U.S. Department of Labor

Mine Safety and Health Administration
Pittsburgh Safety and Health Technology Center
626 Cochrans Mill Road
Pittsburgh, PA 15236

Roof Control Division

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MEMORANDUM FOR MICHAEL DAVIS
District Manager, MNMS&H South Central District

THROUGH: GEORGE H. GARDNER
Chief, Pittsburgh Safety and Health Technology Center

JOSEPH A. CYBULSKI
Chief, Roof Control Division

FROM: CHRISTOPHER MARK
Principal Roof Control Specialist, Technical Support

PAUL L. TYRNA
Geologist, Roof Control Division

SUBJECT: Field Investigation at the U.S. Department of Energy's Waste Isolation Pilot Plant (WIPP), ID No. 29–01857, Carlsbad, New Mexico (RCD Control Number 17AA01)

Executive Summary

The U.S. Department of Energy's (DOE) Waste Isolation Pilot Plant (WIPP) facility is tasked with the safe disposal and storage of radioactive transuranic (TRU) waste resulting from U.S. defense activities and programs involving nuclear weapons research and testing. The safety and health of all workers at the site, including personnel underground, is of paramount importance in carrying out activities at the WIPP site.

The WIPP facility includes waste disposal rooms mined 2,150 feet underground in a 2,000-foot-thick salt formation. Salt was chosen as the repository medium because, unlike other geologic materials, salt is subject to creep that over time closes and seals mine openings. While creep is desirable for containing hazardous waste, it creates ground control challenges for a mining operation. Salt creep at WIPP causes fractures in the roof and the ribs[1], separations along clay seams and anhydrite beds, sagging of the roof, and ultimately roof falls. Over time, creep will

[1] The roof of a mine opening is sometimes called the "back", and the ribs are the side walls.

destroy even the most robust ground support system. Constant vigilance and maintenance is essential to preserve stability and safety.

WIPP established a comprehensive ground control program in order to manage the effects of creep on the stability of the mine openings. The program includes monitoring and evaluation of underground conditions, timely initial installation of ground support, and renewal of ground support as necessary. Prior to the events in February 2014, the ground control program functioned proactively, identifying potential problems and controlling them before they posed any hazard to personnel. WIPP's exemplary ground control accident record testified to the success of the program, with zero unplanned ground falls or ground fall injuries over more than 30 years.

The accidental release of radioactive material in the mine in February 2014 severely impacted WIPP's ground control program. For several months, there was no access to the mine at all. Large portions of the mine were contaminated. Consequently, even after they were eventually accessed, it was very difficult to conduct necessary ground control operations. Miners wearing full-face respirators and protective clothing were capable of installing just a fraction of the roof bolts that they could previously. Even in the uncontaminated areas ground control efforts suffered from the mine's new ventilation restrictions.

The result was that ground conditions deteriorated substantially during this period. In supported areas, relentless creep broke hundreds of roof bolts, and many could not be replaced in a timely fashion. Some broken bolts were not secured and created a falling material hazard. Loose, broken salt built up behind chain link mesh in some locations. New fractures developed in roof brows and other locations. Many locations requiring maintenance have still not been addressed. While none currently appear to present an immediate danger to the miners, the cumulative effect of the deterioration is to increase the overall ground fall risk to a level well above its level prior to 2014. Ground control has become reactive, where emergencies are addressed immediately while lower priorities languish until they become emergencies.

Panel 7 presents another set of challenges. Had it been possible to follow its original schedule, Panel 7 would likely have been filled with waste and sealed by now. Instead, it was left without the necessary roof bolt support for more than 2 years. During that time the long tendon roof bolts that were initially installed in a minimal pattern almost all broke. Without the timely installation of a heavy pattern of long tendons, the rooms were vulnerable to major roof collapse, and on November 4 such an event occurred in Room 4. Fortunately routine roof monitoring identified the developing roof fall weeks in advance, so that access to Room 4 was prohibited and no workers were exposed to the eventual collapse. In Room 5, in an area where chain link mesh was not installed initially, large roof fractures created blocks of loose salt that had to be scaled down. Both of these events would almost certainly have been avoided if ground control had been maintained up to pre-2014 standards.

Panel 8 is another concern. It was only partially developed prior to the 2014 events, and then only "rough cut." Under normal circumstances, it would have been "finish cut" by now, and at least the initial roof support pattern of short bolts and mesh would have been installed. Without this support it is likely that fracturing of the ribs and roof is significantly more extensive than is typically the case for finish cut operations, and indeed access to much of Panel 8 has been prohibited due to “drummy” roof conditions. Moreover, it will likely not be possible to finish cut the Panel 8 development until further improvements in the mine’s ventilation system are completed. Special ground control precautions may be necessary once mining is finally restarted.

To avoid further incidents, WIPP needs to return the ground fall risk to pre-2014 levels, and to a proactive ground control program. Accomplishing this will require accelerated efforts both within and outside the contaminated area. WIPP should identify the resources that will be required to catch up the outstanding ground control issues over a pre-set period of time. Then, equipment, ventilation, staffing schedules, and so forth should be adjusted so that these resources can be utilized to their maximum potential. The proposal to abandon the contaminated Panel 9 area should greatly reduce the effort required. On the other hand, the impending resumption of waste handling activities could negatively impact the resources available for ground control.

Background

U.S. Department of Energy’s (DOE) Waste Isolation Pilot Plant (WIPP) is located 26 miles southeast of Carlsbad, NM. WIPP is tasked with the safe disposal and storage of radioactive transuranic (TRU) waste resulting from U.S. defense activities involving nuclear weapons research and testing. It is constructed 2,150 feet underground in the 2,000-foot-thick Salado Salt Formation, and began accepting waste in 1999. Underground facilities include four shafts, a network of drifts (tunnels), and panels of disposal rooms (Figure 1).

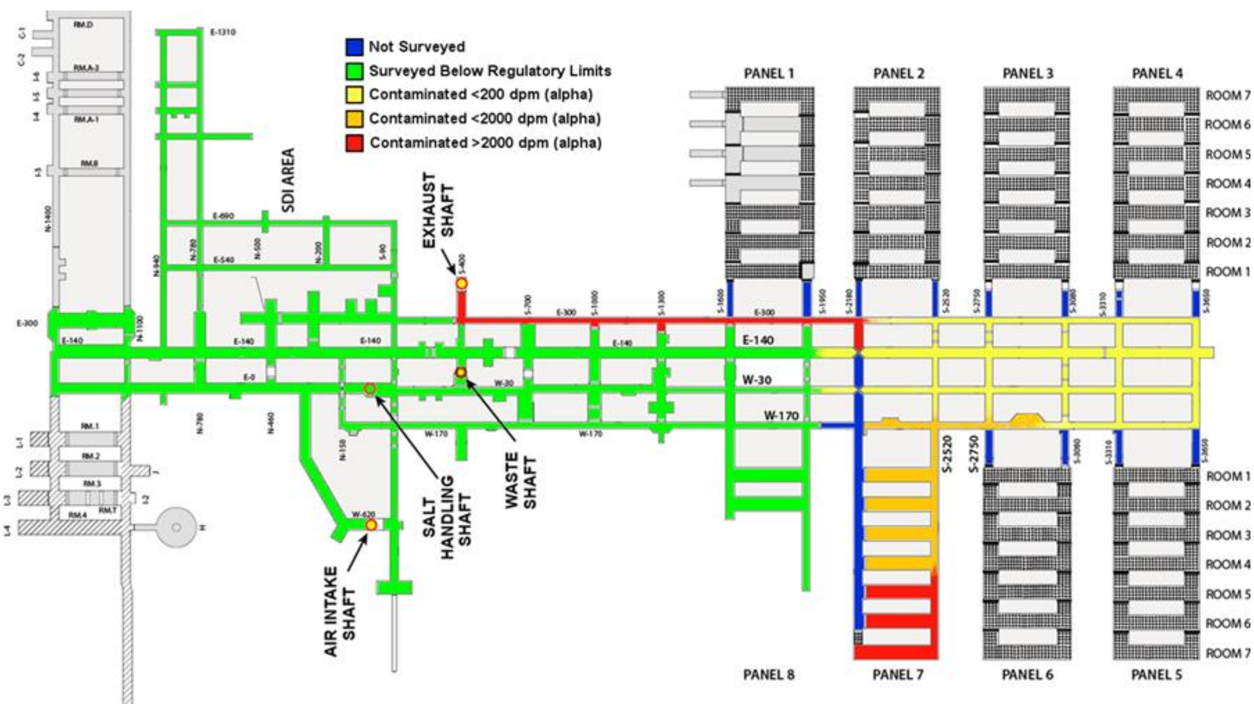

FIGURE 1.—Map of the underground WIPP facility. Also shown are the areas contaminated by the February 2014 release of nuclear material.

The 1992, WIPP Land Withdrawal Act (Public Law No. 102–579, 106 Stat. 4777) included a provision requiring MSHA to inspect WIPP not less than four times each year in the same manner as it evaluates mines under the Mine Act. This requirement was reiterated in the Memorandum of Understanding (MOU) between DOE and MSHA, which was signed October 7, 2014. The MOU states, "The safety and health of all workers at the site, including personnel underground, is of paramount importance in carrying out activities at the WIPP site."

Between September 2014 and October 2016, MSHA inspectors identified 34 deficiencies at WIPP related to ground control. In addition, three falls of ground occurred in January 2015, September 2016, and October 2016. While there was no immediate worker health and safety risk associated with these roof falls, since workers had already been prohibited from entering these areas, they did serve to underline the importance of ground control at WIPP. As a result, MSHA MNM South Central District and the DOE asked MSHA Technical Support to help evaluate ground conditions at WIPP.

The MSHA Technical Support evaluation was conducted during October 24–31, 2016. The MSHA team consisted of Paul Tyrna, Christopher Mark, and David Galizia. The activities of the team were as follows:

October 24: Skeen-Whitlock Building, 4021 National Parks Highway

- WIPP overview—Phil Breidenbach, NWP President Project Manager
- Ground Control Program Overview—Rey Carrasco, NWP Manager, Geotechnical and Mine Engineering
- Ground Monitoring Program—Ed Lewis, NWP Principal Engineer, Geotechnical Monitoring
- Roof Support—Rick Supka, NWP Principal Engineer, Ground Control

October 25–27: WIPP Site

- WIPP/DOE General Employee Training Site Access Training (GET 300)
- Facility Safety Briefing (INF–136)
- Respirator Training and JPM (SAF–630/631)
- Facility familiarization and Site Documented Safety Analysis
- Radiological Worker II, including dressing out in personal protective equipment for practical examination
- Roundtable discussion with underground miners regarding ground control issues at WIPP

October 28: WIPP Site

- Underground survey of E–300 (contaminated area), E–140 Drift, and shop areas.

October 29: WIPP Site

- Underground survey of Panel 7 (contaminated area), Panel 8, W30 Drift, and W170 Drift.
- Discussion with roof bolting machine operators working in Panel 7

Sunday, October 30: Skeen-Whitlock Building

- Discussion and review of geotechnical data in the WIPP database

Sunday, October 31: Skeen-Whitlock Building

- Close-out meeting, with call-ins from MSHA and DOE remote sites

Geology of the WIPP Site

Salt was chosen as a host medium for TRU waste in part because it creeps over time. Creep causes the salt mass to slowly move toward and into the mine openings. Creep will eventually close and seal the mine openings, providing secure containment for the waste and isolating it from groundwater. The creep process begins as soon as an excavation is made. This means that its effects must be controlled throughout the service life of a mine opening.

Figure 2 shows the geology of a typical WIPP mine opening. It shows that the salt contains several persistent layers of anhydrite underlain by thin clay seams. The clay layers constitute planes of weakness along which shearing and separation can take place. The most significant of these layers is "Clay G" located approximately 8 feet above the roof line. Clay G defines the "roof beam" that is the focus of most ground control activities at WIPP. Other clay layers are located higher in the roof, and in the ribs and floor.

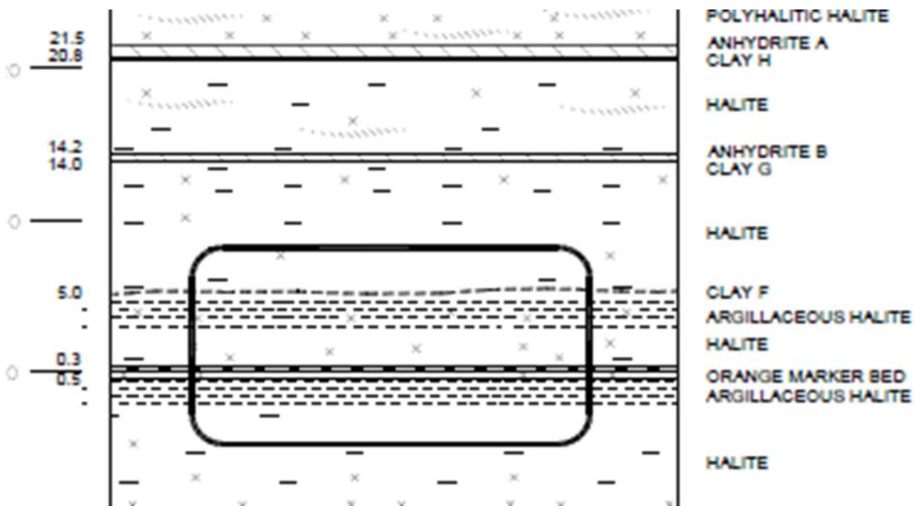

FIGURE 2.—Salt stratigraphy at the WIPP site, showing the outline of a typical drift.

Some portions of the WIPP facility have been developed slightly higher in the salt sequence, so that Clay G forms the immediate roof line. These entries are subject to somewhat different behavior owing to the numerous anhydrite "stringers" found between Clay G and Clay H. As most of these entries are located in Panel 9, which is now slated for abandonment, this report will not address them in detail.

Rock Mechanics

When an opening is initially excavated at WIPP, the horizontal stresses confining the ribs are removed. The vertical stress carried by the adjacent pillars, on the other hand, is increased. In response, the pillars creep into the opening, shortening in the vertical direction and expanding in the horizontal direction. Horizontal pillar expansion applies lateral compressive loads to the roof beam and to the floor, while pillar shortening affects the ribs. No man-made support can slow pillar creep, it is only possible to control its effects.

Displacement rates are particularly high during the "Stage 1" creep that occurs immediately after excavation. Stage 1 creep can cause localized shallow spalls and drummy areas to develop in the roof and ribs. Displacement rates then slow down until they reach the steady state, "Stage 2" creep condition. Rates of steady state creep vary at WIPP, depending on the room width, local extraction ratio, and other factors.

The continuing creep causes "low-angle fractures" to develop in the roof beam (see Figures 3 and 4). These fractures generally begin at the roof line near the ribs and terminate at the clay seam. Eventually the low-angle fractures will coalesce on one side or the other, creating a cantilevered roof beam with a relatively sharp "point" on one end. Once the fractures have coalesced, the beam is free to slide along the clay layer, and the displacement rates accelerate. As the free end of the beam is forced downwards, tensile fractures develop at the top of the beam at its other end, and large gaps develop between the beam and the overlying salt. Unless controlled by heavy roof support, gravity will take over and a roof collapse will ensue. If the beam is supported, it will continue to compress laterally and become severely deformed. Roof bellies of 4 feet or more can develop, accompanied by extensive fracturing and separations (Figure 5).

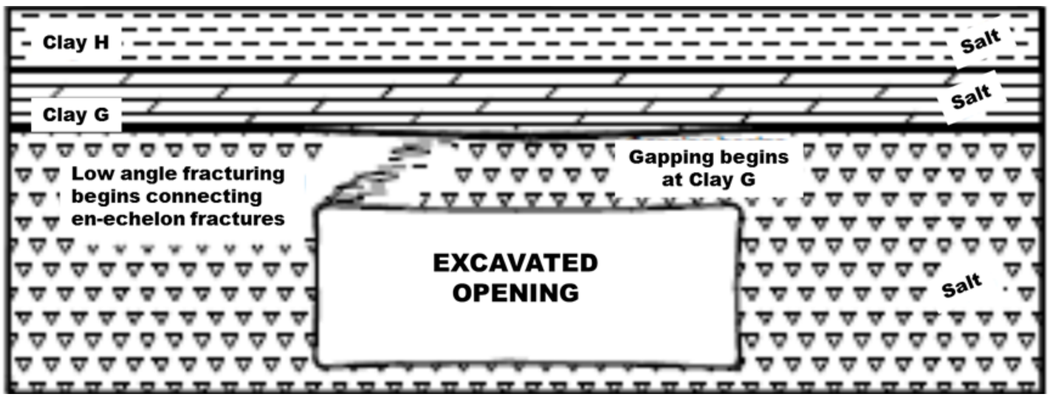

FIGURE 3.—Formation of a low-angle fracture due to creep in a typical drift at WIPP.

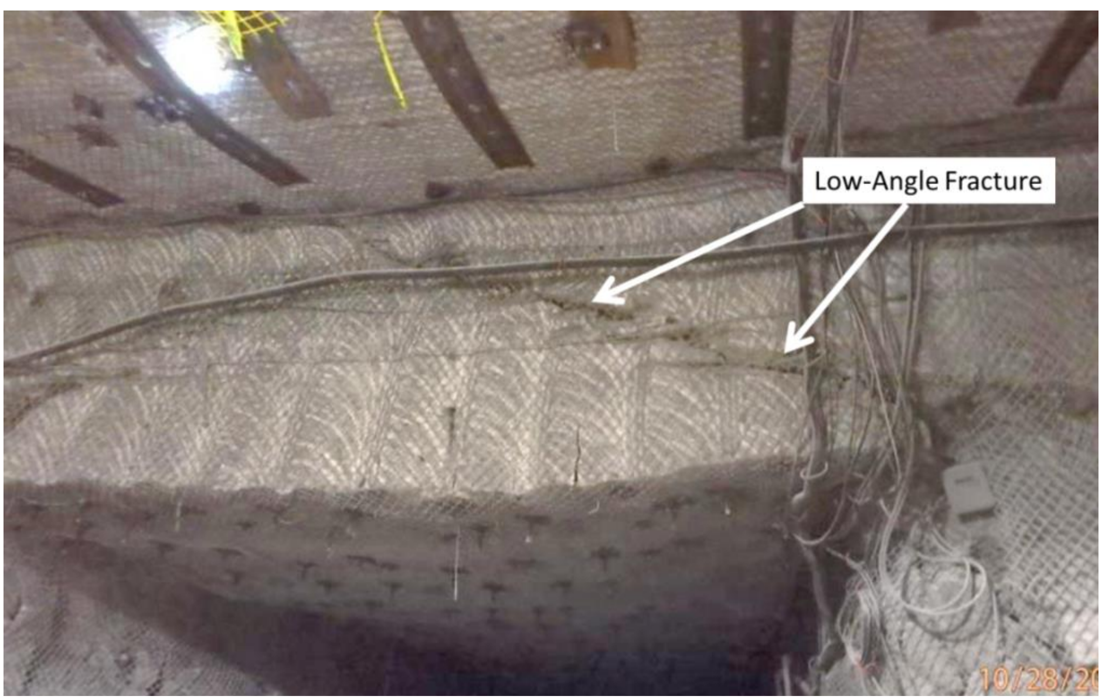

FIGURE 4.—Photograph showing a low-angle fracture exposed in a roof brow.

FIGURE 5.—Severe roof bellying in a WIPP drift supported by long tendons, short bolts, straps, and mesh.

Floor heave, which has more impact on equipment travel than it does on safety, can follow a process that is analogous to roof failure (Figure 6). A floor beam can develop with extensive uplift into the opening. Pillar creep can also cause extensive fracturing in the ribs (Figure 7).

FIGURE 6.—Floor heave in WIPP drift.

FIGURE 7.—Rib fractures contained by short bolts and mesh.

The fact that the roof loading is driven by pillar compression, rather than by in situ horizontal roof stress or by gravity, leads to some unique ground control behaviors. For example, entry orientation has no effect, and the roof behaves essentially the same in crosscuts as in the entries. The low-angle fractures develop on both sides of a heading, and may coalesce on either one.

Perhaps the most unusual feature is that intersections are usually the most stable places in the mine, because the expanding pillars apply less load to the wider intersection span, resulting in smaller roof curvatures and less fracturing. When the lower roof beam was removed in the E–140 Drift, it was observed that "separations tended to decrease substantially in size and occurrence within 50 feet of intersecting cross-drifts, and were absent within intersections" (Terrill and VandeKraats, 1997).

Prior to 2016, the only full-scale roof collapses to have occurred at WIPP were in the experimental Site Preliminary Design Validation (SPDV) rooms. Two of these rooms were purposely left unsupported and allowed to collapse while detailed monitoring was conducted. In addition to illustrating the general roof failure sequence described above, these experiments also illustrated the potential extent of a roof fall. In SPDV Room 1, the ultimate fall cavity was 170 feet long and 7 feet high in its middle section. However, the height of the cavity tapered off from the center of the room and as it approached to within about 50 feet of one intersection. The fall showed no tendency to extend into the intersection (WIPP, 1993).

Mining and Roof Support

Mine openings at WIPP are first “rough cut” to dimensions that are approximately 2 feet smaller in width and height than the planned final dimensions (waste storage rooms at WIPP are approximately 33 feet wide by 13 feet high, the dimensions of the other drifts vary). Roof or rib that is obviously loose is scaled down, but no roof support other than spot bolts are typically installed in the rough cut openings. Any fractures that develop within the skin of the opening are then removed when the “finish cut” trims the ribs and roof.

The initial ground support system is installed with the finish cut and consists of chain link mesh held in place by 4-foot-long, ¾-inch-diameter mechanical anchor roof bolts approximately 5 feet apart.[2] The mesh typically covers approximately the top 8 feet of the rib and about 8 feet of the roof adjacent to the rib. Its purpose is to provide “skin control,” preventing small falls of loose rock from shallow “drummy” roof or from sloughing ribs. Typically the center portion of the roof is scaled but otherwise remains unsupported at this time, though in some cases spot bolts or a light pattern of long tendons may be installed in it. The role of the mesh in preventing falls of loose rock becomes essential as time goes on and extensive fracturing develops in the roof.

Preventing major roof collapse involving the entire roof beam requires a dense pattern of long tendons. Since Stage 1 creep would greatly shorten the life of these bolts, they are typically not installed until about 1 year after excavation. The standard tendons currently used at WIPP are 14-foot long Dywidag threaded bar, ⅞-inch-diameter, made of grade 75 steel. They are anchored with 3 feet of resin in the relatively stable ground above the first clay seam. To extend the life of the bolts as they are subjected to lateral roof movements, the holes are reamed to 3-inch diameters up to a height of approximately 10 feet. Enough long tendons are installed to carry the dead weight of the roof beam with a substantial safety factor, which is typically achieved with approximately 4-foot spacing between bolts.

Over time, the relentless creep causes an average of two or three roof bolts to fail each day (WIPP, 2016). Because of the safety factor calculated into the ground support design, the failure of even a few roof bolts in an area does not substantially increase the risk of a roof fall. Additional bolts must be installed when the safety factor becomes diminished or if monitoring indicates that the convergence rate is accelerating. There is also potential hazard associated with personnel or equipment striking or being struck by a failed roof bolt. In some areas, wire lanyards are attached to the roof bolts to prevent them from falling to the floor if they break.

Roof support is installed using diesel or “hybrid” diesel-electric single-boom roof bolting machines. Figure 8 shows that the roof bolt operator is protected by a canopy, but there is no automated temporary roof support (ATRS) like those required on roof bolting machines used in coal mines. The lack of an ATRS means that a roof bolt operator at WIPP has less protection from loose rock. However, an ATRS would be difficult to retrofit because of the greater height

[2] In the past, metal straps were often installed with the mesh. Over time many of the straps have broken due to creep. Broken straps are not replaced. Apparently, no new straps have been installed during the past 5 years.

of the drifts at WIPP compared with coal mines. In addition, an ATRS might fracture and destabilize a thin, detached layer if too much pressure was applied. So long as mesh is installed on the roof before fracturing develops, roof bolt operators should be protected from loose rock during subsequent rebolting operations.

FIGURE 8.—A roof bolting machine at WIPP.

Geotechnical Monitoring

WIPP maintains an extensive ground control monitoring program designed to detect conditions that indicate instability. The program includes weekly inspections of underground conditions, collection and interpretation of roof stability data, and observations of the performance of installed ground support.

Geotechnical monitoring instrumentation at WIPP consists of convergence points, convergence meters, extensometers, rock bolt load cells, pressure cells, strain gauges, piezometers, and joint meters. Of principal importance are convergence measuring stations installed approximately75 feet apart throughout the underground facility. Convergence measurements typically show that steady state creep is occurring. When an accelerating convergence rate develops without any other explanation, it can indicate that the roof beam is becoming unstable. For example, the steady state creep rate in a typical waste storage room is about 5 inches per year. If the convergence rate increases to 8 or 10 inches per year, then additional roof support may be required. Once new support has been installed, the convergence data typically confirms that the creep rate has returned to its prior steady state level. Convergence data are collected and analyzed manually.

Roof extensometers that monitor movement at several depths into the roof are installed in many locations. Extensometer data is typically collected remotely.

Observation boreholes are drilled at various locations to depths that allow the monitoring of fracture development and offsetting. They are inspected for fractures, using an aluminum "scratch rod." Evidence of roof bolt distress, such as dimpled or cracked bearing plates, is also noted. Surface fractures are also mapped and rated on a regular basis.

Historically, roof bolt failures have been recorded in a database containing the bolt's location in the mine and the type of failure. However, "new entries to the database have not been made since February 2014 due to operational and accessibility restrictions" (WIPP, 2016, p. 44). Similarly, it appears that the observation boreholes have not been monitored regularly since the radiation event. Observation boreholes and extensometer holes must also be redrilled periodically because roof movements close them off, and none have been replaced since the event.

History of Ground Control at WIPP

Prior to 2014, WIPP maintained a very effective ground control program. The program functioned proactively, identifying potential problems and controlling them before they posed any hazard to personnel. For example, the E–140 Drift was inspected weekly, and broken bolts were removed and replaced with new ones. In another example, bi- annual "scaling parties" were conducted during which a crew would spend 2 weeks examining the entire facility and removing loose rock. WIPP's exemplary ground control accident record testified to the success of the program during this period, with zero unplanned ground falls or ground fall injuries over more than 30 years of the facility's operation.

On February 5, 2014, a truck fire occurred at the WIPP site which interrupted underground activities at the mine. Nine days later, a release of radioactive material prevented access to the entire underground facility for weeks. Since then, high efficiency particulate air (HEPA) filters have been required to be in service to remove radioactive particles and mitigate further radioactive releases. The HEPA filters significantly restrict the ventilation airflow underground, however, limiting the number of shifts that diesel roof bolters can be operated.[3] The number of people allowed underground has also been restricted based on evacuation capability. Ground control work is particularly difficult in the contaminated areas, which include Panel 7, Panel 9,

[3] A recent change in the ventilation system has significantly increased the available airflow, which has increased the number of shifts that the roof bolting machines can work. The airflow remains much less than before the release of radioactive material, however.

and the E–300 Drift leading to the exhaust shaft. In these areas, miners wearing full-face respirators and protective clothing can typically only work 3–3.5 hours per shift, often installing fewer than ten roof bolts.

Between April and November 2014, ground control activities were limited to hand scaling. Limited replacement bolting operations did not resume until early in 2015 (DOE, 2016), and then only on a severely restricted basis. A hybrid diesel-electric bolter did not begin installing roof bolts until after August 2015 (WIPP Update, 2015), and a second one that is on site has yet to go into production.

As ground control maintenance operations fell behind, roof conditions deteriorated throughout the facility. MSHA resumed regular inspections of WIPP in September 2014 and ground conditions have been cited 34 times since then.[4] Six of these citations have addressed hazardous roof conditions, and three more addressed rib conditions. The other 25 citations have been for broken, hanging, and unsecured roof bolts and plates that could fall and injure personnel (see Figure 9). In the past, a man lift was routinely used to secure bolts and remove broken ones, but the recent ventilation restrictions have reportedly precluded its use.

FIGURE 9.—A broken roof bolt that has fallen to floor.

[4] The applicable MSHA standard cited in all of these cases is § 57.3360 Ground Support Use, which states, "Ground support shall be used where ground conditions, or mining experience in similar ground conditions in the mine, indicate that it is necessary. When ground support is necessary, the support system shall be designed, installed, and maintained to control the ground in places where persons work or travel in performing their assigned tasks. Damaged, loosened, or dislodged timber used for ground support which creates a hazard to persons shall be repaired or replaced prior to any work or travel in the affected area."

Poor ground conditions became particularly widespread in the south end of the mine, in the area between panels 3, 4, 5 and 6 (all four of which have been filled with waste and sealed). In this area, designated as Panel 9, the drifts were mined in the upper salt horizon, and so they were more prone to deterioration due to the presence of anhydrite stringers in the roof beam. In addition, the entire Panel 9 area was contaminated by the radiological release. For nearly a year the one roof bolter in the Panel 9 area was engaged in rebolting the roof in the E–300 Drift. During this time the roof continued to deteriorate throughout the rest of the panel. Rib hazards also developed, as did floor heave. By October 2016 approximately 1000 feet of the main drifts and crosscuts within Panel 9 were under prohibited access due to unsafe ground conditions, and the decision was made to abandon all of Panel 9. According to a "WIPP Update," the decision considered "worker safety issues, overall issues related to rock bolting and ground control in contaminated areas, efficient use of resources, and the long-term integrity of the underground." Abandoning Panel 9 will also allow crews to focus ground control operations and resources on other areas of the mine.

Before it was abandoned, three roof falls occurred in the Panel 9 area. All three occurred in the access entries that connect the main drifts with abandoned panels. Two of the falls occurred in the S–2750 Crosscut, which had been scheduled for re-bolting prior to the events of February 2014 (WIPP Update, January 2015). The other was in the S–3650 Crosscut, where all the tendons had failed, leaving it essentially unsupported. Personnel access to both access entries was prohibited before they fell in. Because miners did not normally work or travel in these areas, and because the roof falls did not impair ventilation or impede passage, these roof falls would not normally be reportable to MSHA under 30 C.F.R. §50.2(h)(8).

Current Conditions—Panel 7

Panel 7 consists of two access entries (S–2180 and S–2550) and seven rooms. It was developed during 2010–2011. The roof support installed at that time consisted of mechanical bolts and chain link mesh on the upper portions of the ribs and rib sides of the roof. In addition, two rows of 14-foot-long Dywidag bolts were installed down the center of the rooms. It was understood that this pattern of long tendons was insufficient to prevent a major roof fall. However, it was expected that the rooms would be filled with waste before additional support would be necessary. In a measure taken to reduce floor beam buckling, the floor of Panel 7 was "slotted" by the continuous miner, and the slots were filled with run-of-mine salt.

Waste emplacement began with Room 7 of Panel 7 late in 2013. Waste that had recently been stored in Room 7 was responsible for the radiation release in February 2014. When WIPP resumes waste storage, current plans call for it to be placed in Panel 7.

The entire panel is now considered a contaminated area, and Room 7 has since been sealed. Ground conditions have undergone significant deterioration since the radiation release. Most of the original Dywidag long tendons have failed throughout the panel. Remedial roof bolting with a denser pattern of long tendons is now underway.

MSHA Technical Support was able to observe conditions in the six available rooms and in the access drifts during its visit on October 29. MSHA also reviewed the latest monitoring data from the Panel.

Room 6

Like other rooms at WIPP, Room 6 was mined 33 feet wide. A number of pieces of equipment were stored there after the radiation release. Access to Room 6 has been prohibited since September 13, 2016, because of an MSHA citation based on the number of broken and hanging Dywidag tendons. No convergence data has been collected in Room 6 since access was prohibited. As viewed from S–2520, there did not appear to be any severe roof deflection or rib spalling.

Room 5

Beginning in early 2015, two of the three convergence stations in Room 5 indicated accelerating creep. As a result, it was selected for early rebolting. Convergence rates have since reduced back to about 5 inches per year.

Unfortunately, the central portion of the room contained an area along the west rib where no mesh was originally installed. A low-angle fracture had also developed along this rib. Prior to rebolting, a scaler was used to pull down a large, loose piece of roof salt from this portion of the roof. The resulting cavity revealed a large gap between the thin immediate roof and the upper portion of the roof beam. Because this rock is unconfined and unsupported, it was not considered safe to bolt it. Therefore, in the vicinity of the cavity each row of long tendons contains just five Dywidag bolts, while elsewhere the rows consist of seven long tendons.

The north end of Room 5 appears to be in good shape, with small rib falls contained by the mesh. In the south end, several small, thin slabs have fallen from the central portion roof where no mesh was installed.

Room 4

No remedial bolting activity was conducted in Room 4. While one convergence station in Room 4 had indicated an increasing creep rate early in 2015, the other two did not. Then, near the end of September 2016, convergence rates in excess of 10 inches per year developed at two monitoring stations. A subsequent reading just days later indicated that the rates had increased to about 36 inches per year at these two stations, and to 25 inches per year at the third. Such a rapid increase in convergence had never before been observed at WIPP, even in the experimental SPVD rooms.

Anticipating a roof fall, all access to Room 4 was prohibited. The intersection between Room 4 and the S–2520 Drift was fully bolted with a seven-bolt pattern of long tendons, and an extra row of “breaker bolts” was added as well.

Technical Support did not observe anything particularly unusual in Room 4. The initial Dywidag bolts had failed as they had in the other rooms in Panel 7, but the chain link mesh and short bolts were intact. Low-angle fractures were daylighting along the east rib, but the loose rock was controlled by the mesh. The roof fall that occurred in Room 4 after Technical Support’s visit is discussed later in this report.

Rooms 1–3

Room 1 was the only one of these three to have been resupported at the time of Technical Support's visit. A four-bolt pattern of long tendons had recently been installed along its full length. A four-bolt pattern is considered the bare minimum that could carry the weight of the roof beam should an unforeseen major failure develop. Low-angle fracturing was prominent along the east rib, and some floor heave was noticeable.

The overall appearance of Room 2 was similar to Room 1. Some loose, thin slabs of salt were also observed in the middle, unmeshed portion of the roof. These could easily be scaled down. However, the convergence station in Room 2 located nearest the S–2180 Drift does indicate that the convergence rate may be accelerating.

Access to Room 3 was restricted at the time of Technical Support's visit. A 12-foot by 50-foot area of roof damage (thin slab failure) was observed on the east side, about three-fourths of the way toward S–2180. The damage was associated with the edge of the roof wedge. The wedge was controlled by the original mesh and mechanical bolts, though the bolt density might not be sufficient to bear the weight of a large rock like the one that was scaled down in Room 5.

S–2180 Access Drift

This drift carries the return air from Panel 7, and is considered highly contaminated due to the radiation release. It was originally mined 20 feet wide.

Many of the pillar corners ("miters") were observed to be severely fractured, and only partially controlled by the original mesh. Apparently these corners would normally have been fully wrapped in mesh. The roof was also badly broken in the vicinity of several of the miters. The inby miter of Room 3 was dangered off due roof slabbing, and a large slab had fallen from the roof at the outby miter of Room 4. Along the pillar between Rooms 5 and 6, the roof was fractured, the rib had bulged out and was spalling behind the rib mesh, and the mesh was loose in places.

The original two-bolt pattern of long tendons had largely failed. A diesel roof bolter was actively working in the area at the time of our visit, installing a seven-bolt pattern of long tendons. At least six convergence stations in the S–2180 Drift are displaying slightly accelerating creep rates, emphasizing the need for timely resupport.

S–2520 Access Drift

The S–2520 Access Drift appeared to be in good condition. A few small slabs had fallen from the unmeshed central portion of the roof. A hybrid roof bolter was actively reinforcing the drift with long tendons. The convergence data from the drift indicates that creep rates are essentially steady-state throughout. Two of these stations at the inby end of the drift had shown accelerating creep rates that were apparently reduced by roof bolting.

Current Conditions—Panel 8

Panel 8 was only partially developed prior to the 2014 events, and then only "rough cut." Under normal circumstances, it would have been "finish cut" by now, and at least the initial roof support pattern of short bolts and mesh would have been installed. Instead, no supports other than occasional spot bolts were installed. Entry has been prohibited to the S–1950 Access Drift because of widespread drummy roof.

The S–1600 Drift and the rooms within Panel 8 are restricted, and must be sounded for drummy roof each time that they are entered. In S–1600, minor continuous spalling was observed on south rib. There was significant spalling in upper ribs on both sides of Room 1, and the roof was intact with 1–2 feet of deflection.

Boreholes indicated that most of roof degradation was limited to the lowest 2 feet. However, three-fourths of the way into the room (going south) there was a complete borehole occlusion 6.3 feet up into the roof at the Anhydrite B Horizon. The ribs were also fractured in areas, particularly on the miters.

Plans call for these entries to eventually be finish cut, and then for the rest of the panel to be developed. The finish cut should remove the rib slabs and any floor heave. Normally the finish cut does not remove significant portions of the roof, but because the roof is likely to be fractured, in this case roof trimming should be considered.

Unfortunately, finish cut mining will create a lot of salt dust which can clog the HEPA filters. The finish cut may therefore have to wait for a major ventilation change while the roof and ribs continue to deteriorate. It is possible that by the time finish mining begins, it may not be possible to remove all the fractured salt. So that the miners are not exposed to the broken roof, WIPP should consider “place changing” mining methods that keep miners beneath support at all times. This would mean cutting perhaps 40 feet of advance by remote control, and then installing chain link mesh and mechanical bolts before another cut is taken.

Current Conditions—E–300 Drift-Contaminated Area
Technical Support travelled this drift on October 28. The drift is bolted and fully meshed along its entire length. North of S–1600, approximately 4 feet of the floor was removed. The floor is still heaving in this area, and does not appear to be travelable by vehicle. Fortunately convergence rates are low and the roof support appears to be in good shape in this area, which is not affected by the mining in the panels.

The roof of the E–300 Drift was recently rebolted south of S–2520. Between S–1950 and S–3080, there were pervasive tension fractures resulting in detached blocks/slabs in roof. Many broken bolts were observed, together with replacement bolts (on 2–3-foot spacings). Roof deflections of 2.5 feet were typical, with maximum deflections of up to 4 feet. Roof deformations were most severe south of S–2750, but this area is part of Panel 9 and will soon be abandoned. The panel access drifts south of S–1600 have all deteriorated, and access to the one at S–2520 has been prohibited.

Current Conditions—E–140 Drift
The E–140 Drift is the widest of the main entries, 25 feet wide. It is also unique in that the lower roof beam has been removed over much of its length (Terrel and VandeKraats, 1997). The upper roof beam is the same one that is present throughout Panel 9, though the anhydrite stringers are

less prevalent to the north. The roof and ribs of the drift have been fully bolted and meshed along its entire length, and several generations of long tendons have been installed in some areas.

The lower roof beam is still in place north of S–1000 in E–140 drift. Conditions generally looked good, though in one segment the mesh on the ribs was not tied together and should be reinforced. Between S–1000 and S–1600 there is approximately 1–2 feet of deflection, and intersections show relatively little deflection. South of S–1600 significantly more deformation has occurred, and the roof has bellied 3–5 feet. Due to the amount of deformation and the height of fracturing observed in boreholes, the most recently installed long tendons were 18 feet long, the longest in the mine.

Current Conditions—Other Main Drifts

Technical Support was only able to conduct very cursory inspections of other portions of the underground facility. In general, it appeared that routine rebolting and scaling was not always caught up. Broken bolts were not always secured. There were also some areas where the original bolting appeared incomplete because of utilities that were in the way.

In S–170 Drift, south of S–1600, it seemed that approximately 20% of roof bolts had failed. The rib bolt spacing also did not always seem adequate to secure mesh where large pieces of the rib may have fallen. To the north of S–1600, the bolting appeared sparse in the ribs and roof, but full mesh coverage was in place.

Roof brows occur where the roof line in a drift suddenly shifts up or down and are among the most hazardous features in underground mines. In the W–30 Drift, a roof brow was present at the south side of the intersection with the S–1250 Crosscut. A large crack was observed that went across the drift about 5 feet from the edge of the brow. Although the brow was bolted, the bolts were not optimally located to stabilize the brow. Since further creep could create a hazardous situation, more vertical and possibly horizontal support should be considered. Another deteriorating brow was observed at the air intake shaft bottom.

Roof Fall in Room 4, Panel 7

Exactly 5 days after Technical Support visited Panel 7, a massive roof collapse occurred in Room 4. Miners who had been working inby Room 4 just 20 minutes earlier were at the mouth of the panel in the S–2520 Access Drift, and they heard the fall and observed some of its effects. When the fall was accessed the following day, it was found to have extended throughout the entire central portion of Room 7. However, the failure did not damage the bulkhead at the north end, and appeared to terminate at least 30 feet before the intersections, similar to the roof fall in the SPDV experimental room 25 years ago. The extent of the fall did not approach the roof bolts that were installed in the intersection with S–2520.

This event emphasizes the importance of the ground monitoring program at the WIPP facility. Just 5 days before the collapse Technical Support's visual inspection did not indicate that a failure was imminent. The convergence monitoring, on the other hand, gave about a month's warning.

On the other hand, the fact that this roof fall occurred is also indicative of the overall deterioration of ground conditions at WIPP. Under normal circumstances Room 4 would either have been filled with waste and sealed, or supported with a dense patterns of long tendons. The sudden, unprecedented increase in the convergence rate was unexpected, but no room had ever been left unsupported for this long either.

Finally, this event underlines the need for enhanced remote monitoring capacity at WIPP. Once the excessive convergence rate was observed and personnel access was prohibited, no further convergence data could be collected. Thus the eventual collapse was expected, but its timing was unknown. And while the roof fall did not put workers at risk because it did not extend beyond Room 4, ideally no one would have been in Panel 7 when it occurred. Remote monitoring in real time undoubtedly could have led to a more precise prediction of the time of the failure.

Concerns Reported by Miners
Technical Support met with a group of underground miners at the DOE office in the WIPP facility on October 25. We also spoke at length with a miner who was installing roof bolts in the highly contaminated area of Panel 7. United Steelworkers Local 12–9477 President Rick Fuentes also contributed to the close-out meeting on October 31. Some of the concerns that the miners expressed are listed below:

- The ground control program is now “running around putting out fires,” when roof support used to be more systematic.
- Maintenance has fallen behind on floor heave, hanging bolts, and bolts hitting the ground.
- In the past, they were able to bar down more rock than they are able to do now.
- There are areas where bolts have failed without being replaced.
- Not enough people have been trained to run the new hybrid roof bolter.
- The floor heave in E–300 is now too severe to bring a roof bolter in to replace broken bolts.
- Work begins too late in shifts in the contaminated areas
- “The ground in the underground is not waiting on us. Time is not on our side.”
- “We should secure the rooms that we can, and then move on. We should not try to save everything.”

Several miners expressed concern about the cavity in the unmeshed portion of Room 5 in Panel 7. They felt that there was too much loose material around it for it to be bolted safely.

On the positive side, the miners also stated that bolting has recently improved a lot, with three roof bolters operating each day. They said they used to feel that “their hands were tied,” but that it is now a little better.

Conclusions and Recommendations
In summary, Technical Support believes that prior to 2014, the WIPP facility operated with an admirably low level of ground fall risk. The ground control program was proactive, identifying and addressing potential hazards before they posed serious risk. WIPP’s record of zero ground fall injuries and zero unplanned roof falls testifies to the success of this program.

Since 2014, however, the ground fall risk has increased significantly. The roof, ribs, and floor continued to deteriorate all over the facility, but maintenance fell further and further behind. The ground control program became reactive, responding to crises rather heading them off. Some items that were on the ground control priority list prior to the radiation release are reportedly still on the list. As the recent RESPEC report (Keffeler, 2016) stated, "The geotechnical personnel at WIPP have the site-specific experience required to identify when support should be installed, but resources are not typically available until closure has significantly accelerated or significant damage has occurred to the roof."

In essence, much of the facility has been gradually reducing the high margin of safety that was maintained prior to 2014. As the risk level increases, so does the likelihood of unanticipated events. The sudden acceleration in the convergence, and subsequent collapse, of Room 4 in Panel 7 was one such event.

To avoid further incidents, WIPP needs to return the ground fall risk to pre-2014 levels, and to a proactive ground control program. Accomplishing this will require accelerated efforts both within and outside the contaminated area. Specific actions should include:

- Complete bolting in all of unbolted areas in Panel 7
- Renew bolting patterns elsewhere in the mine where creep has broken long tendons
- Remove all hanging roof bolts and plates
- Secure all roof bolts and plates in the facility that could potentially break and fall
- Conduct systematic remedial scaling over the entire facility to remove loose salt, and then schedule future scaling activities on a regular basis
- Revive the broken bolt database and map
- Monitor roof bolting safety factors throughout the facility
- Redrill extensometer and observation holes, and resume monitoring them

WIPP should also develop standard operating procedures (SOPs) to be followed when suspect ground conditions are identified by a workplace exam or from monitoring data. The SOP's should cover:

- Withdrawal of personnel
- Barricading
- Length of time allowed for remediation
- Procedures for remediation

The SOPs should be incorporated in WIPP's training plans.

WIPP should identify the resources that will be required to catch up with the outstanding ground control issues over a preset period of time. Then, it should make sufficient equipment available, including roof bolters and man lifts. Ventilation, staffing schedules, and so forth should be adjusted so that these resources can be utilized to their maximum potential.

The proposal to abandon the contaminated Panel 9 area should greatly reduce the effort required to catch up. On the other hand, the impending resumption of waste handling activities could negatively impact the resources available for ground control.

Unfortunately, until the ventilation limitations are resolved, there is very little that can be done about the rough cut entries in Panel 8. The ground will continue to deteriorate in the interim. When mining finally does recommence, it may be desirable to employ “place changing” mining methods so that the miners are always beneath supported roof.

The roof collapse in Room 4 of Panel 7, and the various other prohibited areas in the facility, have underlined the potential value of real-time, remote monitoring capability. Such a monitoring system could have provided an accurate estimate of time of the impending collapse, so that miners could have been withdrawn. Real-time, remote monitoring would also be valuable during rehabilitation operations in areas that had been prohibited. Given the technology available today, and taking advantage of the fact that permissibility is not an issue at WIPP, it should be possible to develop the necessary capability relatively easily. Ultimately, it should be possible to collect much of the convergence data using modern technologies that do not require miners to take the measurements.

Disclaimer
The conclusions and suggestions presented in this memorandum are based on information submitted by WIPP. Additional copies are being provided to the District for distribution to the mine operator and miners’ representatives. If we can be of further assistance or you have any questions regarding this evaluation, please contact Christopher Mark at 571–481–8098 or Paul Tyrna at 304–547–2312.

cc: W. Francart, Director, TS
B. Goepfert, Chief, Safety Division, MNM

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