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Brine release based on structural calculations of damage around an excavation at the Waste Isolation Pilot Plant (WIPP)*

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ABSTRACT: In a large *in situ* experimental room, circular in cross section, inflow of brine was measured over a five year period. After correcting the measured brine accumulation for initial losses by evaporation into the mine ventilation air, the measurements gave data for a period of nearly three years. Predicted brine accumulation based on a mechanical "snow plow" model of the volume swept by creep-induced damage as calculated with the Multimechanism Deformation Coupled Fracture (MDCF) model was found to agree quantitatively with the experimental results. The calculation suggests the damage zone at five years effectively extends only some 0.7 m into the salt around the room. Also, because the mechanical model of brine release gives an adequate explanation of the measured data, the hydrological process of brine flow appears to be rapid compared to the mechanical process of brine release.

1 INTRODUCTION

One of the more challenging aspects of the development of the Waste Isolation Pilot Plant (WIPP) is the prediction of the inflow of brine into the underground rooms. Although this inflow may be completely the result of Darcy hydrological flow, it may also be the consequence of (or aided by) the time-dependent mechanical deformation and damage of the surrounding salt. The hydrological approach to the inflow problem is typified by the analysis of Webb (1992). WIPP salt is estimated to contain approximately 1.0% brine by volume (Stein 1985) located in the interbeds, clay stringers, or negative crystals. Brine released from these sources into the underground rooms of the repository can react with the steel storage drums and waste to produce gas, with possibly significant consequences for the repository. Gas generation results in pressurization and possible reexpansion of the facility with the attendant potential fracture of the interbeds for some considerable distance into and away from the facility. Because of the influence of the brine on repository performance, it is necessary to be able to predict with some assurance the expected amount of inflow.

In this work, although the mechanism of brine inflow has not yet been firmly established, it is assumed for this evaluation that the process is one of mechanical deformation-aided brine release rather than hydrological flow. Thus, the manner in which the prediction of the evolution of brine is carried forward is through the use of a structural prediction of the amount of damage introduced by the time-dependent deformation of the salt as it creeps inward toward an underground opening. The prediction of the damage requires a sophisticated model of creep and fracture, as well as implementation though a powerful numerical calculational method. Once the damage has been predicted, a model that relates the damage to the increase in permeability or to the release of brine is also required. In this case, a "snow plow" brine release model is proposed which relates the volume swept by the damage to the brine release. Formulation of this problem of interactive mechanical and hydrological effects is of value only if the predictions have some adequate degree of validation against *in situ* measurements.

Presentation of the work includes a summary of the constitutive model of creep and fracture, followed by the development of the brine release model. Next, the details of the *in situ* brine inflow experiment are given. Then, a comparison is made between the calculated and measured brine release. A summary concludes the work.

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2 CONSTITUTIVE MODELS

In this work, brine release is visualized as a mechanical process in which creep deformation causes gradual closure of the room and also produces damage in the salt. The damage, which evolves with time, consists of the formation of microfractures that are thought to link local concentrations of brine in the salt. As a part of the linking process, brine is released into the room. To quantify this process, a constitutive model of creep and fracture of salt was used to determine the extent of the damage zone and then a constitutive model relating the damage to the release of brine was used to predict the brine accumulation.

2.1 *Constitutive model of creep and fracture*

A constitutive model for salt creep and fracture has been developed for use in those cases where the occurrence of microfracturing damage is important, such as in formation of the damaged rock zone (DRZ) around underground excavations, because the damage may alter the hydrological response of the salt. This Multimechanism Deformation Coupled Fracture (MDCF) model (Chan et al. 1992, 1996) is an extension of the Modified Multimechanism Deformation (M-D) steady state creep model, with workhardening/recovery transients, proposed by Munson et al. (1989) for WIPP structural calculations. The fracture aspect of the MDCF model now permits the tertiary, or accelerated, creep transient response to be modeled in addition to the steady state with workhardening/recovery transients. Perhaps more importantly for hydrological concerns, the development of damage produces a small volumetric strain which can be related to increased permeability of the salt. The MDCF model is based on the mechanism maps for creep and fracture as they pertain to the temperature, stress, and pressure conditions of the potential WIPP repository.

In the MDCF model, the fracture induced strains from the formation of microfractures add directly to the continuum creep induced strains to give the overall total creep strain. The creep and damage-induced flow behavior can be described in terms of the generalized kinetic equation:

$$\dot{\varepsilon}^{I}_{ij} = \frac{\partial\sigma^{c}_{eq}}{\partial\sigma_{ij}}\dot{\varepsilon}^{c}_{eq} + \frac{\partial\sigma^{\omega_s}_{eq}}{\partial\sigma_{ij}}\dot{\varepsilon}^{\omega_s}_{eq} + \frac{\partial\sigma^{\omega_t}_{eq}}{\partial\sigma_{ij}}\dot{\varepsilon}^{\omega_t}_{eq} \qquad (1)$$

where $\dot{\varepsilon}^{I}_{ij}$ is the total inelastic strain rate and the power-conjugate equivalent stress measures are σ^{c}_{eq}, $\sigma^{\omega_s}_{eq}$, *and* $\sigma^{\omega_t}_{eq}$ for dislocation creep, shear damage, and tensile damage, respectively. The $\dot{\varepsilon}^{c}_{eq}$, $\dot{\varepsilon}^{\omega_s}_{eq}$, and $\dot{\varepsilon}^{\omega_t}_{eq}$ are the conjugate equivalent inelastic strain rates and $\partial\sigma_{ij}$ is the stress tensor. The continuum creep response has been developed by Munson et al. (1989) to reflect both the steady state and transient responses of creep. The continuum creep processes are the result of dislocation motion and are the main deformation component of the model. From the mechanism maps for steady state creep, the individual mechanisms that can be expected to contribute to the WIPP underground room creep response are (1) a high stress dislocation slip, (2) a mechanistically undefined but empirically specified low temperature, low stress creep, and (3) a high temperature, low stress dislocation climb creep. The transient creep behavior is obtained through a transient response function used as a multiplier on the steady state. The transient response treats both stress loading and unloading.

In the fracture process, microfractures, envisioned to preexist or to be induced during salt creep, are considered to exhibit sliding by shear during creep at low or zero confining pressure, resulting in a deviatoric strain rate (Chan et al. 1992, 1996). Furthermore, some of the sliding microfractures may develop wing-tip cracks, whose opening leads to a dilational strain rate. Thus, fracture response of salt exhibits both deviatoric and dilational characteristics. Opening of the cracks is logically a pressure dependent process, which causes the damage-induced inelastic deformation to depend upon the pressure. The fracture processes are entirely separate mechanisms which may produce dilatant strain. They are distinct from those of the dislocation mechanism-induced, nondilatant strain. The three fracture mechanisms are (1) low stress, stress rupture, (2) high stress, brittle intergranular fracture, and (3) low confining pressure, cleavage fracture. Again, the dislocation mechanism-induced strains and the fracture mechanism-induced strains are additive.

Coupling between the creep and fracture processes occurs because the formation of damage (microfractures) reduces the effective load bearing area and hence increases the effective stress driving the creep process. Further coupling occurs because evolution of the damage depends directly upon the transient creep strain rate. In this work it is not possible to give more than this brief summary of the MDCF model; however, the complete development is given elsewhere (Chan et al. 1992, 1996).

This coupled model has been used previously to calculate the development of the DRZ around the Air Intake Shaft of the WIPP facility, with a successful comparison to an *in situ* measure of damage based on the changes in ultrasonic wave speeds (Munson et al. 1995). As in the current case, this study illustrates the difficulty in making comparisons between model predictions of damage and *in situ* results where the measurements are typically indirect indicators of the damage.

2.2 *Constitutive model of brine release*

The model for brine release is based simply upon the level and extent of the damage in the salt adjacent to an excavated opening. As the salt material deforms by creep, it gradually becomes damaged, which is envisioned as an accumulation of microfractures. These microfractures can potentially link discrete brine pockets or brine-saturated clay concentrations. It seems reasonable that the quantity of brine concentrations linked (brine release) would depend upon the number of microfractures or the amount of damage. We assume that the release of brine is directly proportional to the damage calculated by the MDCF model. This is an example of a classic mechanical or "snow plow" model. Further, two extremes of damage are incorporated into the model. First, a minimum damage level for the threshold linking of brine concentrations suggests appropriately that small amounts of damage may be ineffective in brine release. Second, at some point a certain maximum level of damage is reached that is believed to link all brine concentrations, and further damage does not release additional brine. Currently, it is assumed that only a small amount of damage is necessary to initiate release of brine. In this instance, the threshold value must be very nearly the same as the undisturbed initial damage level in the salt mass. Therefore, the relatively small initial material damage specified in the MDCF model for salt (0.0001) can be substituted for the minimum damage level without having a significant impact on the model. Under these assumptions, the amount of brine released per unit volume is related to the total amount of brine per unit volume, apportioned to the amount of local damage. The apportionment is simply the ratio between the minimum and maximum damage levels, with the caveat that the apportionment cannot exceed unity. This is equivalent to the ratio of areas identified as A_s and A_t illustrated in Figure 1. The total brine released will be an integral expression involving damage evolution, the corresponding volume affected, and the brine content.

Typically, however, the integration is done incrementally using the MDCF model finite element solutions for the damage determined in the creep and fracture simulations around the excavation. For the incremental solution, the representation of Figure 1 becomes a series of discrete elements partitioning the distance into the salt. The apportionment for an element then becomes the damaged area, A_{si}, of the element divided by the total area, A_{ti}, of the element. At any given time (t) in the solution, the brine released (V_b(t)) within the configuration modeled can be computed by summing the apportioned volume of the discretized zone that becomes damaged, as follows:

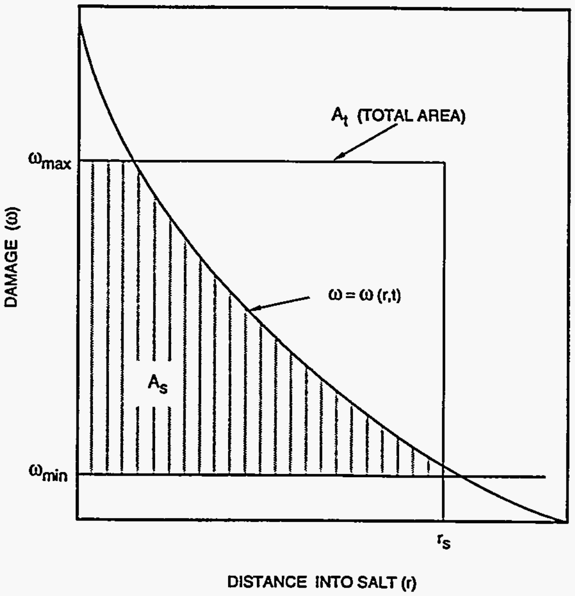

Figure 1. Schematic of Mechanical (Snow Plow) Brine Release Model.

$$V_b(t) = \sum_{x=i}^{n} \frac{(\omega_i(t) - \omega_{min})}{(\omega_{max} - \omega_{min})} f_b V_i \qquad (2)$$

where n is the number of discretized elements in the finite element mesh which exceed the minimum damage level ω_{min}, V_i is the volume of element i, ω_i(t) is the predicted damage, and ω_{max} is the maximum level of damage that is believed necessary to link all brine concentrations.

The behavior of the release model is distinctive. As the damage evolves, progressively more of the salt adjacent to the opening is swept by the damage field, which releases brine according to the level of damage achieved in the damage field. Because the rate of damage accumulation declines with time, the rate of brine release diminishes with time. Further, when the peak damage level exceeds the maximum damage criterion for complete release of brine, the rate of brine release will decrease somewhat more rapidly.

3 *IN SITU* EXPERIMENT

The WIPP underground facility was designed to accommodate a number of *in situ* experiments in order to provide critical input data to the performance assessment process of the long term adequacy of the potential repository. Among these experiments is a specially constructed, large-scale, brine inflow test room (Jensen et al. 1993) located well away from

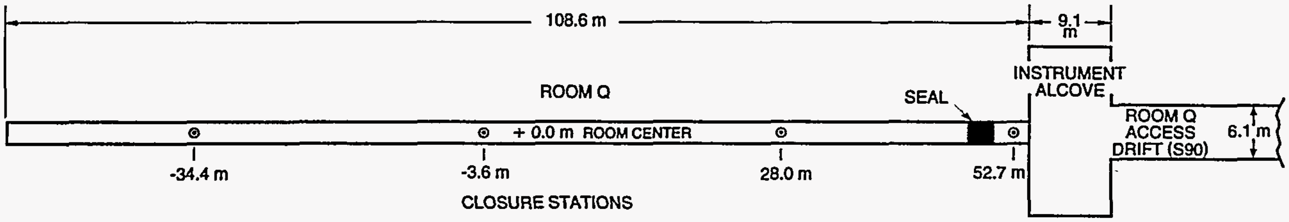

Figure 2. Plan View of Room Q In Situ Experiment.

other excavations. This Brine Inflow Test, illustrated in Figure 2, is conducted in a cylindrical room (Room Q) excavated for the purpose of collecting the brine inflow from the formation. Supplemental instruments also permit determination of the creep closure of the room. The cylindrical geometry is ideal for both hydrological and rock mechanics analyses.

The room was bored in a single pass using a tunnel boring machine. Excavation began on 12 July 1989 and took just 26 days to produce a 2.90-m diameter and 108.6-m-long room. The room is separated from other excavations by an 82.3-m entry passage. Vertical and horizontal remote closure gages were placed at four stations: station 52.7 m at the room entrance, station 28.0 m, station -3.7 m, and station -34.4 m, as measured with respect to the room center. In operation, the experiment measured the amount of brine collected on the floor of the room as a function of time. To reduce the loss of brine through evaporation into the circulating mine ventilation air, a permanent seal was designed and emplaced in the entrance. However, various delays in the emplacement of the seal caused the test room to remain open to the mine ventilation air until 28 March 1991. Prior to this time, no brine accumulation was evident. But subsequently, brine accumulated and was periodically measured volumetrically. The total accumulated brine volume as a function of time (Jensen et al. 1993) is shown graphically in Figure 3. In this graph, the data have been offset vertically by a constant amount to compensate for the unknown loss of brine to the ventilation air during the first two years of operation. After about 4.5 years, the data also show little, if any, further brine accumulation. Although the cause of this change in accumulation is not definitely known, it is believed that a through-going fracture in the room floor, under the seal system, permitted brine to circumvent the seals. A sealed collection station established on the floor external to the permanent seal indeed began to accumulate brine, suggesting flow under the permanent seal. By adding a dye tracer, this flow was confirmed.

Measurements of vertical and horizontal closure were obtained essentially continuously from the time of room excavation. For the three stations interior to the room, closure histories are essentially identical at early times but appear to be slightly diverging as time increases. This effect may be the result of the end effects of the finite-length room. In this regard, less closure is measured at the station nearest the blind end of the room than at room midlength, as would be expected. However, the differences in closure are less than 10% (15 mm) after 6 years. The measured closure histories obtained from the station nearest the center of the room (-3.9 m) are given in Figure 4. Vertical closure is less than the horizontal, probably as a result of the bedded nature of the WIPP salt.

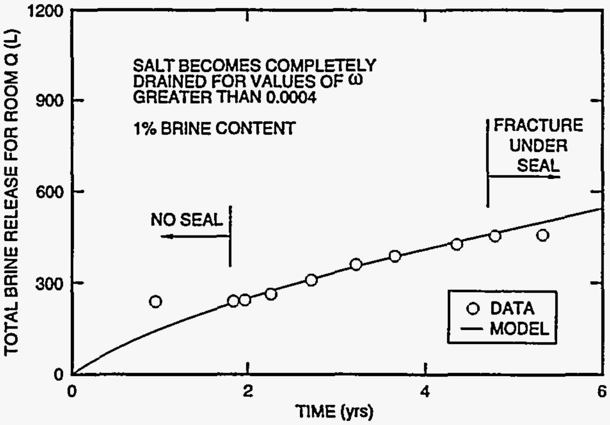

Figure 3. Measured and Calculated Accumulated Brine Release.

4 COMPARISON OF CALCULATION AND EXPERIMENT

The details of the MDCF model of creep and fracture have been incorporated into the finite element code, SPECTROM 32 (Callahan et al. 1989). This code was used to simulate the formation of the DRZ around Room Q. This calculation was a two-dimensional, plane strain simulation with the plane normal to the axis of the cylindrical room. The simulation modeled details of the bedded stratigraphy, including representation of the clay seams as slip lines. The bedded salt layers were argillaceous (clay contain-

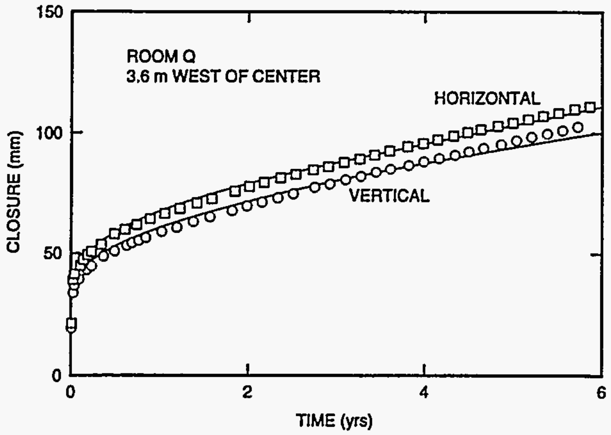

Figure 4. Measured and Calculated Closures of Room Q at the Midstation.

ing) salt with an average clay content of 2.9% by volume. Results of the calculation, as shown in Figure 5 for damage in the radially down direction, suggest that the damage effectively extends to only about 0.7 m (0.48 of a room radius) during the first five years. Actually, even though the damage levels increase, the extent of the damage field does not change very rapidly with time, as indicated by the damage profiles at 5 and 10 years. The details of the damage differ slightly with radial direction around the room, with a notable change in damage at the location of the clay seam that intersects the room near the crown. This change with orientation is apparent in the volumetric strain contours of Figure 6. The levels of damage are quite small, with the damage not exceeding 0.00022 at 5 years and 0.00031 at 10 years. The comparable maximum volume strain is on the order of 0.0015 (0.15%) or less.

The damage contours were used directly in the mechanical brine release model by integration of the

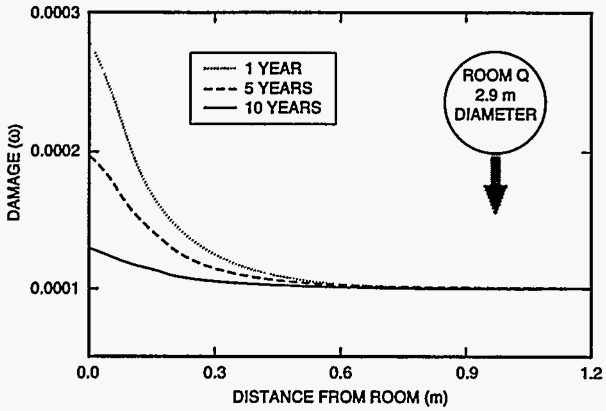

Figure 5. Damage Profiles along a Horizontal Radius at Several Times.

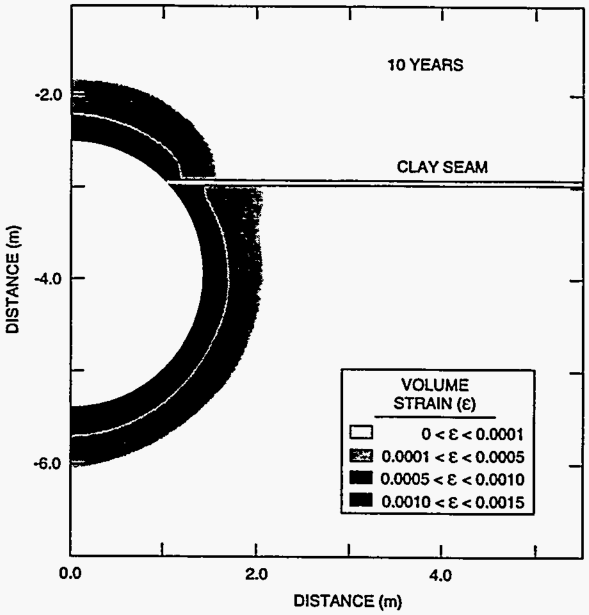

Figure 6. Damage Contours around Room Q at 10 Years.

affected salt volume over the length of the room. This then results in a calculation of the total brine accumulation. As formulated, the brine release model has three parameters, the minimum level of damage for linking of brine concentrations (ω_{min}), the maximum damage (ω_{max}) level at which all of the available brine is released, and the volume fraction of brine available in the salt (f_b). With the volume fraction of brine fixed at 1.0% and the minimum damage level at 0.0001, the only free parameter is the maximum damage. When the maximum damage value is chosen as 0.0004, the predicted total brine release is as given in Figure 3. As is apparent, the measured and calculated brine releases are in quite good agreement over the time interval where the measured values are thought to be accurate. As already noted, the measured brine release is adjusted to account for the unknown initial loss of brine into the ventilation air. This was done by matching the *in situ* data to the prediction at the time of roughly two years. At late times, after 4.5 years, potential loss of brine under the seals is thought to cause the observed lack of agreement.

A direct implication of the adequate prediction using the mechanical model of brine release is that any hydrological process for brine flow must be rapid in comparison to the release through evolution of damage.

With the MDCF model, the room closures are also predicted. These results are shown in comparison to the measured closures in Figure 4. In fact the predicted closures using the complete creep and fracture MDCF model differ little from the previous analyses

(Munson et al. 1993) in which only the continuum creep M-D model was used to simulate the closure. It is evident, especially from the rather small amount of damage, that the fracture strain contribution to the overall strain is quite small for Room Q.

5 SUMMARY

Although brine inflow that accumulates in underground rooms of the WIPP facility may be described by hydrological flow processes, in this work we have shown alternatively that a relatively simple mechanical model of brine release gives reasonable agreement between measured and calculated brine accumulations. The calculations involve the prediction of the evolution of damage using the MDCF model of creep and fracture, with the damage as an input to a "snow plow" model which governs the release of brine from the salt. The range of the mechanical damage is rather small, extending effectively only about 0.7 m (0.48 of a room radius) in five years The volume strain is on the order of 0.15% or less. The volume strains are sufficiently small that the room closures are adequately predicted by either the MDCF or MD model. The reasonable agreement of the model prediction and *in situ* measurements adds support to the validity of the predictive capability based simply on the mechanical aspects of brine release.

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