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SPALLINGS RELEASE

POSITION PAPER

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Abstract

The WIPP Compliance Certification Application contains predictions for releases of contaminants to the surface in the event that an exploratory borehole intercepts the repository horizon. A significant portion of these releases could result from spalling of waste material due to pressure gradients between the waste form and the drilled borehole. The predictions for volumetric releases presented in the Application represent a conservative bound of any releases which could occur due to spallings. This conclusion is based on the inherently conservative approach adopted for the spallings model. This paper evaluates the mechanisms represented by the spallings conceptual model and compares them to those expected to exist within the waste during an actual drilling event. Analysis of the spalling model, evaluation of the effects of cementation, and comparison to analogs show calculated spalling release to bound the potential event.

1. Introduction

1.1 Reasons for this Paper

In its recent review, the Conceptual Model Peer Review Panel (CMPRP) identified 12 specific areas of concern for the conceptual model of spallings during an inadvertent drilling intrusion into the WIPP waste region. As a result of these concerns, the CMPRP states in its supplementary report of December 1996 "*...that because of the many issues of a fundamental nature that are unresolved, it cannot acknowledge that this model does indeed provide a conservative method of calculating Spalling release*" (CMPRP; 1996a) and further that the Spallings model "*is not presently adequate for predicting the future states of the repository*". The mechanism defined by this model is a significant source of the total releases to the accessible environment presented in the WIPP Compliance Certification Application (CCA). As a result of these findings the Project has reevaluated the model. The basic conclusion of this reevaluation is that the spall model as used in the CCA does contain certain inappropriate representations of the physical processes. However the underlying concepts embodied in the models are correct, the mathematical functions used, while they may contain errors in detail, do include the relevant mechanisms and do functionally represent these appropriately. Finally the model as used in the CCA does include numerous conservatisms, and the volumes of release calculated by it do represent an upper bound of expected actual releases.

1.2 Approach Used

This paper details the results of this reevaluation, and specifically addresses both the model, and the inherent conservatism. Thus the paper is intended to provide

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the information needed to enable the CMPRP to reach the conclusion that while the existing model has some technical shortcomings, the basic premises underlying it are valid, it has validity for extrapolating to varied conditions, and its predictions for the WIPP problem are conservative (that is, they overstate the potential release within the range of possible conditions). In presenting these arguments, attention is given to the waste strength and characteristics, to the spallings model, and to comparable analogs.

While it is accepted that the simple, equilibrium model presented in the CCA does not capture the complex, dynamic response which would occur during a drilling intrusion, as will be shown in this paper the model is appropriate to determine the end-state of the process, and the quantitative predictions of the model results do bound the releases. This will be shown first through a description of the probably state of the waste, through a comparison of the model releases to analog studies, and, finally through a reevaluation of the actual model itself.

In bounding the end-state, the model used in the CCA is based on a different approach than a mechanistic tracking of the production of solids. Thus the model assumes that the volume of material transported to the surface can be quantified by determining an equilibrium end-state beyond which further removal and transport of material would not occur. This equilibrium end-state depends fundamentally upon the characteristics of the waste material. The first step in the reevaluation process was to capture the probable states and, hence, material characteristics of the waste. In parallel with the investigation of material characteristics a comprehensive search for analogous settings was conducted. Finally, the conceptual model for spallings was examined to determine if the model had been adequately presented to the CMPRP. As a result of these three activities, additional information has been derived and will be presented in this paper. The most significant findings are:

1) repository conditions necessary to produce a spalling event also dictate a cemented waste form;

2) analogous situations support the quantitative predictions of the spallings model;

3) the mathematical formulation of the model is appropriate for the cemented waste.

Each of these will be supported in the text of the paper. These considerations, taken together, support the conclusion that spallings release, as presented in the CCA, represents an upper bound on any volumetric release which could occur due to a drilling intrusion.

The remainder of this position paper is organized in the following manner. In Section 2 probable future states of the repository and the resultant character of the waste are evaluated, and are addressed in the context of the model application. Analogs and comparative analyses are presented in Section 3. In Section 4 the conceptual model for spallings is discussed and evaluated with regard to the essential assumptions of the model, and in light of the material characteristics and analogs

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presented in the preceding sections. This section also present an analysis of the mathematical formulation of the model, assessment of the model via the experimental program, and a quantitative evaluation of the mechanisms identified by the model. Section 5.0 addresses the various concerns raised by the CMPRP in their supplemental report, and gives the Project responses to those concerns. The conclusions of the paper are summarized in Section 6.

2.0 Material Characterization

This section addresses two basic issues integral to evaluation of the conceptual model for spalling release: 1) the expected characteristics of the waste, and 2) the state of the waste panel. These issues provide bases for conservatism reflected by the conceptual model. When possible, each characteristic is related to the CUTTINGS_S model.

Considerations of the future state of the repository panel at the time of an inadvertent intrusion event includes stratigraphy, compacted waste material, and boundary conditions. Some contributing phenomena are well constrained, such as creep of the surrounding rock salt and initial conditions of the waste. Other characteristics of the setting, such as the form of the degraded waste and existing pressures, exhibit a range of properties. However, physics of the interactions between a borehole and a pressurized waste panel can be bracketed by reasonable extrapolations of known site conditions coupled with ranges of predicted conditions.

Blowout of solids from a subterranean gas-pressurized environment necessitates failure of the material. Failure initiates due to a sudden reduction of pressure at the borehole/material boundary, subsequent material breakup, and transport to the wellbore and out to the surface. Failure of material may occur in several ways.

- It may be ubiquitous near the wellbore manifesting as cracks parallel to the material surface.
- It may be general breakdown of the material to granular substance related to pore-pressure-induced liquefaction.
- It may be general shear failure related to the sudden change in stress at the borehole wall.
- It may involve erosion of granular material surfaces due to gas velocity.

Each of the mechanisms for comminution of materials involves strength of the material.

The current conceptual model for spallings release invokes several assumptions, some of which apply to the material characterization. As modeled, the waste form is assumed to be uniformly grained, silica spheres. A particle size ranging between 40 μm and 0.2 m was sampled in the CCA calculations. The mechanism for particle transport is gas-driven channel flow. Cementation strength is held constant at 1 psi. These two fundamental characteristics, particle size and cementation, are examined here.

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2.1 Uniform Particle Size.

As discussed later in this section, complete degradation of the waste to a uniform particle size is unlikely; rather, a heterogeneous conglomerate is expected. Calculations summarized in Figure 2-1 (Figure 4-9 of Lenke et al.,1996) show that theoretical releases exceed 10 m^3 when uniform particle size is less than 100 μm and the cementation strength is concurrently zero. The assumption of a uniform, granular waste medium is conservative because the probable state of the degraded material would include a range of large blocky residuals and fibrous materials. Such mass could not be transported readily and would tend to clog and restrict any existing channels. Moreover, the conditions in the repository preclude the end state of the waste being a fine grained, uncemented material, so that the assumption of uniform, fine grained sand is considered a very conservative analog by comparison to expected waste conditions. Extraordinarily conservative (and unrealistic) assumptions of uniform, fine-grained, noncohesive waste material embodied in the spallings model are the only conditions that produce a release of any significance to the CCDF.

2.2 Waste/Cement Characterization

The conceptual model includes a 1 psi cementation strength. As shown in Figure 4-9 (op cit), a cementation strength of 1 psi reduces releases to inconsequential levels over the entire range of particle sizes. It is noted that evaluation of cementation strength was not part of model development. Educated speculation regarding cementation strength is therefore important to determination of the conceptual model's conservatism. Gas generation necessary to produce conditions for a potential blowout has a prerequisite of brine introduction. Conceivably, gas is generated by corrosion and possible microbial action. Corrosion utilizes H_2O and precipitates NaCl salt and other dissolved species--such as KCl, $MgCl_2$ and, possibly, Mg-based hydroxides. If no brine is available, the waste remains unaltered; no gas is generated, and no cementation occurs. If gas is generated, brine must be available and cementation follows as a natural consequence. Creation of gas pressure sufficient to remove drilling mud in the drill string would require extensive chemical reaction of the waste with large volumes of brine. The bottom line is that when corrosion consumes brine, cement is precipitated.

Availability of brine in the waste panel can be categorized as follows:

Dry. Without brine, waste is compressed and void space is reduced. Nominally, the original waste form is 85% voids and creep closure eventually reduces the porosity to between 10 and 15%. Pressures would remain nominal, incapable of moving drilling mud up the annulus. Gas generation requires waste degradation through reaction with brine or microbial action in the presence of brine. Bredehoeft and Hall (1996) suggest that CO_2 gas generation caused by microbial degradation is completely mitigated by the addition of MgO, and can "now be safely neglected in analyzing repository

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performance". In a dry condition, gas would not be produced and a blowout possibility is moot.

Undisturbed but wet. If the waste panel receives seeping brine from the Salado, CCA results (Figure 2.1) show that 50% or more of the iron waste remains undegraded. That means that 50% or more of the initial steel remains as rusty pieces of irregular shape and size. As corrosion proceeds, water is consumed and salt ions are precipitated. Degradation of iron (Fe), for example, proceeds as follows: $Fe + H_2O >> Fe(OH)_2 + H_2$. Gas pressure buildup is predicted to exceed hydrostatic in approximately half of the calculated realizations. Therefore, the waste would be partially degraded, comprising irregular shapes with grain boundary cementation. This condition may be "worse" than the inundated condition as it gives rise to possibly large pressures while precipitating less cement than more complete degradation, although the larger and nonuniform waste particles would reduce releases.

Inundated. The waste panel could be inundated if a borehole (termed the E1 intrusion) is drilled into an underlying brine reservoir. Immersed waste would degrade most completely, would generate the greatest amount of gas and would precipitate the greatest amount of cementation. CCA calculations show approximately 15% of the original waste will remain undegraded. In this scenario, essentially unlimited volumes of brine and very effective corrosion are assumed. The chemistry and amount of precipitate can be estimated, as discussed below.

Brine in the Salado contains about 32 kg/m^3 of dissolved solids. Each cubic meter of corroded iron waste precipitates a mass of 6.2, 11.6 and 14.2 kg of KCl, NaCl and $MgCl_2$, respectively. The precipitate from degradation reactions is sufficient to fill about 15% of the available void space (estimated to be 10-15%) within the waste. It is the precipitate that produces cementation strength. An exact mockup of degraded waste material cannot be prepared; however, a conservative analog using playground sand has been evaluated. Evaporating less than one pore volume of Salado brine in playground sand (which has a void space of 33%) produces a surrogate material of considerable strength, as discussed below in a section called Strength Tests. The precipitate of evaporation would be similar to that left behind by degraded waste. The sand void space is much larger than that of the compacted waste, so the cemented strength of the sand would be less than produced by more complete in filling . The sand analog represents a lower strength than would be developed by precipitate in degraded waste because it fills a much smaller fraction of the void space.

2.3 Strength Tests

2.3.1 Background Information

Because of the importance of spallings release to the CCDF, an evaluation of precipitate strength can be of significant quantitative value. Several documents (see references) speculating on waste strength have been produced. These references interpret and discuss cement strength of degraded WIPP waste based primarily on

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anticipated strength of the precipitated NaCl cement. A tensile strength for intact salt in the range of 1.12 to 2.62 MPa is well established from tests on ten different natural salts (Hansen et al., 1984). Finley (1996) presents information regarding tensile strength of uncharacterized waste materials coated with precipitated salt. He estimates tensile strength of salt at approximately 2 MPa. Butcher (1996) discusses why an assumed strength of 1 psi (0.007 MPa) conservatively represents waste tensile strength. Powers (1996) lists several natural analogs such as saline playas and the WIPP excavated spoil pile and qualitatively notes the rapid and significant attainment of strength of saline geomaterials subjected to wetting and drying. Soil strength data for weak sediments summarized by Berglund et al. (1996) range from about 3 to 8 psi. Berglund et al. conservatively estimate strength of salt precipitate (between 2 and 20 psi) and point out that introduction of MgO into the waste panel could increase cement strength. Bredehoeft and Hall (1996) provide insight to precipitate reactions. They conclude with an engineering approximation that 1% of the porosity will be filled with salts. Bredehoeft and Hall note that when a low Salado permeability is used in calculations and MgO is added to the waste, "...a drilling intrusion into the repository will encounter a dry repository, with low gas pressure..." obviating the possibility of a spallings release.

2.3.2. Strength test results

Physical and mechanical characteristics of the waste are likely to govern any potential for solid release in the event of borehole intrusion. The current spallings model uses a conservative cementation strength of 1 psi. As a consequence, the spallings model captures material response that predicts larger volumes of eroded material than would a model based on more cohesive material. This section reports results of simple mechanical testing performed to evaluate basic cohesive strength of precipitate.

A comprehensive material model for future states of waste has not been developed. Because degraded waste material characterization is uncertain, the existing spallings model used a surrogate material--cemented sand--to establish a bounding response of the intruded waste panel. As discussed above, it is recognized that degradation of waste necessitates precipitation of solids. Therefore, it is of value to the deliberation of the spallings model to establish a baseline of actual strength measurements of the precipitated cement. To demonstrate "strength" of the waste, a very simple analog was prepared. These results are only intended to illustrate the relationship possible between strength and cement precipitate

Mixtures of ordinary playground silica sand and WIPP brine were used. The sand was saturated with the brine and dried. The precipitate from one pore volume is therefore responsible for any cementation strength. This analog should establish a relatively "low end" strength, because significant waste degradation would involve influx of much more brine than used for the experiments. Presumably, more complete infilling of pore space with cement would create greater strength than that measured here.

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Test results are summarized in Table 2.1. Indirect tensile strength was selected for these tests owing to limited time available for sample fabrication. Nonetheless, cohesiveness expressed as a tensile strength is expected to be a primary factor in determining the volume of material discharged. Samples were mixed with WIPP brine, salt-saturated WIPP brine and WIPP brine with MgO added. One pore volume of WIPP brine (1 PVWB) gave rise to an average indirect tensile strength of 49 psi (0.34 Mpa). When the WIPP brine was saturated with additional NaCl (1 PVWB+), the strength increased to an average of 86 psi (0.59 Mpa). Addition of MgO (1 PVWBMgO) to the WIPP brine increased the average strength to 114 psi (0.79 Mpa). One crude compression test (1 PVWB) was conducted, yielding an unconfined compressive strength of 130 psi (0.9 Mpa). Strengths thus determined illustrate that the waste surrogate using cohesionless sand is conservative. With only a small fraction of the pore space containing cement, very significant cohesion is obtained.

Table 2.1. Indirect Tensile Strength of Precipitate-Cemented Sand

SAMPLE ID	Thickness (in)	Diameter (in)	Load (lb)	Tensile Strength (psi)
1 PVWB (a)	0.771	1.695	92	45
1 PVWB (b)	0.816	1.621	95	46
1 PVWB (c)	0.786	1.775	125	57
			Average	**49**
1 PVWB+ (a)	0.766	1.738	195	93
1 PVWB+ (b)	0.775	1.680	148	72
1 PVWB+ (c)	0.868	1.751	221	93
			Average	**86**
1 PVWBMgO (a)	0.592	1.730	177	110
1 PVWBMgO (b)	0.538	1.725	165	113
1 PVWBMgO (c)	0.555	1.710	179	120
			Average	**114**

A similar specimen was produced by NMERI. They added ordinary salt brine and 30% MgO to Ottawa silica sand and compressed a billet of the material. That product was extremely well indurated, although its strength was not measured.

Test sample preparation includes a tacit, but reasonable, assumption that the precipitate derived from evaporation is analogous to precipitate derived from chemical reactions. For example, drying by elevating the temperature of the sample could make feasible otherwise kinetically inhibited species. However, the formation of sorel cement components (e.g., brucite and magnesium oxychloride) have been observed in the laboratory under WIPP-relevant conditions. Brucite and magnesium oxychloride are thermodynamically stable phases under WIPP conditions. Thus, there is no significant

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chance of a kinetically inhibited species having formed at the elevated temperatures used to evaporate water out of the simple experiments being responsible for the observed strength.

It is acknowledged that sample preparation creates some uncertainty in the strength results. If in a more extensive examination accelerated evaporation effects result in stronger material then chemically driven cement precipitation, they are probably balanced by other characteristics of degraded waste. Notably, degraded waste would likely comprise encrustated masses and particulates. The amount of brine deposited in natural decomposition of the waste is likely to be far larger than one pore volume used for the sand analogs. More brine consumed results in more volume of precipitate, and presumably greater bonding between particles.

2.3.3 Concluding Remarks

Techniques used to prepare strength test samples must be examined for adequacy. At the moment, it is assumed that degradation of waste, such as rusting, would deposit dissolved salts at the location and on the particles of material resulting from degradation. Local deposition is commonly observed in salt mines or saline playas where foreign materials are rusted and encrusted simultaneously. It is our belief that the precipitate would be deposited in place as degradation proceeds.

Cohesionless sand experiments were used to bound possible spallings release (Lenke et al., 1996). A sand analog was expected to maximize solids release, among the possible material responses. Recognizing the overly conservative nature of the spallings experiments, the model incorporated a value of 1 psi for waste cementation strength, although the experiments did **not** investigate cementation effects. This section has summarized why the assumption of 1 psi cementation strength is a reasonable, yet conservative, accounting for strength of the waste.

3.0 Analog Comparisons

This section explores analogous industrial experiences and relates the experiences to the spallings model application. In some cases, both phenomenology and alternative models are incorporated in the industrial application, providing a relatively complete analog for an inadvertent intrusion into a WIPP panel. Other analogs compare the physical relationships of the spallings model to similar applications. Alternative approaches are also developed. These analog comparisons and alternative approaches to the spallings phenomenon point to the conclusion that the predictions of spallings in the CCDF capture the physics of the situation sufficiently to model bounding situation, that case studies can be used to show predictions of the spallings model agree with the closest available analogs, and that other models are available to describe the complete spallings phenomena.

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3.1 Coalbed Methane Analog

Inadvertent human intrusion into a WIPP waste panel can be analogous to penetration of a coalbed for methane production. The information summarized here is derived from a GRI report (Khodaverdian et al., 1996). Depths of coal beds are comparable to the WIPP (2150 ft). Material comprising coal beds is a reasonable analog for waste products after compression, degradation and cementation. Specifically, certain coals are characterized by a low cohesion, and tensile strength is low in highly cleated coals. Laboratory experience has also substantiated an increased tendency for production of coal particles as the water saturation in the cleat systems becomes higher. The implication is that capillary pressure contributes to maintaining material integrity. This is analogous to the capillary effects postulated by Lenke et al. (1996). Coal is known to have preferred fracture planes (cleat directions) that simulate conditions expected of the WIPP waste, owing to its emplacement scheme.

Field experience is modeled using finite elements, assigning physical and mechanical properties to the coal seam and using an empirically based failure criterion. Wellbore penetration into the coal seam initiates tensile failure, creating a cavity and enhanced permeability in plastic zones of the seam. Tensile stresses, and hence failure of material in the proximity of the wellbore, are principally caused by the pore pressure gradient as fluid flows toward the wellbore. The cavity itself has a limited radius averaging 1.5 ft after initial drilling, similar to the limited cavity exhibited by the Lenke, et al. (1996) laboratory tests.

In many cases, production of coal fines/cleated blocks is only initiated by surging the wellbore, thereby rapidly reducing surface pressure to create the inward gradient. This is usually coupled with injection periods above hydrostatic pressure. Even with low cohesion, cavity size usually stabilizes at an equilibrium level. Extensile fractures created during blowouts do not always communicate directly with the wellbore. Inwardly directed seepage forces cause circumferential fractures similar to layers in a an onion. This phenomenon is also reported in sand production situations (Kooijmen, et al., 1996). Direct communication to the wellbore is through other preexisting cleat systems. Using this analogy, the spallings model assumption of multiple fractures communicating with the wellbore could be a conservative representation.

Numerical /analytical models have been used to simulate surging a coalbed methane well. Polyaxial, i.e. laboratory, experiments have also been performed. The surging model used in methane production assumes that pressure reduction in the wellbore is instantaneous. A material failure criterion is needed to determine the cavity size, the size of the plastic zone, and a stress dependent permeability. Measured cohesion values range between 5 and 15 psi and assume that failure is controlled by cleat shear properties. Calculations match the cavity radii observed in the field. Sensitivity studies completed in the GRI investigations show that lower permeability increases the volume of the cavity because it creates a larger near-wellbore pressure gradient during surging resulting in increased tensile failure (stress conditions more

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favorable for failure). In sensitivity analyses, the cohesion is the single most critical material parameter for predictions of the cavity size and size of the permeability enhanced zone.

A quantitative comparison of the coal seam blowout to a WIPP waste panel was conducted. Well I#2 in the San Juan basin (Khodaverian, et. al., 1996) was used for this comparison. Conditions and geometry of the coal seam were as follows:

Pore pressure	=	1500 psi (10 MPa)
Drilled radius	=	0.5 ft (.15m)
Coal seam interval	=	45 ft (14m)
Initial blowout radius	=	1.5 ft (.46m)

The WIPP panel was assumed to have a height of 2m, and was assumed to experience the same initial blowout radius. Although the pore pressure in Well I#2 is lower than the maximum predicted for WIPP (15 MPa), the calculation is considered valid due to neglect of the confining effects of a thinner layer (2m as compared to 14m for Well I#2). The calculated volume of material released for the WIPP panel was approximately $1m^3$, and falls well within range of the CCA calculations of $0\text{-}4m^3$.

The existing coalbed model, funded by GRI and tested in the laboratory and the field, is a model of the type more likely accepted by the geotechnical community because variants have been successfully used in several applications. At the time of this writing, it has not been possible to fully specialize this model to the WIPP conditions; however, estimates do show reasonable agreement with WIPP calculations. An important observation here is that the coal model is quite sensitive to cohesion and that any finite values of cohesion quickly restrict cavity size (and material ejected). Furthermore, high pressure gradients must be established, maintained, and even repeated (by "surging") to produce large cavities. Even then, cavity size appears to be self-limiting, as observed in the WIPP laboratory experiments on sand.

3.2 Air Drilling Analogs

Air drilling is commonly used in the oil and gas industry, to penetrate relatively dry formations with high modulus. As the circulating fluid, air performs all of the traditional functions of drilling mud, particularly hole cleaning. Significant effort has been expended by the oil and gas industry to determine the circulating conditions which optimize removal of cuttings from a wellbore (Angel, 1957; Machado and Ikoku, 1982; Tian and Adewumi, 1991). Forecasting air drilling requirements necessitates representation of flow mechanics down the drill pipe, determination of pressure losses through bit nozzles and transport of solids-laden cuttings up the annulus to the surface.

The latter (cuttings transport) is very similar to the flow mechanisms encountered when intruded waste enters the wellbore annular cavity. The simulations presented are similar to those of Lenke et al. (1996) in that annular pipe flow relationships are shown and the bases of the analyses are implementation of the fundamental continuity and

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momentum equations. Important differences lie in the fact that Lenke et al. do not explicitly include the presence of the solid particulate. While volumetric concentrations less than four or five percent solids may not dramatically cause additional pressure drops (due to gravitational effects and hindered motion caused by particle interaction), higher, transiently-occurring concentrations may provide significant frictional effects and could inhibit transport of solids to the surface. Further, including particulate matter incorporates additional drag forces. At low concentrations, these may be small. Nevertheless, omission of particulate concentation would seem to be an additional level of conservatism in the model.

Terminal velocity and choking of the annulus are not explicitly addressed. This suggests that the low end production rates (shown in Table 1 of Berglund, 1994), may or may not be adequate to carry the solids out of the hole. At the other end of the spectrum, for the very high permeabilities shown in Table 1, frictional flow in the annulus may be so high that these rates cannot be achieved. In terms of the frictional pressure losses, first order calculations (Katz et al., 1959) suggest flow is limited by the annular dimensions. The physics involved in this analog is currently being examined. Indications are that higher flow rates won't occur because transport in the annulus is tubing limited.

This analog situation is further complicated if some fluid is present. Water, in the form of droplets, will also impede transport to the surface. For the small in-situ saturations, this may not be a major issue.

3.3 Proppant Backflow Analog

During hydraulic fracturing for reservoir stimulation, proppant is injected to maintain long-term conductivity in the created hydraulic fracturing. The proppant commonly used is 20/40 Ottawa sand. A significant problem in hydraulic fracturing is proppant being flowed back into the wellbore when production is started.

Asgian et al., 1994, performed discrete element numerical modeling of particles in a fracture and indicated that particle movement in an hydraulic fracture packed with spherical 20/40 proppant was inhibited if the number of particle layers was less than approximately five and if the pressure gradient in the fracture exceeds approximately 150 psi/ft (more if there are fewer layers). At the WIPP site, detailed modeling would likely show that high fracture conductivities and annular flow choking would preclude these large gradients except very near the wellbore and/or at relatively large times (long enough for a well to be brought under control). Modern surface equipment (rotating blowout preventers) and properly designed wellhead equipment (Curry, et al., 1996) can handle pressure pulses of this magnitude.

3.4 Rock Mechanics Approach

Rather than the voids balance model used in spallings calculations, it is recognized that the blowout spallings is one of time-dependent material failure starting

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at the borehole boundary. The repository would be treated in a cylindrical plane strain geometry and assigned initial values of permeability, density, porosity, stresses, and gas (pore) pressure. Then the drill penetration would be treated as a sudden change in radial stress and fluid pressure at the borehole boundary. After that, the subsequent problem solution would vary with the exact material model chosen and the level of accuracy and detail desired in the solution. Probably the simplest solution would be to assume a Mohr-Coulomb material and a rapid (instantaneous) change in boundary conditions. Then a depth of penetration of shear failure into the material could be calculated based on an effective stress assumption and failed material could be deemed candidate for removal up the hole if the pressure gradient and flow velocity were insufficient. Almost any amount of detail could be added to this approach. For example, the actual time-dependent change in pore pressure as a function of distance into the material could be calculated. This would require a much more difficult coupled calculation of failure. Additionally, a more sophisticated porous compacting soil material model could be used to describe material response. Other variations are possible as well. Inherent to all models of this type are the concept of a changing pore pressure (in time and space) and some type of resulting failure surface progressing into the material and finally arresting. The actual failure would likely have discontinuous aspects (some type of fingering or shell-like behavior) but it would be assumed that the continuum approach correctly averaged this.

As an example of a simple approach of this type, take the case of plane strain shear failure in a medium with cylindrical symmetry about the borehole. The mean shear stress, σ, in the horizontal plane can be shown (Jaeger and Cook, 1976) to be

$$\sigma = \frac{a^2}{r^2}\left(P_w - P_o\right) \qquad 3.1$$

where a is the wellbore radius, r is a radial position in the medium, P_w is the pressure in the well, and P_o is the far-field pressure, or stress. In the undrained (instantaneous) state, P_w is the mud pressure at time of penetration and P_o is the far field effective stress, or the mean horizontal in-situ stress (approximately equal to the total overburden stress) less the initial repository gas pressure. Then, for an effective confining stress, a material strength could be found based on a Mohr-Coulomb assumption and, for example, the table values in Section 2 of this report. This would allow the calculation of a radius of potential initial failure. The subsequent process, however, is time-dependent and self limiting. That is, as repository drainage actually occurs (assuming an initially higher repository than wellbore pressure), both the wellbore pressure and the far field effective stress would tend to increase. The effective stress throughout the repository would also increase as more and more of the load was borne by the skeleton of solid waste material. This would lead to an increase in Mohr-Coulomb strength for any finite value of material fiction. Also, in the case where initial repository pressure is high, effective stress would likely increase more rapidly than wellbore pressure (assuming that mud and gas are flowing up the hole), thus shear stress as defined by the equation would be reduced. Coupled with a

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wellbore pipe transport equation, as in the current model, this approach could be used to calculate material removal.

This approach is valid, and is intuitively attractive since it approaches the problem from a consideration of the physical mechanisms which lead to the spall release. It is the basic approach used in the coalbed methane analog discussed in Section 3.1. However it does suffer from difficulties in implementation due to the unknown, and probably highly variable, detailed condition of the waste in the future, as well as the difficulties inherent in modeling the transient, coupled phenomena associated with penetration by a drillbit. The use by the CCA model of the calculation of an end-state equilibrium void volume was in part driven by difficulties in the mechanistic approach.

Attempts have been made to estimate the likely results of calculations using this mechanistic approach, incorporating various simplifying assumptions to make the problem tractable in the available time. The results indicate that the bounding volumes likely to be calculated will probably be much less than those estimated from the CCA model; however the assumptions needed to make the method tractable also make the results highly uncertain.

3.5 Sediment Erosion Analogy

The field of sediment transport engages many of the same mechanisms as those proposed by Lenke, et al. (1996) to conceptualize the spallings process. Sediment transport in marine systems is governed by the fluid shear velocity, sediment strength and roughness, and average particle size (Stanley and Swift, 1976). Within these aqueous systems, a horizontal sediment bed experiences erosion when upward-directly components of turbulent eddies exceeds the tendency of suspended particles to settle. The establishment of a "suspension criterion" was proposed by Bagnold in 1966, and has formed the basis for numerous theoretical (Glenn and Grant, 1987) and field (Kineke and Sternberg; 1989) studies in the ensuing years. The general form of the criterion is as follows:

$$\frac{\tau}{(\rho_s - \rho) g D} > C \frac{\omega_s^2}{g D} \qquad 3.2$$

where ω_s is the sediment settling velocity, D is particle diameter, g is the gravitational constant, ρ_s and ρ are the sediment and fluid densities, respectively, C is a proportionality constant, and τ is the shear stress. The value of C generally ranges between 0.1 and 0.4 (Stanley and Swift, 1976).The shear stress can be expressed in terms of a shear velocity, U*:

$$\tau = \rho U^{*2} \qquad 3.3$$

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The shear velocity is normally related to the bulk velocity through the introduction of a friction factor, c_f, which directly relates the shear stress to the fluid velocity, U_b:

$$\tau = c_f \rho U_b^2 \qquad 3.4$$

These equations define a relationship between sediment settling velocity, ω_s and the fluid velocity, U_b, as follows:

$$\text{if} \qquad C' U_b^2 > \omega_s^2 \qquad 3.5$$

then erosion will occur. Where C' includes the constants and density terms. It should be noted that this relationship is completely analogous to that posed by Lenke et al, whereby

$$\text{if} \qquad v_f^2 > \omega_s^2 \qquad 3.6$$

where v_f is the velocity in factures, then material is assumed to erode within channels leading to the intrusion borehole.

This analogy shows that the functional form used in the spallings model is consistent with that used in other fields. The form of the equation has been validated in the field of sediment transport, as long as it is possible to define an appropriate shear stress criterion. This aspect of the analogy is discussed in Section 4.3.

3.6 Concluding Remarks

The analogs investigated as part of this reevaluation provide direct comparisons to the spallings release. Where quantitative data are available, most notably in the coal bed methane examples, they indicate that the quantities of release calculated in the CCA are probably larger than may be expected in actuality. Where this quantitative information is not available, for example in air drilling and hydraulic fracture proppant flow back, they indicate that the phenomenology included in the CCA model is appropriate and probably conservative.

The analysis of other approaches, including those based on sediment erosion and rock mechanics, have also helped to support the CCA model. In particular the sediment erosion approach has shown that the functional form of the cementation terms is appropriate, and the magnitude probably conservative. The rock mechanics approach is complex, but indicates that the volumes calculated by the CCA model are probably conservative.

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4.0 Conceptual Model for Spallings

The volume of disposed waste released to the surface during drilling of a borehole through a disposal room consists of the sum of three effects: material eroded by the drill bit (cuttings), material sheared by the drill fluid (cavings), and material expelled by erosional forces induced by the pressure gradient existing between the disposal room and borehole (spallings). The present discussion focuses on releases due to spallings, although some reference will be made to the other two components. A detailed description of these processes and the model developed to quantify releases associated with the processes are found in the CCA. The following paragraphs provide a brief summary of the spallings process in the context of the bounding model used in the CCA, and discuss technical issues supporting the DOE's position that calculations presented in the CCA provide a conservative estimate of the probable releases due to a drilling event.

4.1 Process Description

Three mechanisms are necessary to transport contaminants to the surface: the waste material must first be removed from the mass, then transported to the intrusion borehole, and must finally be lifted from the repository horizon to the surface. The first process can be further subdivided into a transient mechanism caused by seepage forces, and erosion of material due to continued gas flow through blowout-induced fractures within the remaining waste region. These processes are illustrated in Figure 4.1. A complete characterization of processes leading to transport of waste material to the intrusion borehole would require knowledge of properties of the intact waste and of the failed region, as well as an estimation of the geometry of the failed region (Figure 4.2).

Uncertainties associated with the intrusion event were assumed to be captured by bounding conceptual model for spallings was developed for the CCA. This model assumed that the volume of material transported to the surface could be quantified through identification of an equilibrium state, which permits a conservative estimate of releases to the surface. This equilibrium state is assumed to be controlled by the second transport mechanism, i.e., the erosion and transport of material from the repository horizon to the surface following the initial, transient blowout. A conceptualization of the bounding model is presented in Figure 4.3.

The model used in the CCA thus assumed that the volume of material transported to the surface could be quantified by determining an equilibrium end-state at which further removal and transport of material would not occur. The process of removal of material was therefore assumed to be self-limiting (a result which is confirmed by the experiments), and the end-state was assumed to be controlled by the ability of the flowing gas to erode material from fracture surfaces within the waste. Conceptually the model determines the equilibrium void volume rather than explicitly computing the volumes of material released. For this model, quantification of the

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material generated during the early, transient stages of the blowout is not needed. Similarly, a consideration of the details of the transient mechanisms is not necessary .

The end-state equilibrium void volume calculation proceeded as follows:

- The mass flux of gas up the wellbore is calculated using a conventional pipe flow equation, and assuming that the entry pressure at the bottom of the wellbore is constant, and equal to the initial gas pressure in the repository.

- This flux (written as a volume flow rate at constant pressure) is used to calculate the average velocity in the waste *(V)*.

- The average velocity in fractures (v_f) is derived from the fracture porosity (ϕ_f) and the average velocity in the waste:

$$v_f = \frac{V}{\varphi_f} \qquad 4.1$$

  The use of this relationship does not account for the width of the fractures, thus the same velocity is assumed for multiple thin fractures or for a single wide fracture. In effect, this model assumes that no boundary layer exists, and that the velocity in a fracture is constant across the width, an assumption that will tend to overestimate the wall erosion velocity, and thus be conservative.

- Initially it is assumed that the fractures will be narrow, the fracture porosity low and the velocity of gas flow in the fractures high. Under these conditions the waste will be eroded and the fractures will become wider. Eventually a condition will be reached when the fractures are wide enough, the fracture porosity is high enough, and the fracture flow velocity low enough that erosion will cease. At that time the void in the waste will be at an end-state. It is assumed that this limiting condition can be represented by a critical fracture velocity, v_e, and that this velocity is some function of the resistance to erosion.

- The resistance to erosion is assumed to depend on three factors: the gravitational resistance of particles to being "lofted" by gas, resistance to removal due to capillary forces in a partially saturated medium, and resistance to removal due to cementing of the waste particles.

- The end-state equilibrium void volume is then used to calculate the quantity of material which must be removed to achieve that void volume. This is the volume of material calculated to be released.

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4.2 Model Assumptions

This section provides an analysis of the principal model assumptions, and compares these assumptions to experimental results (Lenke, et. al., 1996).

4.2.1 Assumption 1

The essential premise of the conceptual model for spallings is that establishment of the equilibrium state of the waste region also establishes the maximum volume released. Inherent in this approach is an assumption that the equilibrium state can be adequately defined. The conceptual model assumes that the system will achieve equilibrium when the gas flow velocity drops below a critical value. This assumption does not imply that no material will be evacuated from the waste region during the transient blowout. Rather, it assumes that the transient response is captured by the end state of the disturbed waste region.

The validity of this assumption was evaluated by an experimental program conducted by Lenke, et al. (1996). The volume of material released for all particle sizes, at all pressures, and for all test borehole sizes was self-limiting. This suggests that an equilibrium state will be reached during a blowout event and produces qualitative agreement with the essential premise of the spallings model.

4.2.2 Assumption 2

Gas flow through fractures will be much greater than flow through the porous matrix. This assumption permits two significant simplifications to the model. The first is that seepage forces no longer impact the intact matrix, at or near the end state, therefore formation damage due to high pressure gradients will be limited to the initial transient period. The second is that flow through the porous matrix can be neglected.

Castings of the blowout regions in Lenke et.al.'s experiments demonstrated that the void shape ranged from tubular channels to thin shells or lenses. The precise shape of the void volume varied considerably with particle size, but, in general, it can be stated that material was removed from channels. In view of this result, it can be reasonably postulated that gas flow does, indeed, occur primarily in the fractures, since these regions will have considerable less resistance to flow than the intact matrix.

4.2.3 Assumption 3

Gas flow velocity is governed by equations for isothermal flow of gas in a duct with friction with constant pressure boundary conditions.

Spreadsheet calculations conducted during model reevaluationhave shown that the borehole Mach number for the test apparatus ranged from 0.1 to 0.13. Therefore, this assumption is valid for flow through the test borehole. Similar calculations show that

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for the flow in the fractured zone to become transonic the flow must be restricted to a few narrow channels on the order of 100 μm in diameter. It is acknowledged that this transonic flow could exist over a narrow temporal and spatial regime immediately following drilling intrusion. However, any effects due to the resultant shock waves should be captured within the initial transient period and would not affect the bounding volume.

4.2.4 Assumption 4.

The critical value of the erosion velocity, below which no material is eroded, can be mathematically related to the gas velocity required to suspend a particle of known diameter. This assumption directly supports Assumption 1, since it is this term which establishes the end state of the waste.

Experimental results show a clear correlation between particle size and volumetric releases. Volumetric releases also increased as the borehole pressure increased, implying that the fracture porosity necessary to achieve equilibrium is dependent upon the pressure, and, hence, velocity of the gas. As noted in Section 3.5, the process of relating a critical shear stress to particle lofting has been successfully implemented in the field of aqueous sediment transport.

4.2.5 Assumption 5.

Erosion of waste material from fractures is governed by terms related to cohesive forces between particles.

The experimental program did not directly examine cohesion although capillary bonding forces, which are analogous to chemical bonds in terms of their effect, are expected to act to reduce volumetric releases and were present in the experiments. It is therefore reasonable to assume that cohesion due to cementation will also reduce volumetric releases. Section 2.0 presented material which supports the assumption of cementation in the waste. The validity of the functional form for cementation is discussed in Section 4.3.

4.3 Evaluation of Spallings Model

4.3.1 Mathematical Formulation

The preceding paragraphs have established that the assumptions used in the spallings model have either been directly validated through experiments, or are reasonable on the basis of analogy. However it is recognized that the quantitative formulation of the model does have some uncertainties associated with it, and that the analysis used to fit the parameters the model, as discussed in Lenke et. al. may be inadequate. The CMPRP correctly pointed out that these possible inadequacies call into question the validity of the mathematical model used to calculate volumetric releases. However, it can be shown that the dominant term used in the CCA calculations relates

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to cohesive effects and that the quantitative conclusions from the experiments do not impact the CCA calculations. To demonstrate that the cohesive term dominates the release, a simple calculation is presented here

From Lenke, et al:

$$g_{eff} = gF_{ge} + \frac{\sigma_p}{\rho_s R} F_{se} + \frac{\sigma_c}{\rho_s R} F_{ce} \qquad 4.2$$

and

$$v_e^{\,2} = \frac{8 g_{eff} R(\rho_s - \rho_g)}{3 C_D \rho_g} \qquad 4.3$$

The mean particle size used for the WIPP calculations is 151 microns. A tensile strength of 1 psi correlates to 6895 Pa. Using the CCA values of 18.1, 0.0, and 1 for F_{ge}, F_{se}, and F_{ce}, respectively, three terms are calculated to be 177, 0, and 12914, respectively (CCA, Appendix PAR). The magnitude of the term corresponding to cementation (or cohesion) clearly dominates the effective gravity. This equation also shows that the effect of cementation increases as particle size decreases. CCA results show the highest releases only occur for small particle sizes (<100μm). It can therefore be concluded that the CCA results are most sensitive to the effects of cementation. From a practical perspective, it is only necessary to validate the mathematics of the cementation term, and attempts to quantify the gravitational and capillary terms on the basis of experimental data, while flawed, were not relevant to the final CCA calculations since the controlling factor on the waste releases is the cementation effect. It can also be shown that the functional form of the cementation term used in the CCA (that is the tensile term in the effective gravity relationship) is appropriate. This is covered in the following discussion which establishes a critical shear stress criterion deduced from the sediment erosion analogy. This analogy is the closest mathematically to the current model.

4.3.2 Critical Shear Stress Criterion

The discussion in Section 3.5 suggest that the physical mechanism of particle lofting can be related to a shear strength criterion. A critical shearing stress criterion for the waste material can be bounded, and can also be quantitatively related to the cementation strength defined in the spallings model.

The spallings model characterizes the waste as a homogeneous, sediment-type material. Results of extensive field and laboratory testing on analogous materials is available within the published literature. A brief literature search produced the data presented in Table 4.1.

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Table 4.1. Typical Values for Sediment Shear Strength

Sediment Type	Shear Strength (kPa)	Literature Source
Marine Clays	3-149	Chaney and Demar; 1984a
Deep Sea Clays	0.5-70	Silva, et al; 1985
Sand, Silt, Clay Mixture; High (>90%) Water Content	1.8-6.8	Chaney and Demar; 1984b

The lowest shear strength values found correspond to uncompacted sediments with water contents approaching 100%. From the literature, it can be shown that sediments with a small amount of compaction (due to overburden) and moderate water content (<50%) have shear strengths in excess of 5kPa. Surface sediments in aqueous environments are known to experience resuspension during low shear events, with erosion occuring at shear stresses as low as 0.01 Pa. This phenomenon is related to the existence of a fluidized layer of flocculated particles existing within a very thin region (Fukuda and Lick, 1980). This type of layer will not exist in the waste environment. It is, however, notable that values for shear erosion used in the cavings model correspond to this type of sediment. Use of these low shear strengths for cavings therefore represent an extremely conservative analogy.

Berglund (Appendix B) has demonstrated that the cementation strength, σ_c, can be related to the shear stress according to:

$$\tau = \frac{f\sigma_c}{4C_D} \qquad 4.4$$

where f and C_D are the friction and drag coefficients, respectively. A cementation strength of 6.85 kPa corresponds to a critical shear stress criterion of 0.685 kPa (using Berglund's values for f and C_D). This value is clearly bounded by those presented in Table 4.1. The critical erosion velocity deduced from a critical shear stress of 0.685 kPa is approximately 100 m/s.

4.3.3 Comparison to Experiments

The mathematical formulation used in the spallings model related the equilibrium state to a critical velocity, which was, in turn, calculated from an effective gravity. The effective gravity term was developed by assuming that the governing mechanisms related to gravity, and to capillary tension. During experimental data analysis the parameter used to scale the effects of capillary tension (F_{se}) was determined to be zero, and the parameter used to scale true gravity was of order 10. Quantitatively, it can be shown that the effective gravity due to capillary effect should be quite large within the particle size range tested (Figure 4-4). If capillary forces were fully active during the experiments (i.e.; F_{se} on the order of 1), these effects would have overwhelmed those related to gravity. Comparison of the experimental data with previous results derived

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from completely dry material clearly showed that releases were reduced when the granular material was slightly moist. It must therefore be concluded from a phenomonological perspective that capillary forces were active. The result that best fit of the data occurs only when F_{se} was set to zero suggests that either the form of the function is not correct, or that the capillary forces were only weakly active during the experiments, or to a number of other factors, as noted by Lenke, et.al.

In response to concerns raised with regard to the scaling parameters, the formulation of the equation used to calculate the volumetric release was scaled to a constant radius. This resulted in a poor fit between the data and the model predictions. As noted in Appendix B, proper scaling of the volumetric predictions would reduce the model predictions by a factor of 100. If this result is taken a step further and the scaling parameters F_{ge} and F_{se} are re-evaluated, F_{ge} is reduced to 3 (which is of order 1), but F_{se} remains zero. Using these parameter values, the data fit to model predictions is significantly improved.

4.4 Concluding Remarks

The essential premise of the Spallings model is that the volume of releases can be derived from an equilibrium, end-state of a WIPP panel. This premise was vlaidated by the experiments, in that the spallings process was shown to reach an equilibrium state. Other model assumptions have also been validated, either by the experimental program, by analysis of the expected state of the waste (Section 2), or by analogy (Section 3). Evaluation of the mathematical formulation of the model has shown that:

- releases are dominated by the cementation term
- the functional form of the equation is appropriate
- a value of 6850 Pa(1 psi) is appropriate

The uncertainty associated with the remaining terms in Equation 4.2 is large, but this uncertainty does not impact the CCA calculations.

5. Conceptual Model Peer Review Panel Concerns

This section presents the CMPRP concerns and the Project response to those concerns in light of the reevaluation process.

5.1 Notes on specific issues in CMPRP Supplemental Report, Section 3.14.3.3

1. The forces responsible for detaching the waste pieces from their mass do not include the gases exiting the mass into the open gas-filled cavity. The Panel believes this type of gas flow will be largely responsible for the force required to counteract whatever bonding force exists. Such a force might be analogous to the forces (i.e. pressure gradient) on particles or groups of particles at the upper surface of a packed bed nearing the point of fluidization.

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The effect of the tensile effective stresses is not included explicitly, since the detailed nature of transient mechanisms is not pertinent to the equilibrium nature of the model (see discussion on Assumption 1 Section 4.2.1). The model determines the final volume of material released based on a calculation of the equilibrium void volume for particular repository pressures and waste characteristics. As such the details of transient mechanisms need not be included since the model is not summing volumes of solids produced, but rather is computing the void volume under equilibrium conditions. This void volume is controlled by the end-state processes. Note that calcualtions will be presented at the technical meeting which quantify the pressure gradients.

2. The data on tensile strengths were from static tests and were not shown to be applicable in this dynamic situation. It is noted that in the Cuttings/Cavings model, static shear strengths were modified to be applicable to the dynamic situation.

   The waste strength information has been reevaluated, and is discussed in Section 2 of this paper, a significant conclusion of that analysis is that the value used for tensile strength is highly conservative. It is also noted that while the mechanisms controlling the end-state void volume may be rapid (involving, for example, gas erosion at velocities of the order of 100 m/s) they are too slow to be considered dynamic. A dynamic process occurrs at rates equivalent toor greater than the speed of sound. These processes necessitate the use of shock wave physics; the use of this type of analysis is not warranted for the current model. Modification of an already highly conservative strength value is therefore not needed.

3. There is no evidence found in the record that time effect considerations were evaluated in either the development of the equations or in the conduct of the experimental tests.

   As noted in the response to Issue #1, the model is based on predicting an end-state equilibrium void volume, transient mechanisms are not considered, and time is therefore not a necessary parameter. In view of the panel's concerns, the effect of these transients has been examined. As discussed in Section 4.0 any release volumes computed on the basis of transient mechanisms are likely to be less than those predicted here.

4. The bounding equation as presented is not solidly verified not only because of the lack of consideration for the former comment, but also because the testing procedure results do not track the assumptions of equation development. For example, the dropped "g" term dealt with cohesive forces such as water, while the only positive test results achieved were those with moisture-laden sand.

   The issue of "the former comment" (time) is addressed in the responses to issues #1 and #3. With respect to the testing procedures, and the use of the experimental results some further explanations are needed.

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Following the CMPRP's analysis of the model the experiments, their use in defining "effectiveness factors", and the form of the relationship for "effective gravity" as used in defining the limiting erosional velocity, have been reviewed. We agree that the conclusions from the experiments regarding the relative importance of the gravitational and capillary forces were inappropriate. However on reassessing the results of the experiments, and the relative magnitude of the various terms, it has been found that in the final CCA calculations the gravitational and capillary terms are both much smaller than cementation term (σ_c) (see discussion in Section 4.3), and the cementation term completely dominates the mechanisms. Therefore the quantitative experimental data had no effect on the final volumes calculated.

As a practical matter the experiments were only used to demonstrate that:

- *the volume of material removed increases as the gas pressure in the waste increases (increased gas pressure leads to increased pressure gradient up the borehole, increased mass flux up the borehole and increased fracture velocities for the same porosity. Increased pressure therefore means that the fracture porosity must increase to achieve the same fracture velocities).*

- *the volume of material at all flow pressures is limited: the spalling process is self-limiting.*

- *the material is removed from channels.*

5. The effect of cementation was added when formulating the final equations describing the Spallings model and the experimental work did not evaluate these effects.

   This is true, however, as noted in the previous response, the quantitative results of the experiments were not in fact impactive to the final CCA calculations (since the effect of gravitational and capillary forces were dominated by the cementation). In response to the panel's concern, surrogate materials using WIPP brine were prepared and tested to quantify tensile strength. Results are reported in Section 2.3.2 of the position paper text. Attainment of significant strength through salt precipitate demonstrates further the conservatism embodied in the conceptual model. The validity of the conceptual model to a cemented material, and the results of analogs, have been addressed in more detail in Sections 2, 3 and 4 of the text..

6. Evaluations of the models did not include analogues from other industrial or scientific disciplines to determine a basis for reasonableness. The DOE was apparently not as successful in conducting such an evaluation as it was for the Cuttings/Cavings model. The coal mining methane gas stimulation example is good; however several others are expected to be applicable such as chemical engineering processes (for example fluidized beds) and the work over the years on particulate transport in volcanology. There may be existing correlations to these processes that are directly applicable.

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The Panel's suggestions are valuable, and we have pursued some of these analogs, as discussed in Section 3. It is likely that further investigations of analogs would be part of any future work.

7. The experiments were basically quasi steady state, rather than demonstrating the dynamic situation. Uniform particle distribution was used rather than a more realistic range of particle sizes. No control was maintained over the moisture content of the sand. All of these issues would seem to impact the relationship between the experimental system and the repository.

   Firstly it should be noted that, as discussed under Issue #4, the experimental results were not actually used in the CCA calculations, since the erosion was dominated by the cementation term. Additional points regarding this issue are addressed below.

   With regard to the quasi-steady state of the experiments we note firstly that while the situation is fast, it is not dynamic. "Dynamic" in this sense refers to things happening at the speed of sound, while the blow-out occurs in minutes. Calculations are being made, and will be presented to the CMPRP at the upcoming meetings, to indicate the rate of pressure changes during a drill penetration of the pressurized repository. These show that indeed the depressurization is rapid, but not dynamic.

   With regard to particle size distributions the panel is correct in pointing out that the particle sizes in the repository will probably be non-uniform. However, we note that a) a variety of particle sizes are included through the calculations through the sampling of ranges (although for each calculation only a single particle size is used), and b) the use of uniform sizes is probably conservative since no account is taken of the likelihood of bridging where non-uniform sizes are used, and c) additional conservatism results from the use of uniformly spherical particles which minimizes bridging. The limiting effect of fracture opening on the ability to transport particles is not included. Further discussion is included in Section 2.1.

   With regard to moisture content note that moisture content was determined and controlled at the start of experiments, although it was not controlled during the tests. Again note that due to the overwhelming effect of cementation on waste strength the results relative to capillary effects were not used in the final calculations.

8. The experimental results should be subject to scaling which was not found by the Panel to be addressed. Also the data did not include measurement of pressure drops at various locations throughout the system (for example, at the cavity-waste interface). Both of these issues might be reanalyzed without further experimental work.

   The point regarding the effect of scaling is valid if the experiments were in fact used for quantitative data, rather than for confirmation of mechanisms. Note however that

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the CCA results do not depend on the quantitative experiment results. The data have been rescaled, and the Panel is referred to Appendix B for details.

In considering the point made regarding pressure drops, we also note that these drops are important in considering the transient effects of tensile effective stresses. As noted in Section 4 these transient effects are not explicitly modeled, but are included in the final equilibrium volume calculation.

9. While the concept of cementation was included in the model, the process by which this cementation would occur was not addressed in the experimental program.

   Cementation is included in the model, and is in fact the dominant factor involved in limiting spalling. A discussion of the processes for cementation occurring is given in Section 2.3.2, including description of limited scoping experiments which were undertaken to estimate cementation strength. The approriateness of the mathematical formulation is presented in Sections 3.3 and 4.3.

10. Flow velocities that approach transonic or beyond have not been considered and, if velocities are transonic during the spalling process, might require a factor addressing increased effects on the pressure across the cavity-waste interface boundary.

    Flow velocities at end-state conditions reach a maximum of the order of 100 m/s (225 mph), or about 30% of the speed of sound in air in the experiments, or 8% of that for hydrogen in the repository. (These values were calculated during the model reevaluation process). As noted elsewhere mechanisms during the early transient stages are not a consideration in the CCA model.

11. The process as modeled does not have a provision for processes occurring at times of high pressure gradients. It would appear realistic that some volume of the waste dislodged from the matrix would be a spall produced by a process largely unrelated to the gas velocity parallel to a surface.

    As noted in response to other issues, the reason high pressure gradients are not included in the model is that it is an equilibrium end-state model, in which a final equilibrium void volume is calculated rather than the sum of solids produced. As such the final result is not impacted by transient processes that occur early. Therefore while the panel's comment may well be true, the volume they refer to is included in the final equilibrium volume.

12. Because of many unresolved issues of a fundamental nature, (the panel) cannot acknowledge that this model provides a conservative method for calculating Spalling releases.

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A reevaluation of the model conservatisms has been performed in response to the CMPRP review. As discussed in the text the following major conservatisms may be identified:

- *Repository pressures are assumed to stay constant, rather than decaying*
- *Material strength is taken as 1 psi, when likely values will be of the order of 50 - 100 psi.*
- *Uniform particle distributions are assumed, without any account of bridging or the effects of tortuous pathways, or the presence of lrage and fibrous particles*
- *The outer radius for spalling is taken as the effective room radius. In fact this radius will be less, and will be controlled in part by the ability of narrow fractures to transport large particles.*
- *The effects of fluid viscosity in limiting flow up the wellbore is not included.*
- *The effects of boundary layers in fracture flow velocities are not included, which maximizes these velocities and erosion.*

5.2 Additional notes on Summary Statements in Section 5.0

Summary Statement #1:

An adequate basis for the parameters used in the mathematical expression of the model has not been developed. In particular, ignoring capillary forces and correlating tensile strength with surface erosion have not been adequately supported by either first principles or experiment.

The basis for the parameters is discussed in Section 4. Some of the main points made in that section are:

- *the model calculates an end-state void volume for a particular set of conditions, using a critical erosion velocity formulation*

- *the critical erosion velocity depends upon gravitational, capillary and cementation terms. For typical conditions in the repository, and for a highly conservative cementation strength of 1 psi, the cementation term dominates.*

In regard to the points on capillary forces and the use of a tensile strength the following are noted:

- *Capillary forces are not ignored. As explained for the CCA the experiments were used to determine that their effect was small. Although this conclusion was not appropriate from the experiments, these effects are minimal in comparison to the cementation terms, and therefore do not impact the release volumes.*

As discussed in Sections 3.3 and 4.3 several points can be made to support the correlation of tensile strength with surface erosion. Firstly the "lofting" velocity is

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frequently used to determine critical erosion conditions in sediments in an aqueous environment (Section 3.3). Secondly an evaluation of shear stresses likely on the walls of a channel indicate that a shear criterion would predict lower critical velocities, and thus higher release volumes (Section 4.3). Finally it should be noted that the shear strength of cemented geological materials is generally higher than their tensile strength.

Summary Statement #2:

The principal assumptions upon which the mathematical model is based appear to be incomplete. Waste removal by entrainment in gas flow is expected to occur in a highly dynamic sequence principally involving a spalling process driven by gas flow out of the porous waste normal to the eroded surface. Subsequent erosion by gas flow parallel to the eroded surface in channels which form is not expected to be the primary effect controlling the volume of spall, particularly in early times. In addition, the DOE has not adequately shown that the steady-state assumptions of the model conservatively approximate releases associated with the dynamic process of spall, and the possibility of transonic velocities has apparently not been considered.

This statement would be appropriate if the model were based on a classical, mechanistic approach in which the volumes of solid material produced by all mechanisms were calculated and summed. However, as discussed in Section 4, this is not the case. The model is based on calculating an end-state, equilibrium void volume by determining the volume of void needed for velocities to reduce to the point where the limiting mechanism (erosion) ceases. As such a consideration of the detailed transient mechanisms (which may indeed produce the largest volume) is not needed, and while erosion is believed to be the limiting process, it is not necessary in this model for it to be a major volume contributor.

- *With regard to the issue of transonic velocities it should be noted that velocities at the end state have maximum of the order of 8% of the speed of sound in hydrogen.*

Summary Statement #3:

The experiments conducted in support of this model appear to have been designed to reproduce the assumptions upon which the model is based rather than to simulate the dynamic repository system. Although the experiments may support adoption of specific model parameters, they do not demonstrate that the model adequately represents future states of the repository.

We note here that the experiments were erroneously interpreted as providing information on the relative importance of gravitational and capillary effects. In fact the various terms for the resistance to erosion are dominated by the cementation term, and the experimental results are not needed quantitatively. What the experiments do demonstrate is that the process is self-limiting, erosion appears to be a limiting effect, and the geometry of the resulting void includes channels. These results are believed to

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translate to the repository, however it should be noted that the experiments are not expected to "represent the future state of the repository".

6. Summary and Conclusions

In response to findings included in the Supplemental Report of the Conceptual Models Peer Review Panel the spallings model used in the CCA has been reevaluated by the WIPP Project team. The results of this reevaluation are included in this paper, and are summarized below.

It is accepted that the simple, equilibrium model presented in the CCA does not capture the complex, dynamic response which would occur during a drilling intrusion. Instead the model used in the CCA is based on a different approach than a mechanistic tracking of the production of solids. It assumes that the volume of material transported to the surface can be quantified by determining an equilibrium end-state of the void produced in the waste beyond which further removal and transport of material would not occur.

The reevaluation discussed in this paper shows that the bounding model is appropriate to determine the end-state of the process, and the quantitative predictions of the model results do bound the releases. This is shown by an analysis of the probable state of the waste, by a comparison of the model releases to analog studies, and, finally through a reevaluation of the actual model itself.

The most significant findings are:

1) The repository conditions necessary to produce a spalling event also dictate a cemented waste form. Thus spalling is caused by gas pressure, while corrosion, which is one of the primary sources of this gas, will cause salt to be precipitated in such a way as to provide a cement. The resulting waste strength is likely to be considerably higher than the 1 psi assumed in the CCA.

2) A consideration of analogous situations, and alternative approaches, support the quantitative predictions of the spallings model. In particular quantitative estimates based on work on coalbed methane cavitation indicate volumes less than calculated in the CCA.

3) The mathematical formulation of the model is appropriate for the cemented waste. In addition, evaluation of the size of various factors which will limit erosion indicates that the process will be dominated by cementation: gravitational and capillary effects included in the CCA model are small enough that they do not impact the results. A side effect of this result is that the quantitative predictions based on the experiments presented to the panel have no impact on the volumes calculated in the CCA.

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7.0 References

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Appendix A: Implementation of Spalling in the WIPP Performance Assessment and Implications of Spallings Model Results to the Compliance Certification

Introduction

This addendum provides an overview of the performance assessment conducted in support of the WIPP Compliance Certification Application (CCA), and summarizes the role of spallings in the compliance determination. Information presented here is summarized from Chapter 6 and Appendix SA of the CCA. Additional relevant information is available in those sources.

Summary of Performance Assessment Methodology

The DOE evaluates compliance of the WIPP with the Containment Requirements of 40 CFR § 191.13(a) using a performance assessment methodology based on EPA requirements and guidance. The process begins with a comprehensive consideration of the features, events, and processes that are relevant to disposal system performance. Those features, events, and processes that are shown by screening analyses to have the potential to affect performance are included in quantitative calculations using a system of linked computer models to describe the interaction of the repository with the natural system, both with and without human intrusion. Uncertainty is incorporated in the analysis through a Monte Carlo approach in which multiple simulations (or realizations) are completed using sampled values for imprecisely known or naturally variable input parameters. Distribution functions are constructed that characterize the state of knowledge for these parameters, and each realization of the modeling system uses a different set of sampled input values. For the WIPP Compliance Certification Application (CCA), values were sampled for 57 input parameters, and a sample size of 100 resulted in 100 different values of each parameter. Performance assessment calculations, therefore, use 100 different sets (vectors) of input parameter values.

Probabilities of scenarios composed of specific combinations of features, events, and processes are estimated based on regulatory criteria (applying to the probability of future human action) and the understanding of the natural and engineered systems. As required by regulation, results of the performance assessment are shown as a complementary cumulative distribution function (CCDF) that displays the probability that 10,000-year cumulative radionuclide releases from the disposal system will exceed the values calculated for each scenario considered in the analysis. Cumulative radionuclide releases are calculated for each scenario considered and probabilities of the scenarios are summed for each realization of the modeling system to construct distributions of CCDFs. Sampling of the input parameters was performed in three separate replicates resulting in three independent distributions of CCDFs and allowing the construction of three independent mean CCDFs, each based on 100 individual CCDFs. The DOE's determination that the WIPP is in compliance with 40 CFR §

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191.13(a) is based on the location of the overall mean CCDF below and to the left of limits specified by the EPA. Each of the 300 individual CCDFs also falls below and to the left of the compliance limits.

Aspects of the Performance Assessment Relevant to Spalling

Undisturbed Performance

An evaluation of undisturbed performance, which is defined by regulation (see 40 CFR § 191.12) to exclude human intrusion and unlikely disruptive natural events, is required by regulation (see 40 CFR § 191.15). Evaluation of past and present natural geologic processes in the region indicate that none has the potential to breach the repository within 10,000 years.

Behavior of the disposal system is dominated by the coupled processes of deformation of the rock surrounding the excavation, fluid flow, and waste degradation. Each of these processes can be described independently, but the extent to which each process occurs will be affected by the others.

Deformation of the rock immediately around the repository begins as soon as excavation creates a disturbance in the stress field. Stress relief results in some degree of brittle fracturing and the formation of a disturbed rock zone (DRZ) surrounding excavations in all deep mines. For the WIPP, the DRZ is characterized by an increase in permeability and a decrease in pore pressure, and may ultimately extend a few meters from the excavated region. Salt will also deform due to deviatoric stress by creep processes and move inward to fill voids. This process of salt creep will continue until deviatoric stress is dissipated and the system is once again at stress equilibrium.

The ability of salt to creep, thereby healing fractures and filling porosity, is one of the fundamental advantages of using it as a medium for geologic disposal of radioactive waste. For the WIPP, salt creep provides the basis for the design of the compacted crushed salt components of the shaft seal system that will compact to yield properties approaching those of the intact salt within 200 years. The salt creep will also cause the DRZ surrounding the shaft to heal rapidly around the concrete components of the seal system. In the absence of elevated pressure in the repository, salt creep would also eventually result in substantial compaction of the waste and the healing of the DRZ around the disposal region. Understanding the coupling of salt creep with fluid flow and waste degradation processes suggests that fluid pressure within the waste disposal region will be sufficient to maintain significant porosity within the disposal region throughout the performance period.

Characterization of the Salado Formation indicates that fluid flow does not occur on time scales of interest in the absence of an artificially imposed hydraulic gradient. This lack of fluid flow is the second fundamental reason for the choice of salt as a medium for geologic disposal of radioactive waste. Lack of fluid flow is a result of the

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extremely low permeability of the evaporite rocks that make up the Salado. Excavation of the repository has disturbed the natural hydraulic gradient and rock properties and has resulted in fluid flow. Small quantities of interstitial brine present in the Salado move toward regions of low hydraulic potential and brine seeps are observed in the underground. The slow flow of brine from halite into more permeable anhydrite marker beds and then through the DRZ into the repository is expected to continue as long as the hydraulic potential within the repository is below the hydraulic potential in the far field. The repository environment will also involve gas, and fluid flow, therefore, must be modeled as a two-phase process. Initially, the gas phase will consist primarily of air trapped at the time of closure, although other gases will form as a result of waste degradation. The gas phase pressure will rise due to creep closure, gas generation, and brine inflow, creating the potential for flow outward from the excavated region.

Consideration of waste degradation processes indicates that the role of the gas phase in fluid flow and the pressure history of the repository will be far more important than would be expected if the initial air were the only gas present. Degradation of waste can generate significant additional gas by two processes:

(1) the generation of hydrogen gas by anoxic corrosion of iron, iron alloys, and aluminum, and
(2) the generation of carbon dioxide and methane by anaerobic microbial degradation of waste containing cellulose, rubber, or plastic.

The coupling of these gas generation reactions to the processes of fluid flow and salt creep is complex. Gas generation will increase fluid pressure in the repository, thereby decreasing the hydraulic gradient and deviatoric stress between the far field and the excavated region and inhibiting the processes of brine inflow and salt creep. Anoxic corrosion will also consume brine as it breaks down water to oxidize iron and release hydrogen gas. Thus, corrosion has the potential to be a self-limiting process, in that, as it consumes all water in contact with iron, it will cease. Microbial reactions are also considered to be dependent on the presence of water to occur, although their net effect is uncertain. It is assumed that microbial reactions will result in neither the consumption nor creation of water.

The total volume of gas that may be generated by corrosion and microbial degradation may be sufficient to result in repository pressures that approach lithostatic. Sustained pressures above lithostatic are not physically reasonable within the disposal system, and fracturing of the more brittle anhydrite layers is expected to occur if sufficient gas is present. The conceptual model implemented in the performance assessment causes permeability and porosity of the anhydrite marker beds to increase rapidly as pore pressure approaches and exceeds lithostatic. This conceptual model for pressure-dependent fracturing approximates the hydraulic effect of pressure-induced fracturing and allows gas and brine to move more freely within the marker beds at higher pressures.

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Overall, the behavior of the undisturbed disposal system will result in extremely effective isolation of the radioactive waste. Concrete, clay, and asphalt components of the shaft seal system will provide an immediate and effective barrier to fluid flow through the shafts, isolating the repository until salt creep has consolidated the compacted crushed salt components that will permanently seal the shafts. Around the shafts, the DRZ in halite layers will heal rapidly because the presence of the solid material within the shafts will provide rigid resistance to creep. The DRZ around the shaft, therefore, will not provide a continuous pathway for fluid flow. The DRZ is not expected to heal completely around the disposal region or the operations and experimental regions, and pathways for fluid flow may exist indefinitely to the overlying and underlying anhydrite layers (Marker Beds [MB] 138 and 139 and anhydrites a and b). Some quantity of brine is expected to be present in the repository under most conditions and this brine may contain actinides (which dominate the radionuclide inventory and are therefore the elements of primary regulatory interest) mobilized as both dissolved and colloidal species. Gas generation by corrosion and microbial degradation is expected to occur and will result in elevated pressures within the repository. These pressures will not significantly exceed lithostatic, because fracturing within the more brittle anhydrite layers will occur and provide a pathway for gas to leave the repository. Fracturing is expected to enhance gas and brine migration from the repository, but gas transport will not contribute to the release of actinides from the disposal system. Brine flowing out of the waste disposal region through anhydrite layers may transport actinides as dissolved and colloidal species, but the quantity of actinides that may reach the accessible environment boundary during undisturbed performance through the interbeds is insignificant and has no effect on the compliance determination. No migration of radionuclides whatsoever is expected to occur vertically through the Salado or through the shaft seal system.

Disturbed Performance

Performance assessment is required by regulation to consider scenarios that include intrusions into the repository by inadvertent and intermittent drilling for resources. The probability of these intrusions is based on a future drilling rate of 46.8 boreholes per square kilometer per 10,000 years. This rate is based on consideration of the past record of drilling events in the Delaware Basin consistent with regulatory criteria. Active institutional controls are assumed to be completely effective in preventing intrusion during the first 100 years after closure and passive institutional controls are assumed to be effective in reducing the drilling rate by two orders of magnitude for the 600 years that follow the 100 years of active control. Future drilling practices are assumed to be the same as current practice, also consistent with regulatory criteria. These practices include the type and rate of drilling, emplacement of casing in boreholes, and the procedures implemented when boreholes are plugged and abandoned.

Results of the performance assessment indicate that human intrusion provides the only mechanism for significant releases of radionuclides from the disposal system. These releases may occur by five mechanisms:

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(1) cuttings, which include material intersected by the rotary drilling bit,
(2) cavings, which include material eroded from the borehole wall during drilling,
(3) spallings, which include solid material carried into the borehole during rapid depressurization of the waste-disposal region,
(4) direct brine releases, which include contaminated brine that may flow to the surface during drilling, and
(5) long-term brine releases, which include the contaminated brine that may flow through a borehole after it is abandoned.

The first four of these mechanisms operate immediately following the intrusion event and are collectively referred to as direct releases. The accessible environment boundary for these releases is the ground surface. The fifth mechanism, actinide transport by long-term groundwater flow, begins when concrete plugs are assumed to degrade in an abandoned borehole and may continue throughout the regulatory period. The accessible environment boundary for these releases may be the land surface or the lateral subsurface limit of the controlled area. Because performance assessment results indicate that no releases to the accessible environment will occur as a result of long-term flow up a borehole, either by flow to the surface or by subsurface groundwater transport, this pathway is not discussed further in this summary.

Repository conditions prior to intrusion will be the same as those described for undisturbed performance and all processes active in undisturbed performance will continue to occur following intrusion.

Cuttings and Cavings

In a rotary drilling operation, the volume of material brought to the surface as cuttings is the cylinder defined by the thickness of the unit being drilled and the diameter of the drill bit. The quantity of radionuclides released as cuttings is therefore a function only of the activity of the intersected waste and the diameter of the intruding drill bit. Like all parameters that describe future drilling activities, the diameter of a drill bit that may intersect waste is speculative. The DOE uses a constant value of 12.25 inches (0.311 meters), consistent with bits used at the WIPP depth in the Delaware Basin today. The activity of the intersected waste may vary depending on the type of waste intersected, and the DOE considers random penetrations into remote-handled (RH)-TRU waste and each of the 569 different waste types identified for contact-handled (CH)-TRU waste.

The volume of particulate material eroded from the borehole wall and brought to the surface as cavings may be affected by the drill bit diameter, the effective shear resistance of the intruded material, the speed of the drill bit, the viscosity of the drilling fluid and the rate at which it is circulated in the borehole, and other properties related to the drilling process. The most important of these parameters, after drill bit diameter, is the effective shear resistance of the intruded material. In the absence of data describing the reasonable and realistic future properties of degraded waste and backfill,

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the DOE has used conservative parameter values based on the properties of fine-grained sediment. Other properties are assigned fixed values consistent with current practice. The quantity of radionuclides released as cavings depends on the volume of eroded material and its activity, which is treated in the same manner as the activity of the cuttings.

Spallings

Unlike releases from cuttings and cavings, which will occur with every borehole intrusion, spalling releases will occur only if pressure in the waste-disposal region exceeds the hydrostatic pressure in the borehole. At lower pressures, below about 8 megapascals, fluid in the waste-disposal region will not flow toward the borehole. At higher pressures, gas flow toward the borehole may be sufficiently rapid to entrain particulate waste. If spalling occurs, the volume of spalled material is affected by the physical properties of the waste, specifically its tensile strength and particle diameter. As is the case for the effective shear resistance for the waste, WIPP-specific experimental data are not available to support parameter values for the tensile strength and average particle diameter of degraded waste and backfill. The DOE has based the parameter values used in the performance assessment on reasonable and conservative assumptions.

The quantity of radionuclides released as spalled material depends on the volume of spalled waste and its activity. Because spalling may occur at a greater distance from the borehole than cuttings and cavings, spalled waste is assumed to have the volume-averaged activity of CH-TRU waste rather than the sampled activities of individual waste streams. RH-TRU waste is isolated from the spallings process and does not contribute to the volume or activity of spalled material.

Direct Brine Flow

Radionuclides may be released to the accessible environment if repository brine enters the borehole during drilling and flows to the ground surface. The quantity of radionuclides released by direct brine flow depends on the volume of brine reaching the ground surface and the concentration of radionuclides contained in the brine. As is the case for spallings, direct releases of brine will not occur if repository pressure is below the hydrostatic pressure in the borehole. At higher repository pressures, if mobile brine is present in the repository, it will flow toward the borehole. If the volume of brine flowing from the repository into the borehole is small, it will not affect the drilling operation and flow may continue until the driller reaches the base of the evaporite section and installs casing in the borehole. This length of time is estimated to be 72 hours, consistent with current practice. Larger brine flows or large gas flows could cause the driller to lose control of the borehole and fluid flow, in this case, could continue until repository pressure drops or the hole is contained. The maximum length of time that such flow would be allowed to continue before the borehole would be controlled by the driller is 11 days, consistent with current drilling practice in the Delaware Basin.

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Contributions of the Individual Release Mechanisms to the Total Release

Examination of the normalized releases resulting from cuttings and cavings, spallings, and direct brine release provides insight into the relative importance of each release mode in terms of its contribution to the location of the mean CCDF and the compliance determination. As shown in Figure 1 (identical to Figure 6-41 of the CCA), releases from cuttings, cavings, and spallings dominate the mean CCDF. Direct brine releases are less important and have very little effect on the location of the mean. Subsurface releases resulting from groundwater transport are less than 10^{-6} EPA units and make no contribution to the location of the mean CCDF.

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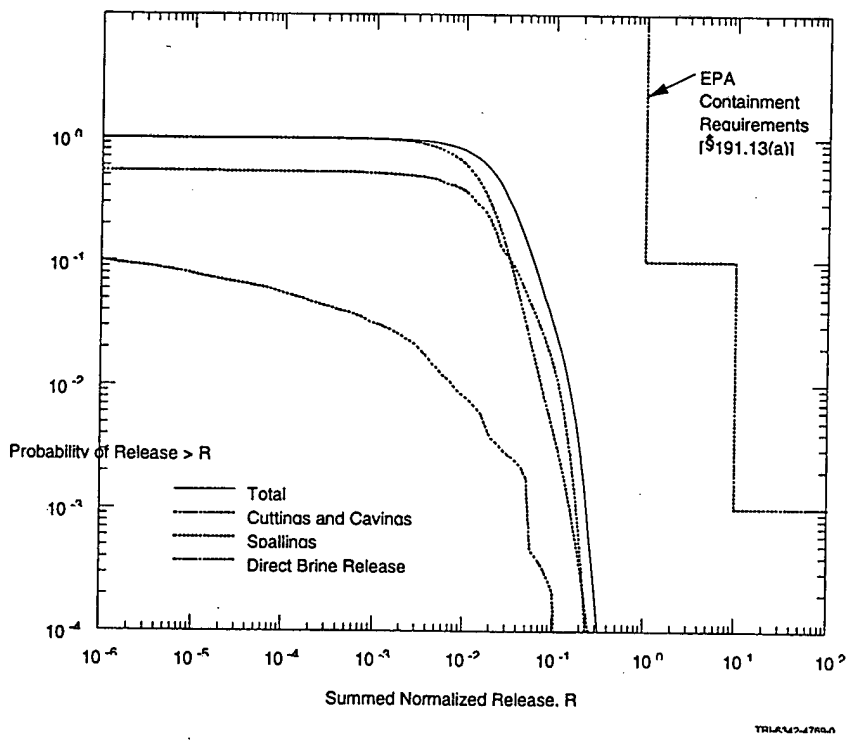
Figure 1. Mean CCDFs for Specific Release Modes, Replicate 1. Mean CCDFs are shown for the total normalized release (this curve is one of the three mean CCDFs used in the compliance application to establish the location of the overall mean used for comparison with the containment requirements) and the normalized releases resulting from cuttings and cavings, spallings, and direct brine releases. The mean CCDF for subsurface releases resulting from groundwater transport is not shown because those releases were less than 10^{-6} EPA units and the CCDF cannot be shown at the scale of this figure. This figure is the same as Figure 6-41 of the CCA.



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Appendix B:

Memoranda Received from J.W. Berglund

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The University of New Mexico

New Mexico Engineering Research Institute
Albuquerque, NM 87131-1376
USA

Memorandum to: K Knowles SNL 6121
From: Jerry W. Berglund 6849 UNM/NMERI
January 15, 1997
Subject: Spallings Radius

The solid volume released by a blowout event at WIPP has been derived and described in the users manual for the code CUTTINGS_S (Ref 1). The volume released was shown to be

$$V_{ol} = \frac{A_{borehole} V_{borehole} r_o}{v_e}(1-\phi) \qquad (1)$$

where $A_{borehole}$ is the area of the borehole annulus
$V_{borehole}$ is the gas velocity at the borehole entrance
v_e is the velocity above which erosion occurs in the waste fractures
ϕ is the matrix porosity of the waste at the time of intrusion
and r_o is the equivalent radius of a WIPP disposal room based on plan area

The radius r_o actually represents the radius of the damaged region around the borehole which for simplicity was assumed to be defined as the equivalent radius of a WIPP disposal room. This assumption exaggerates the size of the damaged zone since both experiment (Ref 2) and physical reasoning argue against using such a large damage radius. This assumption does, however, overpredict releases and thus is conservative with respect to the compliance measure as will be shown below.

Lets assume that the damaged region extends to a radius r which now represents the true radius of fracturing in the waste. Then the new solid volume $\overline{V_{ol}}$ released by a blowout event at WIPP can be written

$$\overline{V_{ol}} = \frac{A_{borehole} V_{borehole} r}{v_e}(1-\phi) \qquad (2)$$

If the average fracture porosity of the cylindrical damaged region is C then $\overline{V_{ol}}$ can also be written

$$\overline{V_{ol}} = \pi r^2 HC(1-\phi) \qquad (3)$$

where H is the height of the repository at the time of intrusion

Solving equation 2 for r and substituting into equation 3 yields

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$$\overline{V_{ol}} = \left(\frac{A_{borehole} V_{borehole}}{v_e} \right)^2 \frac{(1-\phi)}{\pi HC} \tag{4}$$

The solid release volume is now independent of the damage radius r but data for the average fracture porosity C is required.

Lets now compute the ratio of the new spall volume to the old. Dividing equation 4 by equation 1 obtains

$$\frac{\overline{V_{ol}}}{V_{ol}} = \frac{\left(\frac{A_{borehole} V_{borehole}}{v_e} \right)^2 \frac{(1-\phi)}{\pi HC}}{\frac{A_{borehole} V_{borehole} r_o}{v_e}(1-\phi)} = \frac{A_{borehole} V_{borehole}}{v_e r_o CH\pi} \tag{5}$$

The erosion velocity can be written (Ref 1)

$$v_e^{\,2} = \frac{4 g_{eff} d(\rho_s - \rho_g)}{3 C_D \rho_g} \tag{6}$$

where g_{eff}= effective acceleration of gravity, d= particle diameter, $\rho_s =$ particle density, $\rho_g =$ gas density, and C_D is the coefficient of drag. Since $\rho_s \rangle\rangle \rho_g$ then $(\rho_s - \rho_g) \approx \rho_s$ and equation 6 becomes

$$v_e^{\,2} = \frac{4 g_{eff} d \rho_s}{3 C_D \rho_g} \tag{7}$$

The effective acceleration of gravity is related to the parting stress between particles. For non-zero cementation stresses, the effect of cementation rapidly overwhelms the bonding effect of gravity and consequently it becomes the only significant contribution to the effective gravity. Thus when cementation is active the effective acceleration of gravity can be written (Ref 1)

$$g_{eff} = \frac{3}{4} \frac{\sigma}{\rho_s R} \tag{8}$$

where σ is the cementation stress and R is the particle radius

In terms of particle diameter equation 8 becomes

$$g_{eff} = \frac{3}{2} \frac{\sigma}{\rho_s d} \tag{9}$$

Substituting equation 9 into equation 7 obtains

$$v_e^{\,2} = \frac{2\sigma}{C_D \rho_g} \tag{10}$$

Substituting equation 10 into equation 5 the volume ratio can be written

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$$\frac{\overline{V_{ol}}}{V_{ol}} = \frac{A_{borehole} V_{borehole}}{r_o C H \pi} \left(\frac{C_D \rho_g}{2\sigma} \right)^{0.5} \qquad (11)$$

For the WIPP CCA computations (Ref 3)

$A_{borehole}$=0.0435 m^2 (12.25" drillbit, 8" collar)
$V_{borehole}$=100.27 m/s (this is a choking velocity at the borehole entrance--from the CCA calculations)
C=0.22 (Based on limited data from experiments described in ref 2)
r_o= 17.1 m (Based on CCA database)
H= 2.0 m (Approximate compacted repository height)
$\rho_g = \frac{p}{RT}$ = Hydrogen gas Density in Repository
p= Repository pressure 15x10^6 Pa (Maximum possible)
R = Gas Constant for Hydrogen 4123 (N·m/kg/°K)
T= Absolute Temperature of Repository 300 °K (From CCA Database)
C_D= Coefficient of drag < 1 (From CCA Calculations) assume 1

Using these values equation 11 becomes

$$\frac{\overline{V_{ol}}}{V_{ol}} = \frac{0.455}{\sqrt{\sigma}}$$

The value for σ (cementation stress) used in the CCA computations was 6895 Pa (1psi).

Thus $\frac{\overline{V_{ol}}}{V_{ol}}$ = 0.00548 and the solid release volume computed based on a model independent of the damage radius r is less than 1% of the solid release volume calculated in CCA 1996 using the model based on the equivalent radius of a room r_o .

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Memorandum to K. Knowles SNL 6121
From : Jerry W. Berglund 6849 UNM/NMERI
January 15, 1996
Subject: A Shear Failure Criterion for Borehole Spall

In the current spall model for solids blowout in the CUTTINGS_S code (Ref 1) it is assumed that individual particles attached to a channel wall are dislodged when drag forces from the flowing gas in the channel acting on the particle exceed the normal force bonding the particle to the wall. In the model this bond strength is assumed to be directly related to the macroscopic tensile strength of the wall material. However the drag forces that act on the bonded particle are perpendicular to the measure of bond strength used for failure and this inconsistency has been a source of controversy.

In what follows the failure model will be recast in terms of shear stresses and shear failure rather than tensile failure thus removing the inconsistency. It will also be shown that the tensile (lofting) model for spall as is currently in CUTTINGS_S is conservative with respect to spall releases when compared to the shear model.

A principal assumption in the spall release model is that flow occurs in channels and that flow of gas erodes the wall material. Consider now a long channel with a cross-section approximately in the shape of a circular cylinder with a mean diameter of D. Gas is assumed to flow along the channel at a mean velocity v. The pressure drop in the gas that occurs over a distance L is (Ref 2).

$$\Delta p = f \frac{L}{D} \frac{\rho v^2}{2} \qquad (1)$$

where f is the pipe friction factor and ρ is the fluid density

The pressure drop arises from the action of wall friction acting on a fluid element. For steady flow, static equilibrium of a fluid element of length L and diameter D requires that (using equation 1)

$$v^2 = \frac{8\tau}{f\rho} \qquad (2)$$

where τ is the shear stress acting on the tube wall.

It is now necessary to determine a value of shear strength to use in this model. There are data available to estimate a lower bound for the tensile strength of the waste. In fact a value of 1 psi was chosen based on the strength of materials believed to be analogous to a worst case state of decomposed WIPP waste (Ref 3). It is well known (Ref 4) that materials placed into a state of uniaxial tension also must withstand shear

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stresses. On planes at 45 degrees to the axis of uniaxial tension, a shear stress of 1/2 of the magnitude of the uniaxial tension stress exists. These planes are also subjected to reduced tensile stresses again of a magnitude 1/2 of the uniaxial tension stress. In our case, assuming a 1 psi tensile strength, shear stresses of 1/2 psi must also exist prior to failure of a uniaxial tension specimen. To account for uncertainties in how the shear strength on a particle level is actually related to test data, the shear strength can be reduced further but for the moment lets assume a particle shear strength of 1/2 the uniaxial tensile strength.

Lets now compare equation 2 to the form used in CUTTINGS_S (Ref 1).

The erosion velocity can be written for the tension failure (lofting) model as (Ref 1)

$$v_e^{\,2} = \frac{4 g_{eff} d\left(\rho_s - \rho_g\right)}{3 C_D \rho_g} \tag{3}$$

where g_{eff}= effective acceleration of gravity, d= waste particle diameter, $\rho_s =$ particle density, $\rho_g =$ gas density, and C_D is the coefficient of drag. Since $\rho_s \rangle\rangle \rho_g$ then $\left(\rho_s - \rho_g\right) \approx \rho_s$ and equation 3 becomes

$$v_e^{\,2} = \frac{4 g_{eff} d \rho_s}{3 C_D \rho_g} \tag{4}$$

The effective acceleration of gravity is related to the parting stress between particles. For non-zero cementation stresses, the effect of cementation rapidly overwhelms the bonding effect of gravity and consequently it becomes the only significant contribution to the effective gravity. Thus when cementation is active the effective acceleration of gravity can be written (Ref 1)

$$g_{eff} = \frac{3}{4}\frac{\sigma}{\rho_s R} \tag{5}$$

where σ is the cementation stress and R is the particle radius

In terms of particle diameter equation 5 becomes

$$g_{eff} = \frac{3}{2}\frac{\sigma}{\rho_s d} \tag{6}$$

Substituting equation 6 into equation 4 obtains

$$v_e^{\,2} = \frac{2\sigma}{C_D \rho_g} \tag{7}$$

or using the same notation as for the shear model (equation 2)

$$v^{\,2} = \frac{2\sigma}{C_D \rho} \tag{8}$$

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The shear model (equation 2) and the lofting model (equation 8) are very similar in form. Both are directly proportional to a waste strength measure and inversely proportional to the product of fluid density and a "friction" measure.

The solid volume released due to spall (Ref 1) is inversely proportional to the erosion velocity v. Thus it is possible to compare the releases from the shear and lofting models using these two equations. The resulting ratio of spall volume due to shear to that due to lofting is then

$$\frac{V_{ol_{shear}}}{V_{ol_{lofting}}} = \frac{1}{2}\sqrt{\frac{\sigma}{\tau}\frac{f}{C_D}} \qquad (9)$$

Now lets substitute some typical numbers into equation 9

$f = 0.08$ (very rough pipe (Ref 1))
$C_D = 0.2$ (lowest value used in CUTTINGS_S model (Ref 1))

$\frac{\sigma}{\tau} = 2$ (Based on Mohr's circle for uniaxial tension (Ref 4))

thus equation 9 gives $\frac{V_{ol_{shear}}}{V_{ol_{lofting}}} = 0.447$. For this ratio to be equal to one, i.e., for the shear model to give the same results as the lofting model at the same selected values of C_D and f, a shear strength of 1/10 of the chosen tensile strength would have to be chosen. This analysis shows that the releases computed using a lofting model for v (Ref 1) is conservative with respect to a consistently derived shear erosion model.

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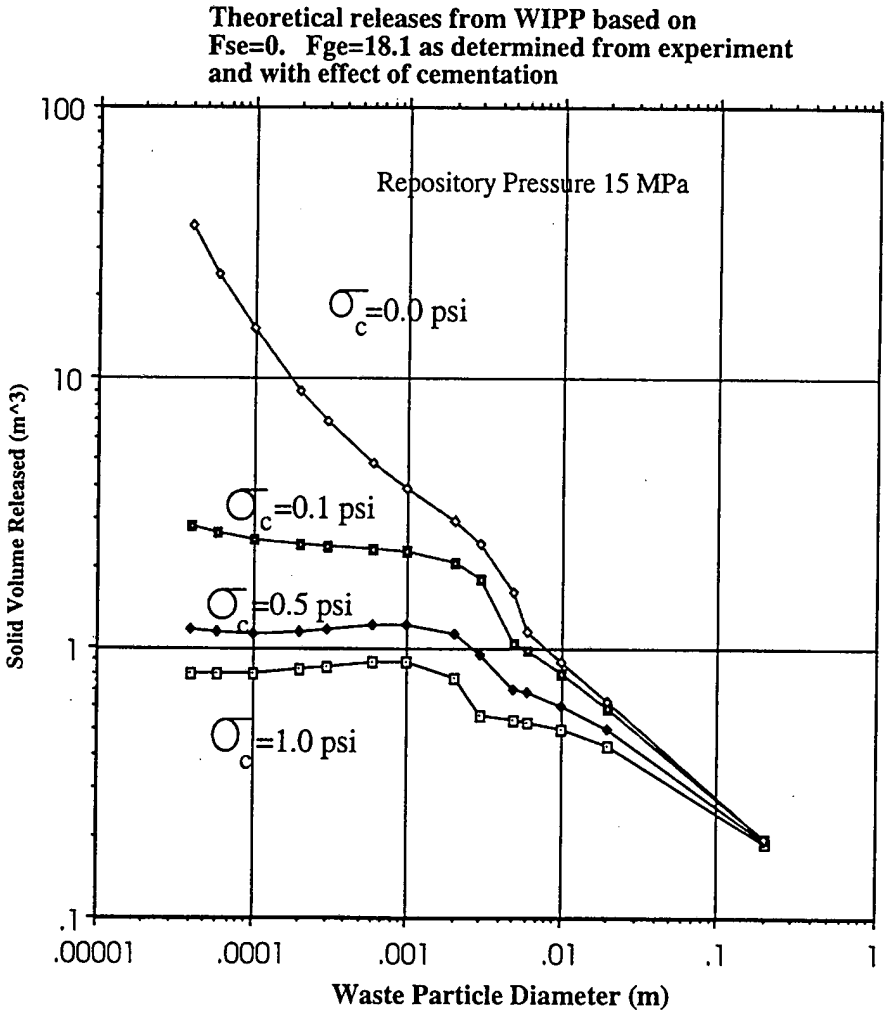

Figure 2-1. Figure 4-9 from Lenke, et.al., 1996.

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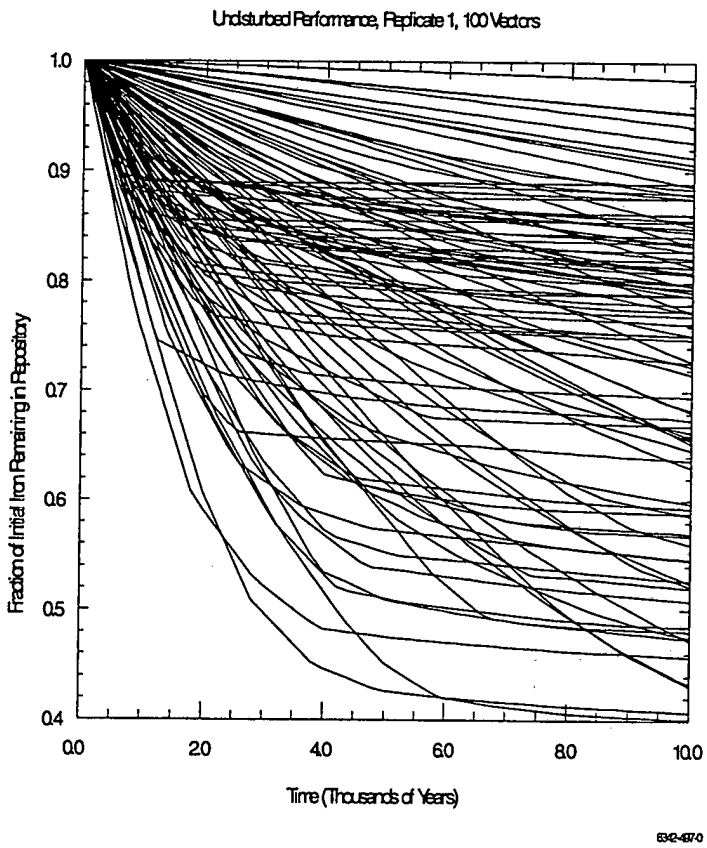

Figure 2-2. Fraction of iron remaining for undisturbed repository performance.

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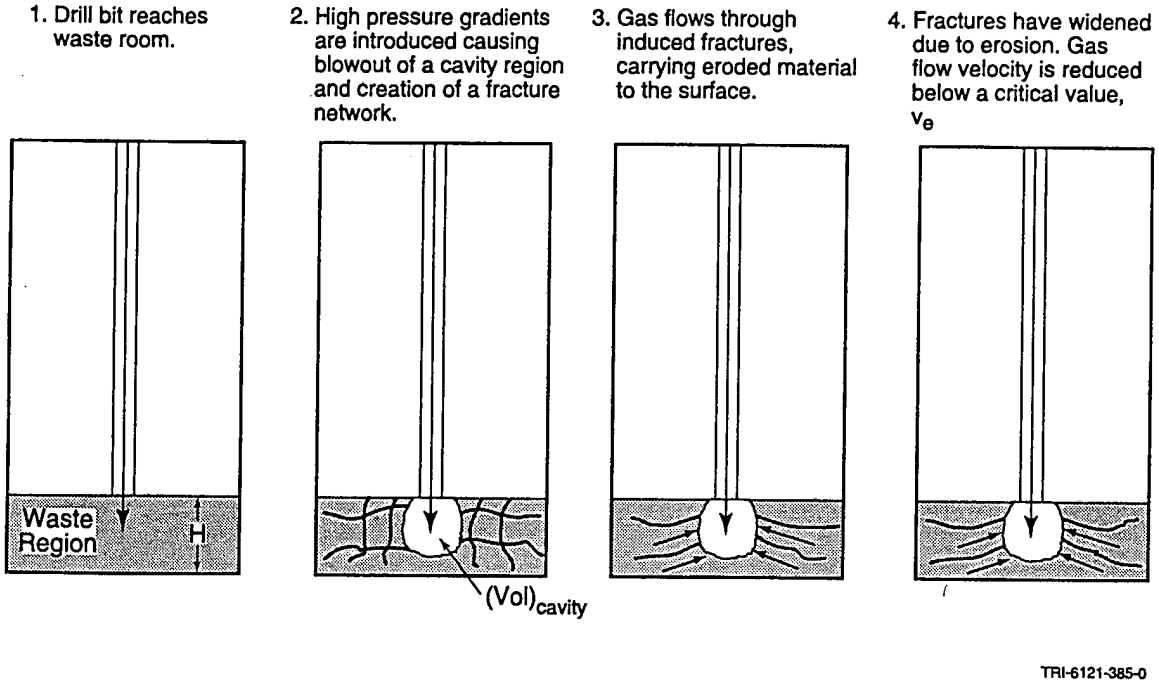

Figure 4-1. Schematic of mechanisms resulting in contaminant to the surface during a gas blowout of the WIPP horizon.

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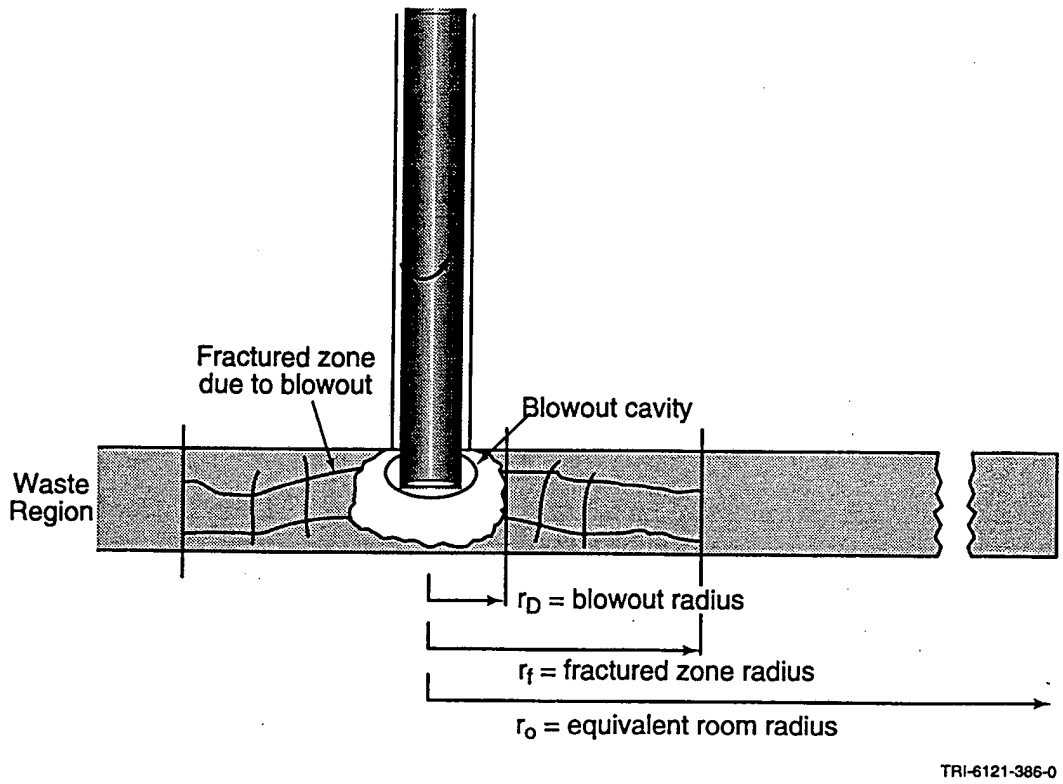

Figure 4-2. Schematic of gas blowout at WIPP repository horizon.

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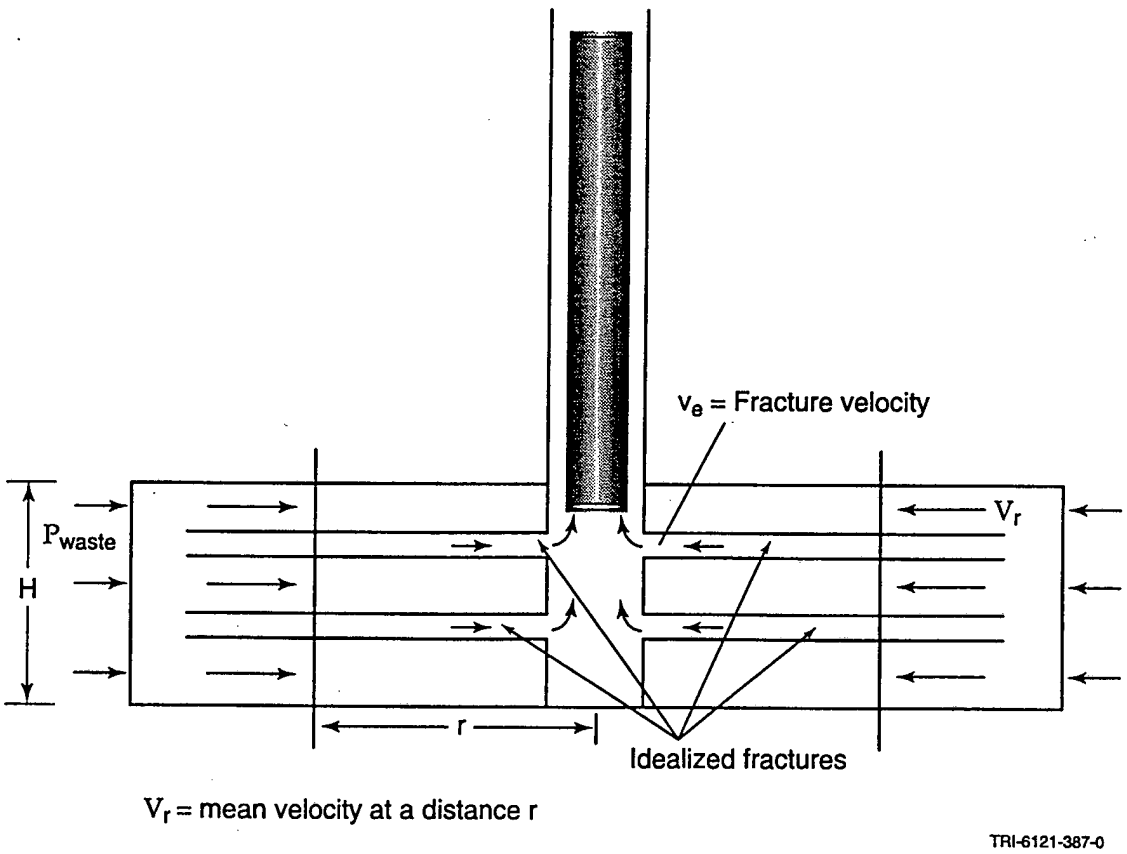

Figure 4-3. Conceptual model developed to quantify volumetric releases during gas blowout

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