering activities that may be required for final WIPP decommissioning and abandonment. It is intended to be a guide in determining further directions for the sealing program and to

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PLUGGING CRITERIA FOR DRILLHOLES AT WIPP SITE

CONDITION 1: TERMINATION IN SALADO WITHIN ZONE 2 PLUS 1000'

WPC

CONDITION 2: TERMINATION BELOW SALADO/CASTILE INTERFACE WITHIN ZONE 3

WPC

CONDITION 3: ALL OTHER PENETRATIONS WITHIN ZONE 4

SNM

Figure 4.

identify obvious issues that require further development and understanding. Specifically, based on current knowledge, the following points are appropriate:

Primary sealing materials are planned to be commercially available cement-based grouts, concretes or native salt, tailored to match the properties of the sealed-zone host rock. The Rustler, Salado, and Castile Formations will themselves provide the geological barrier needed to restrict fluid intrusion to the facility horizon. Vertical penetrations within a nominal 1000-ft separation from the underground workings that do not penetrate the Castile, or are within 5000 ft and do penetrate the Castile, will be treated as candidates for final sealing activities. These distances discussed in Appendix B are subject to modification pending further calculations and collection of data. The total number of holes (summarized from Appendix A) for each condition suggested for WPC are:

Condition:

Penetrations:*

1 - 1000 ft

14 Wellbores; 3 shafts**

2 - 5000 ft

4 Wellbores

Within the underground drift/tunnel workings in the Salado Formation, extensive use of native salt as backfill/seal materials will minimize geochemical concerns and provide for the long-term recompaction and isolation features of the WIPP facility.

Continued research and development within the Sandia Plugging and Sealing Program is directed toward obtaining the data required to support geologic isolation of the WIPP emplaced wastes. Research and development will continue during construction and operation of the WIPP storage facility.

*Note: A limited number of shallow foundation holes (less than 200 ft deep) have been drilled under separate contract for the USDOE (designated "B" holes) and are not included in this tally. These do not qualify under WPC since penetrations of the Rustler did not occur. These will be plugged under SNM criteria.

** Two shafts drilled as of date of report.

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Appendix A

List of Existing Boreholes Within Zone 4 of the WIPP Site That Were Considered for Applications of the WIPP Plugging Conditions and Criteria

WIPP Site Exploration Penetrations

Zone 1

Designation	TD (ft)	Condi- tion	Criteria	Remarks
All shaft pene- trations into into Salado		1	WPC	3 shafts (2 completed, 1 planned)
ERDA 9	2886	1	WPC	16" casing to 40'; 10-3/4" casing to 1045'; 7" casing to 2883' Rework to WPC*
B-25	901	1	WPC	Cased to Salado; Rework to WPC*
<u>Total</u>	<u>WPC</u>			<u>SNM</u>
2 Boreholes 3 shafts	2; Rework 2 to WPC 3;			None

Zone 2

Hydro 1	856	1	SNM	7" casing to 848'
Hydro 2A	563	3	SNM	6 5/8" casing to 511'
Hydro 2B	661	3	SNM	6 5/8" casing to 609'
Hydro 2C	795	1	SNM	6 5/8" casing to 742'
Hydro 3	902	1	SNM	6 5/8" casing to 897'
WIPP 18	1060	1	WPC	7" casing to 16'
WIPP 19	1038	1	WPC	7" casing to 8'
WIPP 21	1049	1	WPC	7" casing to 20'
WIPP 22	1450	1	WPC	7" casing to 20'
P-2	1895	1	WPC	Rework;* plugged as SNM
P-3	1675	1	WPC	Rework;* plugged as SNM
Industrial: There are no industrial penetrations within Zone 2.				
<u>Total</u>	<u>WPC</u>			<u>SNM</u>
11	9; Rework 2 to WPC			2 (None plugged and abandoned)

*These holes were plugged or cased in accordance with SNM criteria but qualify under WPC.

Zone 3

<u>Designation</u>	<u>TD (ft)</u>	<u>Condi- tion</u>	<u>Criteria</u>	<u>Remarks</u>
WIPP 12	3720	2	WPC	Rework;* casing to 1013'
WIPP 13	3856	2	WPC	Rework;* casing to 1023'
P-1	1591	3	SNM	Casing to 794'
P-4	1857	1	WPC	Rework;* plugged as SNM
P-5	1830	1	WPC	Rework;* plugged as SNM
P-6	1573	3	SNM	Plugged
P-9	1796	3	SNM	Plugged
Industrial:				
I-374	1538	3	SNM	Plugged
I-375	1746	1	WPC	Rework* plugged as SNM
I-376	1702	3	SNM	Plugged
I-377	1876	3	SNM	Plugged
I-456	1975	3	SNM	Plugged
I-457	1885	3	SNM	Plugged
D-207	1613	3	SNM	Plugged
BU	15,225	2	WPC	Rework to WPC
DOE-1	4,060	2	WPC	Under construction

Total

WPC

SNM

16

7; Rework 6 to WPC

1 (8 plugged and
abandoned)

*These holes were plugged or cased in accordance with SNM criteria but qualify under WPC.

Zone 4#

<u>Designation</u>	<u>TD (ft)</u>	<u>Condi- tion</u>	<u>Criteria</u>	<u>Remarks</u>
Hydro 4A	415	3	SNM	Casing to 365'
Hydro 4B	529	3	SNM	Casing to 477'
Hydro 4C	661	3	SNM	Casing to 610'
Hydro 5A	824	3	SNM	Casing to 775'
Hydro 5B	925	3	SNM	Casing to 881'
Hydro 5C	1076	3	SNM	Casing to 1024'
Hydro 6A	525	3	SNM	Casing to 475'
Hydro 6B	640	3	SNM	Casing to 590'
Hydro 6C	741	3	SNM	Casing to 699'
P-7	1574	3	SNM	Plugged
P-8	1660	3	SNM	Plugged
P-10	2009	3	SNM	Plugged
P-11	1940	3	SNM	Plugged
P-12	1598	3	SNM	Plugged
P-13	1576	3	SNM	Plugged
P-14	1545	3	SNM	Casing to 775'; Plugged to 775'
P-15	1465	3	SNM	Casing to 635'; Plugged to 620'
P-16	1585	3	SNM	Plugged
P-17	1660	3	SNM	Casing to 750'; Plugged to 731'
P-18	1998	3	SNM	Casing to 1138'; Plugged to 1125'
P-19	2000	3	SNM	Plugged
P-20	1995	3	SNM	Plugged
P-21	1915	3	SNM	Plugged
WIPP 11	3580	3	SNM	Casing to 985'
WIPP 14	1,000	9	SNM	Casing to 111'
WIPP 33	840	3	SNM	Casing to 38'
WIPP 34	1820	3	SNM	Casing to 38'
I-458	1750	3	SNM	Plugged
I-459	1855	3	SNM	Plugged
D-104	1596	3	SNM	Plugged
D-120	1500	3	SNM	Plugged
D-123	1880	3	SNM	Plugged
F1	1747	3	SNM	Plugged
F-70	1603	3	SNM	Plugged
F-82	1684	3	SNM	Plugged
F-91	1788	3	SNM	Plugged
F-92	1818	3	SNM	Plugged
WRT-1	4776	3	SNM	Plugged/abandoned
G1	4475	3	SNM	Temporarily abandoned Cotton Baby
CB-1	4150	3	SNM	Temporarily abandoned Cabin Baby
<u>Total</u>	<u>WPC</u>	<u>SNM</u>		
40	0	19 (21 plugged and abandoned)		

Summary:* Penetrations to be Plugged Within WIPP Zone 4 Boundary

<u>Zone</u>	<u>Total Penetrations</u>	<u>WPC</u>	<u>Criteria SNM</u>	<u>Plugged and Abandoned</u>
1	2	2; Rework 2 to WPC		
1	3 shafts	3 (shafts)	0	0
2	11	9; Rework 2 to WPC	2	0
3	16	7; Rework 6 to WPC	1	8
4	<u>40</u>	<u>0</u> <u>0</u>	<u>19</u>	<u>21</u>
Totals	69	18 Rework 10 to WPC	22	29
Plus	3 shafts	3 shafts	0	

For sealing criteria purposes:

- 18 wellbores plus 3 shafts require WPC plugging criteria.
(10 of these wellbores require rework to satisfy WPC.)
- 22 wellbores need plugging in accordance with SNM criteria.
29 wellbores have been plugged and abandoned.

* Note: A limited number of shallow foundation holes (less than 200 ft deep) have been drilled under separate contract for the USDOE (designated "B" holes) and are not included in this tally. These do not qualify under WPC since penetration of the Rustler formation did not occur. These will be plugged under SNM criteria.

Note: All holes within Zone 4 qualify under SNM; WPC does not apply under the 1000 ft/5000 ft conditions)

Appendix B

Estimates of Vertical Penetration Growth Based on Fresh Water Intrusion

It is worthwhile to discuss the conservatism of the 1000 ft and 5000 ft conditions suggested in the report based on whether or not the penetration establishes a connection between the upper and lower aquifers at the WIPP site as sketched in Figure B1. We assume that the salt formation is 1000 ft thick and contains an 8" diameter plugged wellbore. This plug is assumed to perform in the same fashion as the BCT⁵ plug where the following results were obtained: Flow rate was 600 cc/day through a 6-ft-long 8" diameter grout plug being pressurized by a 2000 psi brine source.

For purposes of establishing the hypothetical wellbore flow, we suggest a similar grout plug, 120 ft long with the same differential pressure, 2000 psi. We will later discuss whether or not this source pressure is reasonable. For illustrative purposes we define Q_P under Darcy flow conditions, relative to the BCT flows, where Q_{BCT} is 600 cc/day as:

$$\frac{Q_P}{Q_{BCT}} = \frac{\frac{KA}{\mu} P}{\frac{KA}{\mu} BCT} \frac{\nabla P_P}{\nabla P_{BCT}} \quad \text{or}$$

$$Q_P = Q_{BCT} \frac{\nabla P_P}{\nabla P_{BCT}} = Q_{BCT} \frac{L_{BCT}}{L_P}$$

Figure B-1. Schematic for Dissolution Estimate

where we have assumed that both the plug and fluid properties in each case are the same as is the source pressure. Then for a plug length $L_p = 120'$ compared to the BCT plug length $L_{BCT} = 6'$,

$$Q_p = \frac{6}{120} (600 \text{ cc/day}) = 30 \text{ cc/day} \sim 1.0 \times 10^{-3} \text{ ft}^3/\text{day}$$

Further, assuming Q_p is a freshwater flow rate through the plug into the salt, and assuming instantaneous dissolution of the salt upon contact with the freshwater, on a per volume basis, on the order of 20 percent dissolution of salt can be estimated. That is for each cubic foot of freshwater introduced into the salt, a new volume of 0.2 cubic foot will be created. Thus, this new volume V_p is given by

$$\begin{aligned} V_p &= 0.2 Q_p = 2 \times 10^{-4} \text{ ft}^3/\text{day} \\ &= 0.073 \text{ ft}^3/\text{year} \end{aligned}$$

Thus, we see that for a plug similar to, but longer than, the BCT plug, the newly created volume per cubic foot of freshwater intrusion is about $0.1 \text{ ft}^3/\text{year}$. Thus, a plug that is 10 times less competent than the 50 microdarcy BCT plug will have a $1 \text{ ft}^3/\text{year}$ wellbore growth rate; if it is 100 times less competent (5 millidarcies), the wellbore growth rate will be $10 \text{ ft}^3/\text{year}$.

For argument's sake, and to account for possible long term degradation of item plug from 50 microdarcies at emplacement, let us assume the 5 md plug performance and estimate the time it will take to expand the wellbore radially to 50 ft over the full 1000 ft length which corresponds to a 10 percent effect on the 1000 ft separation condition.

For an initial wellbore diameter of 8 inches, 1000 ft long, the volume is 350 ft^3 . At some time later the wellbore is assumed to have expanded radially to 50 ft so that the new volume is 8 million ft^3 . Neglecting the initial volume as trivial compared to the new volume, and at a growth rate of $10 \text{ ft}^3/\text{year}$, it will take 800,000 years to achieve this growth. As a matter of practical experience, 5 md plugs can easily be constructed with present technology. Similarly, the assumption of a 2000 psi source pressure differential across the plug cannot be achieved. Hydrostatic testing at the WIPP site has established that the head differential between the upper and lower aquifers is on the order of 10's of ft so that actual source pressure differentials are of the order of 10's of psi rather than the assumed 2000 psi. Note also that this upper/lower aquifer connection is restricted by the 5000 ft rather than the 1000 ft condition. Thus, on a worst case basis, assuming a 2000 psi differential across a 5 md plug, 120 ft long, an assumed radial growth of 50 ft reflects a 1-2 percent effect on the suggested 5000 ft separation condition. Thus, to get a 10 percent effect requires 4 million years, and projections for periods of this magnitude are

beyond all reasonable engineering experience. Additionally, the observations of large scale vertical connections, between aquifers in this region, ie, breccia pipes, shows that lateral dissolution does not continue to grow over large distances (> 1000 feet) and even the vertical permeability is eventually reduced and flow eliminated.

Clearly, even with these simplistic estimates, a restrictive plug, performing in the few millidarcy regime, can provide facility and public safety protection for times on the order of millions of years. Longer and tighter plugs can extend this period by orders of magnitude, the same magnitude of time for which the waste material lifetimes are of concern.

Calculations based on site specific parameters regarding plug flows are planned within the plugging and sealing program which will further refine the expected plug protection periods.

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