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6 January, 1998

JAN 1998

Lawrence G. Weinstock
Acting Director, Office of Radiation and Indoor Air
U.S. Environmental Protection Agency
401 M Street, S.W.
Washington, D.C. 20460

in WIPP Library

Dear Larry:

Enclosed is a report by John Bredehoeft, Drilling with Air and Mud into WIPP—Revisited, discussing the implications for direct releases of recent DOE research and modeling concerning the spallings process. Main points are:

(a) In an air drilling intrusion, about 50 to 2000 m^3 of waste fails (i.e., breaks loose). The intrusion would cause "stuck pipe," followed by a cleanout procedure, releasing 300 m^3 per day and possibly the entire failed volume.

(b) In a mud drilling intrusion at high repository pressures (12 to 14.8 MPa), about 3 to 800 m^3 of waste fails. The intrusion would cause "stuck pipe," followed by cleanout, releasing 43 to 238 m^3 per day and possibly the entire failed volume.

(c) EEG has shown that spallings releases ranging from 8 to 64 m^3 violate §191.13. Thus, releases in the ranges shown almost certainly violate §191.13.

(d) Waste form modifications, specifically, elimination of the gas-generating steel waste drums, must be reconsidered by DOE and EPA.

DOE and EPA have considered neither air drilling, nor the significance of the recent research, which suggests that "stuck pipe" and large releases will occur frequently. We request that EPA carefully review this report in its WIPP compliance determination.

Very truly yours,

Lindsay

LINDSAY A. LOVEJOY, JR.
Assistant Attorney General

LALJr:mh

The HYDRODYNAMICS Group
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DRILLING with MUD and AIR into WIPP—REVISITED

prepared for: **NEW MEXICO ATTORNEY GENERAL**

John Bredehoeft
January, 1998

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CONTENTS

I INTRODUCTION

The Achilles Heel of WIPP is human intrusion. Most reviewers of the facility agree that undisturbed, and in the absence of nearby boreholes, the facility is safe. When WIPP was selected as the site for a repository several decades ago it was known that there were economic potash deposits in the vicinity of the facility. At the time WIPP was sited within the Delaware Basin, a basin in which oil was discovered many decades ago, there were not oil and gas fields in the immediate vicinity of the proposed repository. Now there are oil and gas fields around the land withdrawal boundary; the fields are thought to extend beneath the repository. The drilling rate specified for consideration in the EPA criteria for certifying WIPP makes a number of drilling intrusions into WIPP practically certain. It is these intrusions that pose the greatest risk of a release and that could violate the EPA standard.

The NEA/IAEA International Peer Review(IRG)(1997) commented in the conclusions of their report on the WIPP site and the Compliance Certification Application (CCA) process; they stated:

4.1 Observations on the Specificity of the WIPP Case

The WIPP project, and CCA, are different in several respects from geological disposal projects, and assessment documentation, in other countries.

- *The WIPP facility is sited in an area in which mineral resources are being actively and extensively exploited.*
- *The regulator has provided detailed guidance on the assessment approach, documentation and, for the assessment of future human actions, model assumptions.*
- *The CCA is tightly focused on compliance, and does not represent a full safety case as understood in most countries.*

These observations are statements of facts, not criticisms. Such differences, however, have had a strong influence on DOE, and have been taken into account by the IRG in formulating its conclusions.

The comments of the NEA/IEEA International Peer Review were polite; however, their remarks were clearly not a ringing endorsement of WIPP. The IRG went on to comment:

- *the probabilistic approach applied by the DOE deals only with parameter-based uncertainty. Conceptual model and scenario uncertainty, are not discussed in the CCA. These are considered to be important internationally.*
- *the EPA has ruled that DOE needs only consider a limited set of future human actions, and has specified the assumptions to make in assessing these actions. Thus some scenarios that might affect safety have not been evaluated. This lack of a logically-argued explanation for the choice of scenarios analysed, or evaluation of other scenarios, leads to the impression that the assessment is arbitrary.*

Finally the IRG stated:

The case of disturbed performance is less clear: supplementary analyses by the DOE indicate that a risk target would be met in respect of an exploratory borehole drilling scenario. The CCA does not (and need not) make the case that this is the most important scenario to consider and, therefore, the IRG cannot reach a definite judgment.

It is incumbent on EPA and DOE collectively to do everything reasonable to mitigate the impact of human intrusion on the safety of WIPP. As we suggest below, changing the waste form by eliminating the steel drums gets rid of the major remaining source of gas—hydrogen. This eliminates many of the concerns associated with a drilling intrusion. This change would make WIPP much less vulnerable in a drilling intrusion, and ultimately safer.

DRILLING INTRUSION—AN UNFINISHED INQUIRY

In the 14 months since DOE submitted its Compliance Certification Application (CCA) to EPA there have been several changes in how the phenomena associated with drilling intrusions are conceptualized. Even with the CCA submitted, the analysis of WIPP has been a moving target. The changes in conceptualization are a result of 1) further analyses by DOE, especially as a result of questions raised by the Conceptual Model Peer Review Panel regarding spallings, 2) analyses by EPA as part of their evaluation of the CCA, and 3) questions raised by concerned parties. These changes in the conceptual models are significant; the implications of the changes on the safety of the facility have not been fully examined. Among the changes in concept are:

1. **A change in the conceptual model of spallings** that resulted from the review by the Conceptual Model Peer Review Panel (Wilson et al., 1997). The Panel did not accept DOE's earlier models for spallings. A new model was generated that predicted the volume of material that failed, in both tension and shear, around the borehole during a drilling intrusion (Hansen, et al., 1997).

2. **Experiments on surrogate waste** that show that the permeability is in the range of 10^{-14} to 10^{-15} m^2, much lower than the values in the range 10^{-13} m^2 used in Performance Assessment (PA) (Hansen, et al., 1997).

3. **A recognition that drilling with air into WIPP is viable** (Bredehoeft, 1997). Drilling with air increases the release of waste from the repository significantly (EEG, 1997). ***Drilling with air has not been analyzed by either DOE or EPA in their evaluation of WIPP.***

4. **Modeling of a drilling intrusion into waste with permeability in the range of 10^{-14} m^2, and lower, indicates a large volume of failed material around the borehole, even with mud in the borehole.** This leads to a *"stuck pipe"* scenario under conditions different than those hypothesized by Berglund (1994) that are currently used in the CCA. Stuck pipe now seems much more probable. Stuck pipe increases the volume of waste brought to the surface (Berglund, 1994).

5. **In the case of air drilling, modeling of the volume of failed material around the borehole during a drilling intrusion also indicates large volumes** (Bredehoeft, 1997). It too suggests that stuck pipe is much more probable than hypothesized by Berglund (1994).

6. **Both DOE and EPA have attempted to bound the size of spallings releases based upon the particle sizes that can be transported by the flow of gas up the borehole; these investigations are not coherent, contradict one another, and are incomplete in considering all the relevant phenomena** (EPA, 1997a, EPA, 1997b, Hansen et. al., 1997).

7. **The New Mexico Environmental Evaluation Group (EEG) analyzed the significance of increases in spallings, and showed that an increase by a factor of 16 times violates the EPA disposal standard** (EEG, 1997).

Several of the new hypotheses indicate that releases sufficiently large to violate the EPA disposal standard are probable. These changes in concept suggest a much higher probability of violating the disposal criteria than previously suggested by PA.

DEFINITIONS

Before proceeding it is useful to restate the definitions used by DOE to describe the phenomena of concern (Berglund, 1994) :

1. ***Cuttings:*** are the waste contained in the cylindrical volume created by the cutting action of the drill bit passing through the waste.

2. ***Cavings:*** waste that erodes from the borehole in response to the upward-flowing drilling fluid within the annulus.

3. ***Spallings:*** waste introduced into the drilling fluid caused by the release of waste generated gas escaping to the lower pressure borehole.

II FAILURE AROUND BOREHOLE

The new DOE conceptual model of spallings involves dynamic failure around the borehole caused by the drilling intrusion.

THE DOE SPALLINGS SCENARIO—FAILURE ANALYSIS

Spallings in the current Performance Assessment (PA) are thought to occur from a drilling intrusion when the repository pressure is above hydrostatic. The usual scenario is that drilling encounters the repository. When the repository pressure is higher than the weight of the mud column used in drilling, the mud is blown from the hole—a *blowout,* and gas then flows up the borehole carrying with it particles from the waste—these particles are the spallings. To recapitulate: 1) there is blowout of the drilling mud; 2) this is followed by a flow of gas from the repository that carries with it particles of the waste.

Spallings are one of the more difficult of the calculations associated with the repository. The Conceptual Model Peer Review Panel iterated back and forth with Sandia before it was satisfied that the spallings model was reasonable (Wilson et al., 1997). It finally settled on a model that was based upon a limiting size for the cavity formed in the waste after a drilling intrusion. The limiting size was determined by the amount of material that failed dynamically around the borehole (Hansen et al., 1997).

MATERIAL FAILURE AROUND BOREHOLE—MUD IN THE BOREHOLE

How large the failure of material is during a drilling intrusion was the subject of the recent analysis by DOE (Hansen et al., 1997). The work by Hansen, et al. (1997) shows that a dynamic tensile failure happens rapidly around the borehole; the failure occurs within a few milliseconds to a few seconds. The GASOUT code of Schatz (1997) was designed to model dynamics of the processes involved.

The processes involved in a drilling are several, are coupled, and complex. GASOUT is designed to model 1) the flow of gas from the pressurized repository, 2) the dynamic failure of material in both shear and tension around the intruding borehole, and 3) the dynamic expulsion of the mud from the borehole. The code calculates the amount of material failed around the borehole. It does not model gas transport of spalled material in the borehole; it assumes that all the material that fails around the borehole is carried up the hole. In the case of larger failed volumes this assumption is invalid. Even though GASOUT may not handle transport appropriately; it is good at describing the dynamics and volume of failed waste.

SENSITIVITY OF VOLUME FAILED TO WASTE PERMEABILITY

The amount of failed material goes up as the permeability of the waste is lowered, with either mud or air as the drilling fluid. Recent experiments on surrogate waste suggested a permeability in the range of 10^{-14} to 10^{-15} m^2 (Hansen, et al., 1997). Figure 1 is the result of running GASOUT, with mud in the hole, at different waste permeabilities. GASOUT was designed to model a drilling intrusion with mud in the borehole—we are running it in its design mode. Care must be taken in running GASOUT; the code will run until the entire column of drilling fluid is blown out of the borehole. However, longer runs of the code often yield what seem unreasonably large volumes of failed waste. The failed volumes are not as smoothly varying as one would like. We restricted the simulated time of the blowout to 10 seconds following the drilling intrusion; even so, the failed volumes of waste at the lower permeabilities are large.

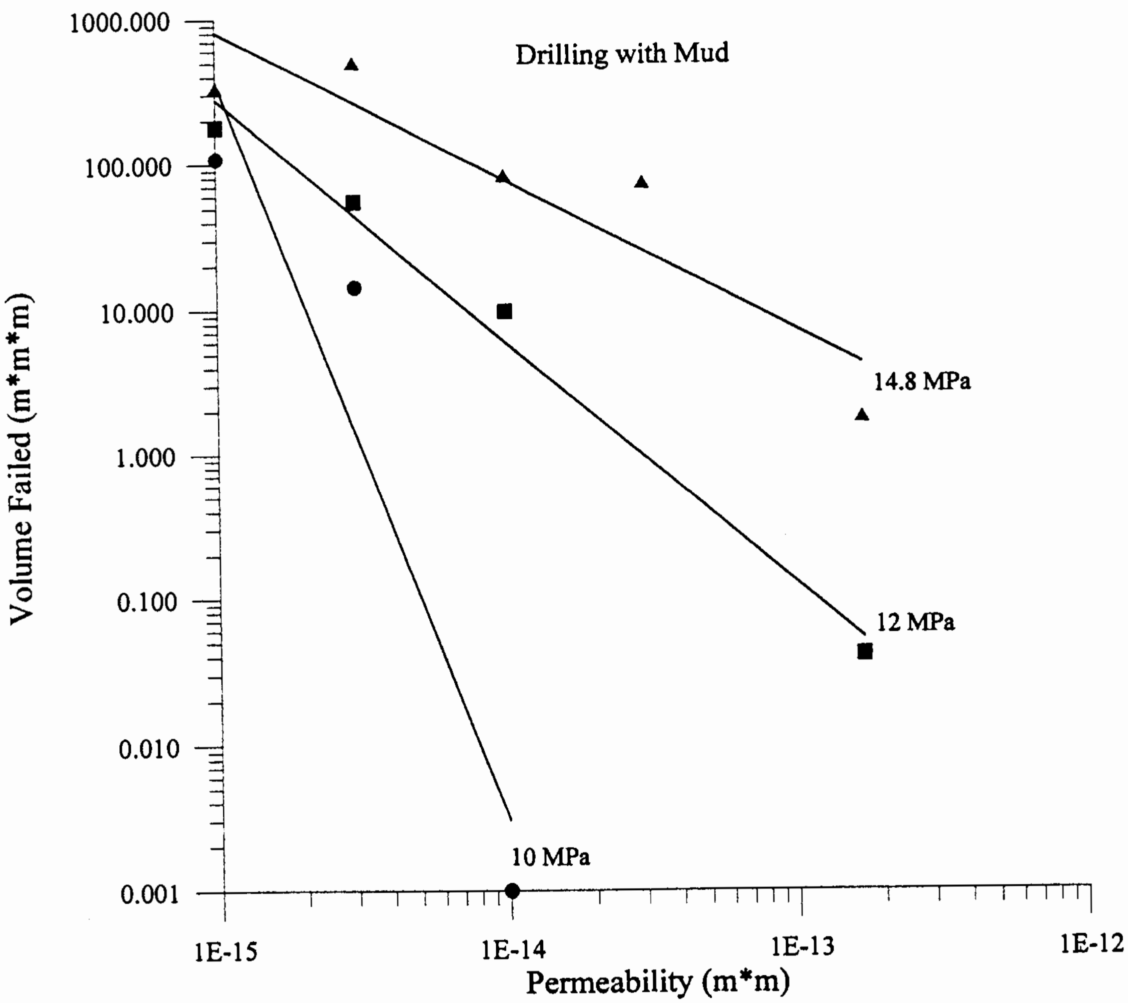

Figure 1. Predicted amount of failed material during drilling penetration of the repository, estimated by GASOUT (Schatz, 1997)—with mud, run in the cylindrical mode. The tensile strength of the waste is 10 psi. The lines are best fits through the data; repository pressure is indicated in MPa.

The Spallings Peer Review Panel commented on the changes in failed waste volume as a function of its permeability (Wilson et al., 1997):

"It was noted by the Panel that the waste permeability values were the same as those used in performance assessment (1.7 x 10^{-13} m^2), rather than the lower value of about 4 x 10^{-15} m^2 experimentally determined for the surrogate waste. ....in view of the analog information relating to lower permeabilities with higher pressure gradients and therefore larger cavity volumes, the panel requested DOE to further discuss the consequences of assuming higher waste permeability in the analysis than may actually exist in the degraded state. In responding, the DOE referred to sensitivity studies on waste permeability that had been performed with the quasi-static method in which the waste permeability was reduced to 1 x 10^{-15} m^2. The results indicated that although the pressure gradients did increase at lower permeabilities, the volumetric flow of gas was insufficient to eject the mud from the borehole and therefore no spall event could occur.

The Peer Review Panel recognized that the volume of failed material increases with lower permeability, even when there is mud in the hole—as shown by Figure 1.

Curiously, Hansen et al. (1997, p. 3-35) explored the effect of permeability on spalling in the case of mud, but did not report results for the failed volume of material other than at a waste permeability of 1.7 x 10^{-13} m^2. At permeabilities of the order of 10^{-14} m^2 with high repository pressure (12 to 14.8 MPa), GASOUT, with mud in the borehole, predicts failed volumes ranging from approximately 10 to 1000 cubic meters (at a tensile strength of 10 psi)—see Figure 1. EEG (1997) in its comments to EPA came to similar conclusions regarding the volumes of failed waste material that would accompany a drilling intrusion.

EEG (1997) pointed out that magnesium oxide backfill, in the presence of brine, will tend to precipitate and cement the waste. This will decrease the waste permeability. This too suggests that the permeability could be lower than the 1.7 x 10^{-13} m^2 assumed in the CCA..

III AIR DRILLING

Neither Sandia or EPA investigated a drilling intrusion using air drilling; all the analyses assumed the borehole was filled with drilling mud. ***How large the failure is in the case where the drilling fluid is air has not been analyzed by either DOE or EPA.***

AIR DRILLING

In a report dated October, 1997 (Bredehoeft, 1997), prepared for the Attorney General of New Mexico, we argued that drilling with air was a viable technology in the Delaware Basin and could be used in the vicinity of WIPP. We went to some length to show that it was feasible at WIPP. We had letters supporting the fact that it is being done to comparable depths and below in the Delaware Basin.

Drilling with air eliminates the column of mud in the hole. This means the pressure at the bottom of a hole, being actively drilled, is greatly reduced. This has a number of consequences for a potential release of material from WIPP:

1. Releases will occur below 8 MPa (the pressure at the bottom of a column of drilling mud at WIPP depth) pressure in the repository.
2. The release of contaminated brine to the surface during drilling will increase because of the reduced pressure in the borehole (EEG, 1997). EEG explored this aspect of drilling with air extensively.
3. Spallings will be increased because of the reduced borehole pressure.
4. The amount of waste material that fails within the repository is increased with the reduced borehole pressure.
5. Because of the increase in the volume of failed material within WIPP, a scenario involving *stuck pipe* appears to be probable.

Neither DOE or EPA has analyzed the full consequences of drilling into WIPP with air. All of the scenarios involving drilling into WIPP analyzed both by DOE and EPA involve drilling with mud as the drilling fluid.

POTASH MINED AREAS

Drilling with air eliminates the problems of lost circulation of drilling mud. Further review of the WIPP literature suggests it may be the method of choice for drilling where potash is believed to have been mined. In the questions and answers Jack Ahlen, an acknowledged drilling expert, commented (WIPP Inadvertent Intrusion Advisory Panel, 1995):

"Lost circulation will be a significant problem once the potash enclave is opened for drilling.........Drilling with air through this part of the hole will significantly reduce the impact of the open cavities on circulation."

THE AIR DRILLING SCENARIO

Air drilling is quite different from the mud drilling scenario presented above. One of the design criteria for air drilling is that the minimum velocity of the air flow be a kilometer per minute—16.7 m/sec (Lyons, 1984). The compressor capacity is selected so that the minimum velocity of air flow is maintained in the annulus of the hole. Figure 2 is calculated from Equation 4-5 in Lyons (1984) and shows the minimum air flow necessary to support given rates of drilling.

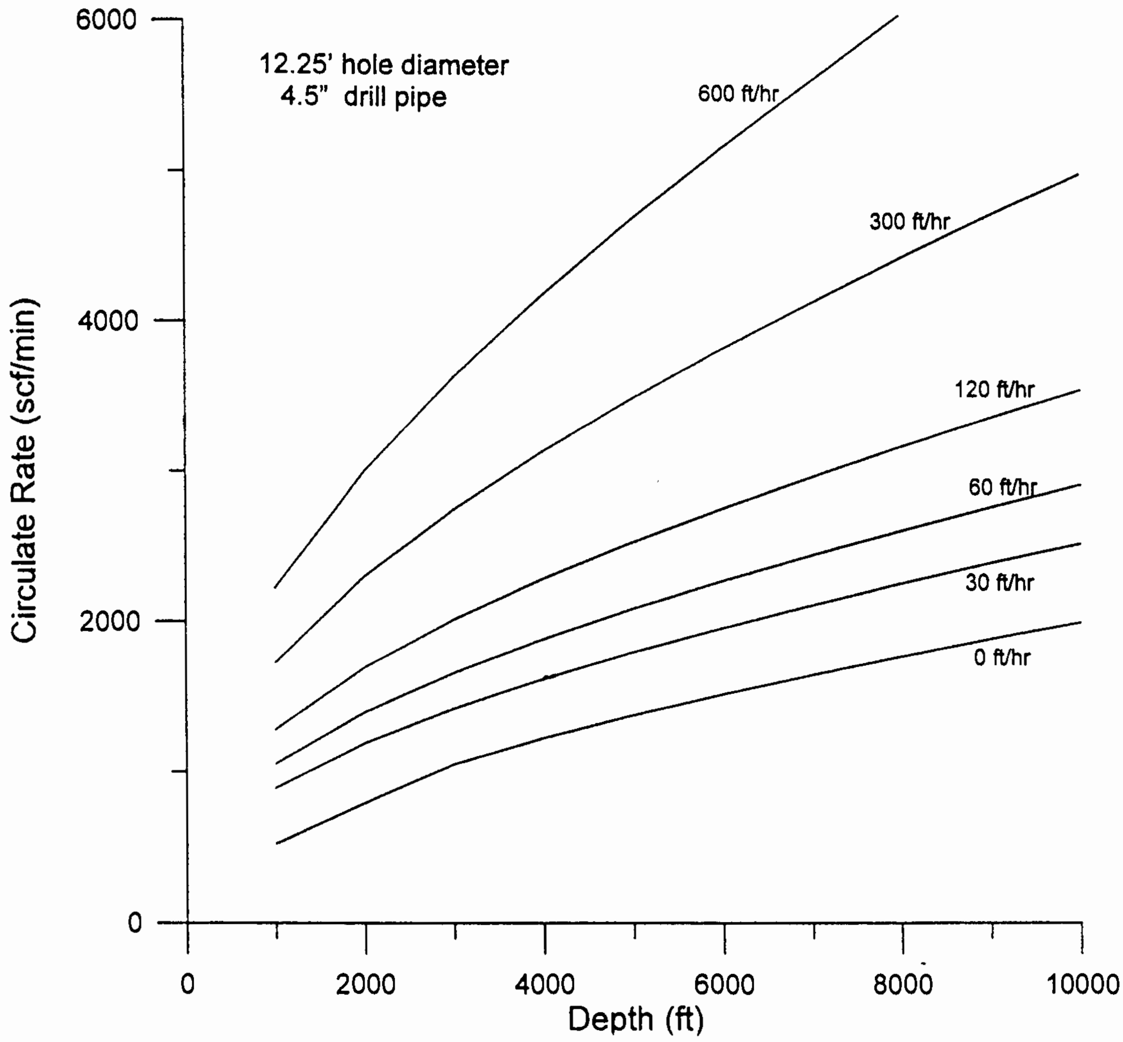

Figure 2. Air circulation rate versus depth for various drilling rates; the 0 drilling rate curve is the capacity necessary to simply circulate the air (calculated from equation 4-5, Lyons, 1984).

For the air drilling scenario, let's presume that one wishes to drill to a depth of 3000 feet at a drilling rate between 60 and 100 feet per hour. Figure 2 indicates that one needs a set of compressors capable of providing approximately 1800 scf/min—two standard 900 scf/min compressors.

We can translate the drilling rate into a capacity to remove cuttings from the hole. A drilling rate of 60 feet per hour means a penetration rate of 1 foot per minute. Figure 2 is calculated to remove 1 hole diameter of cuttings of rock with a relative density of 2.7 at the specified drilling rate. In other words for 12.25 inch hole that one expects to drill, at drilling rate of 60 feet/hour, one would remove 0.82 cubic feet of rock per minute. At 2100 feet this would require approximately 1300 scf/min of air circulation.

If one is drilling with a circulation rate of 1800 scf/min at 2100 feet, one has a capacity to drill at approximately 120 feet/hour, or about 2 feet/min. This means that one has the ability to remove approximately 1.6 ft^3/min of rock at this depth—or approximately 0.0008 m^3/sec.

The question now becomes ***what happens if one is drilling, circulating air at 1800 scf/min, and drills into WIPP?***

MATERIAL FAILURE AROUND THE BOREHOLE—AIR AS DRILLING FLUID

The pressure in the annulus when drilling with air at a depth of 2100 feet is less than 2 MPa—not 8 MPa, the weight of an equivalent mud column.

In our earlier report (Bredehoeft, 1997), we replaced the hypothetical mud in the GASOUT code with air and looked at how much failed material occurred within the repository. GASOUT assumes that all the material that fails will be carried up the borehole. This assumption, while appropriate for small failed volumes, is inappropriate when the volume of failed material is large. Nevertheless, GASOUT provides a good representation of the failure processes within the repository. It should provide a reasonable projection of the volume of material that fails within the repository even if we replace the column of mud with a column of air in the code.

Our use of GASOUT is summarized in Figure 3; it shows the volume of failed material in the air drilling scenario. The volumes are large; however, they are only a factor of 2 to 4 times larger than with mud—see Figure 1. GASOUT also suggests that the failure of material occurs quickly—in a matter of a few seconds. In making the calculations for Figure 3 we restricted the simulation of the blowout to the first 5 seconds after the repository is penetrated.

We also explored the effect on the failed volume of the tensile strength of the waste using GASOUT. Figure 4 shows the volume of waste failed during an air drilling intrusion for different repository pressures and tensile strength. In this instance the permeability is constant at 1.7×10^{-13} m^2.

EEG (1997) came to a similar conclusion that the volume of failed material associated with a drilling intrusion would be large, especially at the permeabilities of waste likely to exist in WIPP.

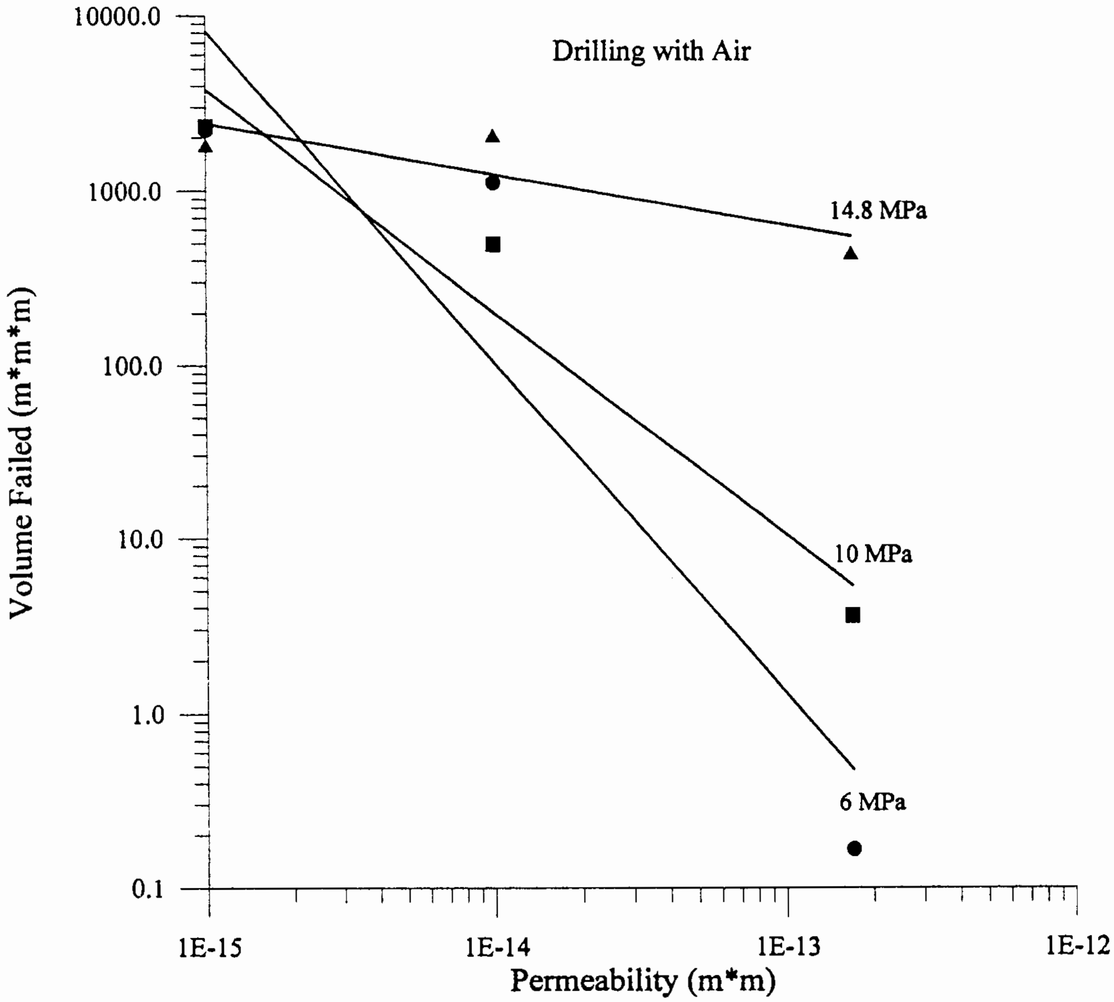

Figure 3. Failed volumes during a drilling intrusion with air predicted by GASOUT—in the cylindrical mode; waste tensile strength is 10 psi. The lines are best fit lines through the data; the repository pressure is indicated in MPa.

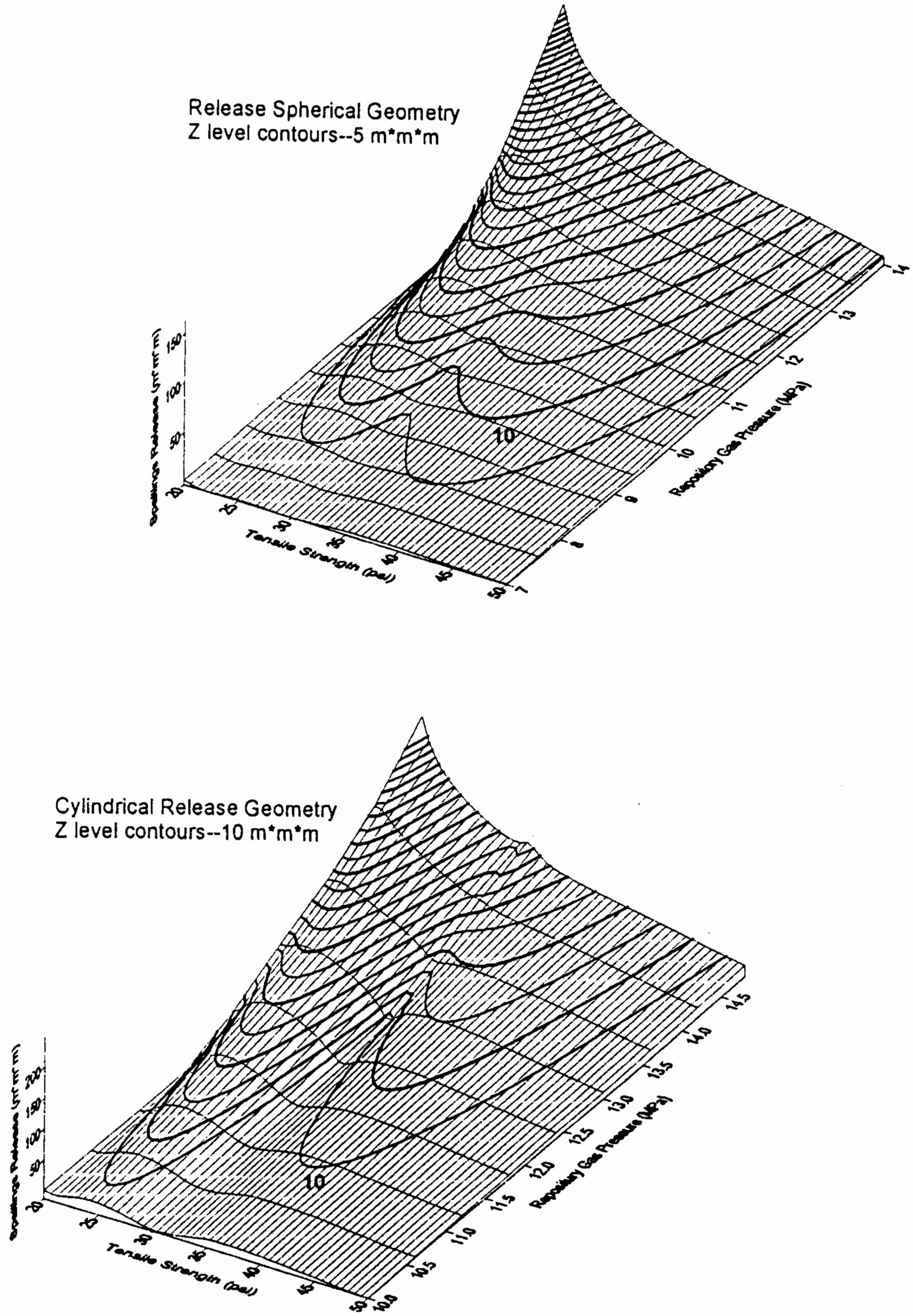

Figure 4. Failed volumes for an air drilling intrusion at varying repository pressure and tensile strength for a constant permeability of 1.7×10^{-13} m^2, predicted by GASOUT.

IV STUCK PIPE

In the earlier analysis Berglund (1994) suggested that stuck pipe was only a problem when the waste permeability was less than 10^{-16} m^2. Figure 5 is taken from Berglund (1994). Since the waste permeability was assumed in the CCA to be 1.7 x 10^{-13} m^2 stuck pipe was not regarded as a problem.

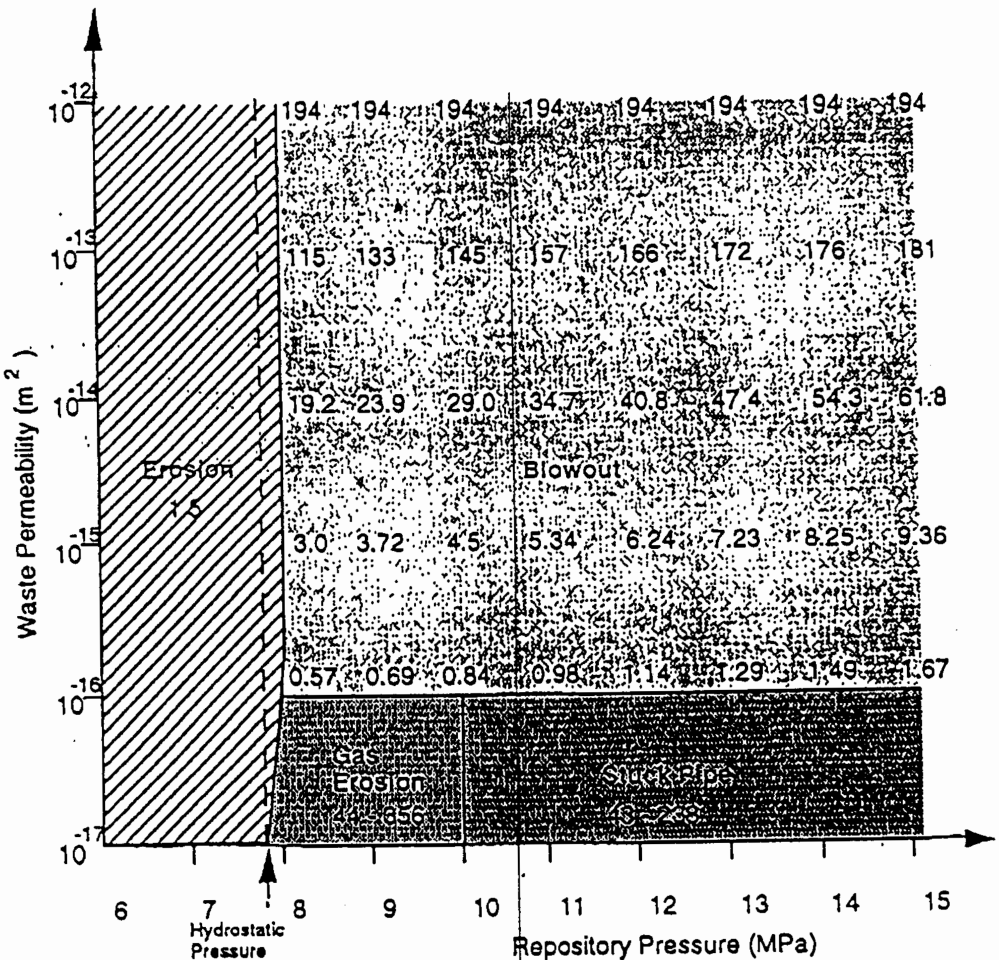

Figure 3 Volume (m³) of Compacted Waste Released to the Accessible Environment (Upper bound for blowout, lower and upper bounds for Gas Erosion and Stuck Pipe)

Figure 5. Figure from Berglund (1994) predicting the release from each type of drilling intrusion scenario.

However, as suggested above, the more recent model suggests very large volumes of failed material at low permeabilities, permeabilities above 10^{-16} but in the range 10^{-14} to 10^{-15} m^2 where a blowout does not occur. Given volumes of failed waste as large as indicated above, it is likely that the circulating drilling fluid, either air or mud, cannot cope with these volumes, and stuck pipe is likely.

DRILLING WITH MUD

At waste permeabilities between 10^{-14} and 10^{-15} m^2, and lower, the flow of gas from the repository is insufficient to blow the mud from the hole—a spallings release does not occur (Hansen et al., 1997). However, at these lower permeabilities the amount of failed material is large, even with mud in the hole, as shown above—Figure 1. It seems likely that even though the mud is not blown from the hole the amount of failed material is sufficient to "stick" the pipe. EEG came to a similar conclusion (EEG, 1997). These scenarios contradict Berglund's (1994) earlier conclusion that stuck pipe was not a problem until the waste permeability was lower than 10^{-16} m^2. Berglund's conclusion was based upon an earlier model of drilling intrusion that now has been replaced.

AIR DRILLING

Let's return to the air drilling scenario outlined above. If one is drilling with a circulation rate of 1800 scf/min at 2100 feet, one has a capacity to drill at approximately 120 ft/hr, or about 2 ft/min. This means that one has the ability to remove approximately 1.6 ft^3/min of rock at this depth—or approximately 0.0008 m^3/sec. If one drills into WIPP the drilling circulated air plus the flow of gas from the repository cannot remove the volume of failed material; the failed volumes are simply too large. Instead, material will pile up around the drill pipe blocking the flow of air. There will be a condition of stuck pipe. Again the question is ***what happens next?***

Waste particles do not have to be suspended to be transported in the repository toward the borehole. Saltation is effective as a transport mechanism. Saltation is the process of rolling material along a surface with the flow of gas; it is the process that builds sand dunes, for example.

Let's go back a few moments to the point where the repository is drilled into. If the waste permeability is high, we will get a kick of gas from the repository. This gas will be largely hydrogen, and as such flammable. The driller will notice that he has encountered an additional flow of flammable gas, probably with a noticeable increase in solid material. This will alert him to fact that something different has been encountered.

If the volume of failed material is such that it cannot be transported out of the hole by the combined flow of the drilling circulated air and the flow of gas from the repository then circulation is blocked and drilling stops—we have a condition of "stuck pipe". As suggested above, this scenario seems likely in the case of a large volume of failed material, as indicated by GASOUT.

CLEAN OUT

Berglund (1994) describes the typical clean out procedure after sticking the drill pipe:

"When sticking occurs the driller will usually initiate a cleanout procedure wherein the drill bit is raised and lower repeatedly into the sticking formation to clear the obstruction. The process can be continued for as much as 12-24 hours if it is shown to be effective."

The other variation on this procedure is to raise the drill string above the obstruction (as Bergland indicates), and then drill out the obstruction, lowering the bit slowly in an effort to efficiently remove all the cuttings as drilling proceeds. ***How much material is brought to the surface during drill operations to free stuck pipe?***

In the case of a large volume of material initially failed, it is reasonable to expect that much of the failed material will be eroded by further drilling. Most of the failed material will eventually reach the land surface—as cavings. If the GASOUT calculations are at all correct, the volume of failed material is large.

Berglund (1994) estimated the volume of material that could be brought to the surface during a 12 to 24 hour clean out, with mud as the drilling fluid. His estimates ranged from 43 to 238 m^3 of waste. While Berglund's numbers are not quite as large as the largest estimated volumes of failed material, they are within 1 or 2 orders of magnitude. They suggest a violation of the EPA disposal criteria. These volumes assume a limit of 24 hours for the period of cleanout. However, if the cleanout proceeds successfully it could continue for several days.

Drilling with air at a rate of 1800 scf/min, we showed above that one had a capacity to remove rock from the hole at a rate of approximately 0.0008 m^3/sec. If one drilled out waste that plugged the hole, one could remove approximately 70 m^3/day. As one drilled out the failed waste, more would be carried to the hole by gas flowing from the repository. If one added a third 900 scf/min air compressor, a unit that is often on site for potential use should there be a problem, one increases the drilling rate to 600 ft/min, or by a factor of 5 times. This means one would have the capacity to remove approximately 300 m^3/day.

RELEASE VOLUME—MUD AND AIR

Dale Rucker, of the New Mexico Environmental Evaluation Group (EEG) staff, used the Sandia PA results to explore how large the spallings release would have to be to violate the EPA standard (EEG, 1997). He showed that if the spallings are increased in the PA calculations by a factor of 16 the CCDF violates the EPA criteria. In PA the spallings release volumes are sampled from a distribution that ranges for 0.5 to 4.0 m^3. Rucker's result indicates that if the range of releases is sampled from a distribution that is increased by a factor of 16 times, to 8 to 64 m^3, the EPA standard would be violated (EEG, 1997).

The volume of waste is estimated from GASOUT, and summarized in Table 1.

Table 1. Estimated failed waste volume (m^3) using GASOUT (Schatz, 1997)—see Figures 1 and 3, lines of best fit. For these calculations the waste has tensile strength of 10 psi. During clean-out much of this volume would be carried to the land surface.

Waste Permeability	10^{-13} m^2	10^{-14} m^2	10^{-15} m^2
MUD DRILLING			
Repository Pressure			
10 MPA	0 m^3	0 m^3	300 m^3
12	0.1	3	200
14.8 (lithostatic)	10	100	800
AIR DRILLING			
Repository Pressure			
6 MPA	0.8	50	2000
10	10	200	3000
14.8 (lithostatic)	700	1200	2000

We reiterate that the EEG (1997) determined that the EPA criterion is exceeded in the range of 8 to 64 m^3—PA samples a range of spallings releases. Our analysis suggests that at lower waste permeabilities the EPA criterion is clearly exceeded; it may be exceeded even at low repository pressures.

Assuming air drilling at the higher capacity of 2700 scf/min we can easily drill out the failed volume of material, in most instances in less than one day; at the lower drilling capacity of 1800 scf/min, it would take a number of days to drill out the maximum amount of failed material at the higher repository pressures.

V SPALLINGS—PARTICLE TRANSPORT

An alternate method used to examine the magnitude of the spalling release is to examine the size of the particles that could be transported up the borehole by the release of gas from the repository. Both Sandia and EPA used this method of analysis; however, their results are markedly different.

EPA

EPA issued two supporting documents as part of its proposed certification ruling—Technical Support Documents, III-B-10 & 11: Spallings Evaluation (EPA, 1997a, EPA 1997b). These two documents analyze the particle size of material that might be carried by a gas release that followed the blowout described above. The analysis modeled the rate of gas flow from a WIPP room to a borehole after the mud was removed—step 2 in the mud blowout scenario discussed above. They explored waste permeabilities up to 500 md, and concluded that the maximum size of particles that could be transported by the flowing gas was generally less than 100 microns—less than 0.1 mm. In the extreme case, of a 2 foot drilling penetration into the repository and a waste permeability of 500 md, the maximum size particle that could be transported was 570 microns.

Based upon this analysis EPA agreed with the CCA calculations done by DOE that suggested the total spallings releases would be in the range sampled by PA—0.5 to 4 m^3 of waste material. This size release was shown in the CCA to be well within the certification limit.

SANDIA

Sandia did a similar analysis to that of EPA in which they attempted to examine the maximum size of particle that could be transported to the surface during a spalling event. Figure 4 is taken from SAND97-1369 (Figure 4-22). Figure 4 indicates that the maximum size particle that can be transported is approximately 30 mm (30,000 microns—3 cm).

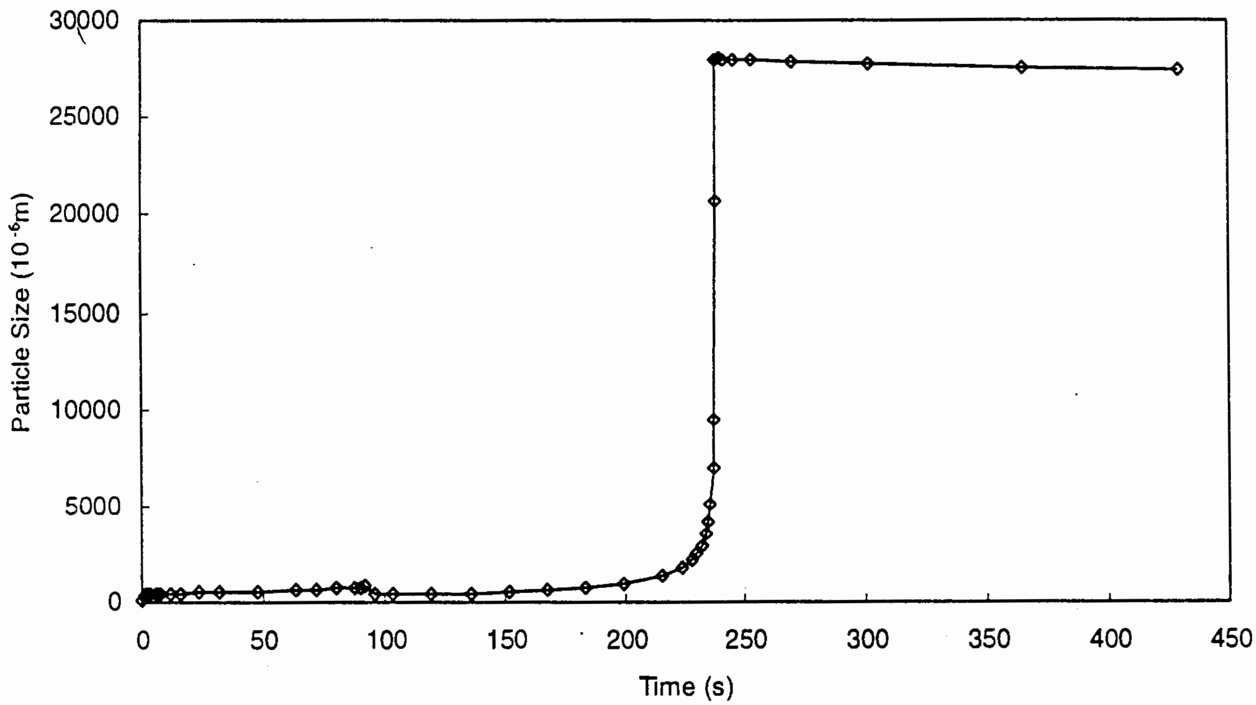

Figure 6. Maximum size of particles (diameter) expelled as a function of time (Figure 4-22, Hansen et al., 1997).

The discrepancy between the two models is marked; the results are approximately two orders of magnitude, or more, different. Clearly both models cannot be appropriate for this analysis. The two investigations by DOE and EPA are not coherent and contradict one another (EPA, 1997a, EPA, 1997b, Hansen et. al., 1997).

In both cases the models omit the process of the drilling and actions of the driller. They do not full describe the entire drilling process. These are critical omissions as we show above.

VI ENGINEERED BARRIERS

The problems of large releases occur almost entirely as a result of gas pressure in the repository coupled with low tensile strength of the waste. Engineering the waste can eliminate both of these factors.

1. Gas is created within WIPP as a result of hypothesized microbial degradation of cellulose waste. The magnesium oxide backfill was added to the waste to "get" the carbon dioxide created by cellulose degradation. The quantity of magnesium oxide proposed to be added is twice that needed to tie up the carbon dioxide. It is thought to be effective; it therefore "gets" carbon dioxide as a gas, and eliminates it as a problem.

2. The other major source of gas is the steel drums destined for WIPP. The drums are thought to undergo anoxic corrosion that will generate hydrogen. Hydrogen is expected to be the major gas to be encountered in the repository.

Hydrogen can be eliminated by getting rid of the steel drums. This is not a difficult engineering fix. It eliminates the other major problem associated with the drilling intrusion. It certainly increases the confidence in the safety of WIPP; as such it seems worth the cost.

DOE has not yet analyzed the effectiveness of waste form modifications in reducing spallings and clean out releases. The previous Engineered Alternative Cost/Benefit Study does not consider spallings or associated drilling intrusion releases. The burden is on DOE to investigate fully waste form modifications that may significantly improve the performance and safety of the repository. EEG (1997) also made an argument for waste form modifications. They showed that perhaps as much as 85 % of the volume of waste slated for WIPP will be repackaged. Eliminating the steel drums during this repackaging would be extremely beneficial.

Eliminating gas generation within WIPP eliminates many of the problems associated with a drilling intrusion. Carbon dioxide was eliminated by backfilling with magnesium oxide. Hydrogen can be eliminated by getting rid of the steel drums.

VII SUMMARY AND CONCLUSIONS

In the 14 months since DOE submitted its Certification Application to EPA there have been changes in how the phenomena associated with drilling intrusions are conceptualized. Although the Application was submitted, the analysis of WIPP has been a moving target. The changes in conceptualization are a result of 1) further analyses by DOE, especially as a result of questions raised by the Conceptual Model Peer Review Panel regarding spallings, 2) analyses by EPA as part of their evaluation of the Application, and 3) questions raised by concerned parties. These changes in the conceptual models are significant; the implications of the changes for the safety of the facility have not been fully examined. Among the changes in concept associated with a drilling intrusion are:

1. **A change in the conceptual model of spallings** that resulted from the review by the Conceptual Model Peer Review Panel (Wilson et al., 1997). A new model was generated that predicted the volume of material that failed around the borehole during a drilling intrusion (Hansen, et al., 1997).

2. **Experiments on surrogate waste** that show that the permeability is in the range of 10^{-14} to 10^{-15} m^2, much lower than the values in the range 10^{-13} m^2 used in Performance Assessment (PA) (Hansen et al., 1997).

3. **A recognition that drilling with air into WIPP is viable** (Bredehoeft, 1997). Drilling with air increases the release of waste from the repository significantly (EEG, 1997). Drilling with air has not been analyzed by either DOE or EPA in their evaluation of WIPP.

4. **Modeling of a drilling intrusion into waste with permeability in the range of 10^{-14} m^2, and lower, indicates a large volume of failed material around the borehole, even with mud in the hole..** This leads to a *"stuck pipe"* scenario under conditions different than those hypothesized by Berglund (1994), conditions that are currently used in the CCA. Stuck pipe now seems much more probable. Stuck pipe increases the volume of waste brought to the surface (Berglund, 1994).

5. **In the case of air drilling, modeling of the volume of failed material around the borehole during a drilling intrusion also indicates large volumes** (Bredehoeft, 1997). It too suggests that stuck pipe is much more probable than hypothesized by Berglund (1994).

6. **Both DOE and EPA have attempted to bound the size of spallings releases based upon the particle sizes that can be transported by the flow of gas up the borehole; these investigations are not coherent, contradict one another, and fail to model the complete process** (EPA, 1997a, EPA, 1997b, Hansen et. al., 1997).

7. **The new Mexico Environmental Evaluation Group (EEG) analyzed the significance of increases in spallings, and showed an increase of a factor of 16 times violates the EPA disposal standard** (EEG, 1997).

Several of the new hypotheses indicate large releases of waste are probable. These release are sufficiently large so as to violate the EPA disposal standard. This suggests a much higher probability of violating the disposal criteria than previously suggested by PA.

At lower permeabilities, with mud in the borehole, the volume of failed material associated with a drilling intrusion is large, as we showed above and as EEG (1997) indicated. This suggests that stuck pipe is more likely than the earlier analysis of Berglund (1994) indicates. Berglund (1994) ruled out stuck pipe until the waste permeability reached 10^{-16} m^2. The recent work by Hansen et al. (1997) suggests that stuck pipe is likely with waste permeabilities in the range of 10^{-14} m^2, and lower. Experiments on surrogate waste indicated a waste permeability of 4×10^{-15} m^2. Stuck pipe now seems like a much more probable scenario, and should be included in PA, even when drilling with mud.

The GASOUT model suggests a large volume of waste will fail in an air drilling penetration of WIPP. The failure would happen so rapidly that it will exceed the capacity of the drilling air circulation plus the repository gas flow to remove material. A "stuck pipe" seems likely. This suggests attempts on the part of the driller to clean out the hole. This further indicates that large volumes of repository material could be brought to the surface by the cleanout, and subsequent drilling through the repository with air.

Drilling with air is not a scenario that either DOE or EPA has analyzed as part of the CCA. Stuck pipe was ruled out based upon earlier models and higher assumed waste permeability. We conclude:

1. ***Stuck pipe is one of those scenarios that was previously eliminated from consideration in PA on the basis of assumed high waste permeability, but the recent analyses indicate it needs to be included in PA, both drilling with mud and/or air.***

2. ***Releases from air drilling into the repository should be included as one of the possible intrusion scenarios in the Performance Assessment of WIPP.***

ENGINEERED WASTE FORM

Serious consideration needs to be given to eliminating the steel drums from the repository. Many of the problem scenarios associated with a drilling intrusion occur because of high gas pressure in the repository. These can be ruled out by removing the steel drums from the waste. This would greatly increase the confidence in the safety of the repository. EEG (1997) suggested that 85 % of the waste destined for WIPP will be repackaged. Eliminating the steel drums as part of the repackaging would be most beneficial in eliminating the remaining major source of gas in WIPP.

3. ***Confidence in the safety of WIPP would be greatly increased by engineering the waste form so that steel drums were eliminated; this gets rid of the remaining source of high gas pressure.***

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