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WIPP PANEL SIMULATIONS WITH GAS GENERATION[1]

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ABSTRACT

An important issue in nuclear waste repository performance is the potential for fracture development resulting in pathways for release of radionuclides beyond the confines of the repository. A series of demonstration calculations using structural finite element analyses are presented here to examine the effect of internal gas generation on the response of a sealed repository. From the calculated stress fields, the most probable location for a fracture to develop was determined to be within the pillars interior to the repository for the range of parameter values considered. If a fracture interconnects the rooms and panels of the repository, fracture opening produces significant additional void volume to limit the excess gas pressure to less than 1.0 MPa above the overburden pressure. Consequently, the potential for additional fracture development into the barrier pillar is greatly reduced, which provides further confidence that the waste will be contained within the repository.

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is a research and development facility authorized to demonstrate the safe disposal of radioactive Transuranic (TRU) waste generated by the United States defense programs. The WIPP facility has been constructed in the bedded salt deposits of the Salado Formation in southeastern New Mexico. To be in accord with existing Environmental Protection Agency regulations, the proposed repository must isolate the radioactive waste from the environment for as long

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as 10,000 years. An important issue addressed in this work is the potential for fracture development resulting in pathways for the possible release of radionuclides or contaminated gases beyond the confines of the repository.

As shown in Figure 1, the present WIPP design has eight panels in the southern portion of the facility, each composed of seven disposal rooms. The waste will be contained in drums or other containers placed in the rooms, in the drifts connecting the disposal rooms, and in the entry drifts. The northern portion of the facility, which consists of the former experimental and Site and Preliminary Design Validation (SPDV) areas, will not be backfilled or used for storage of waste. After the containers are placed in the rooms, crushed salt or some other type of engineered backfill will be placed over, around, and between the containers to fill part of the void space. As salt in the surrounding formation creeps inward in response to overburden loads, the volume of the remaining void space will decrease and the waste and backfill will compact. Concurrent with room closure, naturally occurring brine can enter the rooms through hydrological flow from the surrounding salt and interbed materials. This process may be aided by creep-induced damage, producing a disturbed rock zone (DRZ) around the underground excavations. Typically, brine will accelerate the decomposition and corrosion of the waste and waste containers to produce gaseous products. Gas pressurization may retard the closure process, extend preexisting fractures, create new fractures, or cause separation or parting of the weaker, more brittle members in the host formation.

A number of studies on the generation of gas and the subsequent structural response of the repository have been reported (e.g., Butcher and Mendenhall [1993]). Because of computer capacity limitations in many of these calculations, the structural behavior of the repository storage rooms with appropriate room contents was inferred from analyses of simple configurations. Symmetry conditions placed on the calculations permitted the simulation of either a single isolated room or an infinite array of rooms. The obvious drawbacks to the simplified calculations are that the differences in room response because of location in a finite array of rooms and the detailed response of the full repository with various room and pillar sizes are not treated accurately. Advances in computer technology have now made it feasible to model full repository cross sections, including room contents, with concurrent gas generation.

In the simulations presented here, a complete panel of seven rooms and the associated entry system of two drifts, with a vertical symmetry plane, was used to represent the entire WIPP repository cross section. This model is used in a series of demonstration calculations to simulate creep closure of the repository, pressure caused by gas generation, and potential fracture response from stress states induced by gas generation. Specifically, the demonstration calculations treat (1) the effects of the uncertainty in gas generation rates on the repository system where fracture is prohibited, (2) the effects of gas generation on the stress fields within the pillars interior to the repository and in the barrier pillars around the repository, (3) the effects of fractures on repository gas pressures and corresponding fracture opening, and (4) the effects of the nonstorage volumes in the northern portion of the facility. The results of these calculations suggest that consideration of the entire repository response impacts the magnitude of repository overpressurization (i.e., gas pressure exceeding the initial lithostatic state of stress) and the extent of fracture development. Also, while a complete resolution to questions about the initiation and propagation of fractures cannot be provided by this investigation, it does provide information regarding the expected gas pressures. If these pressures are sufficient to cause fractures to initiate in the salt or interbeds, then calculations can be performed to determine whether preexisting or newly generated fractures will open to relieve pressurization.

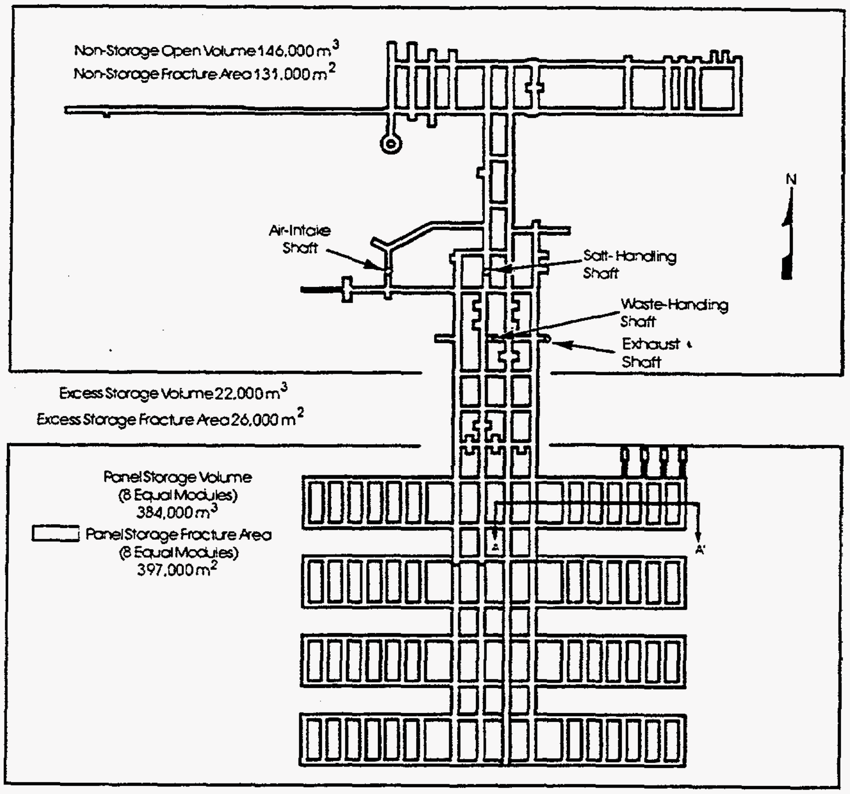

Figure 1. Plan View of the Proposed Underground WIPP Facility.

PROBLEM DESCRIPTION

The problem analyzed involves the simulation of the time-dependent creep of the salt surrounding the WIPP repository and concurrent gas generation produced by decomposition and corrosion of the TRU waste. The salt was assumed to be impermeable to gas and the behavior of the gas within the rooms was assumed to be governed by the ideal gas law. All of the underground workings were assumed to be connected with free gas flow between rooms; therefore, gas pressure is in equilibrium throughout the repository. The contents contained within the panel (i.e., type and quantity of waste, backfill, and void space) were assumed to be uniformly distributed throughout the panel and are identical to the contents to be stored in a typical disposal room, unless specifically noted. The effects of fractures on repository gas pressure were analyzed by assuming a preexisting fracture through the pillars within the confines of the repository which is permeable to the gas. Aspects of the nonstorage-mined volume were accounted for in one of the repository simulations by assuming average values for initial porosity and gas generation per unit volume that take into account the overall repository. The remainder of this section provides a more detailed description of the problems solved, including a description of the finite element model, material model for salt, assumed gas generation rates, and characterization of the room contents.

Finite Element Model

Although an exact geomechanics evaluation of the proposed WIPP repository facility involves the three-dimensional configuration, it remains currently practical to solve only the two-dimensional repository problem using the finite element method, especially when the surrounding salt displays time-dependent creep deformation. The planned waste disposal area in the southern portion of the facility comprises eight panels of seven rooms each, and four haulage ways that provide access and ventilation to the panels. The storage area is symmetric about a vertical plane between the two center haulage ways that divides the panels into two groups, each containing four storage panels, and the associated entry system of two drifts. It is possible to obtain a very reasonable simulation of the complete repository through a two-dimensional representation of an entire storage panel, as denoted by the cross-section A-A' in the plan view of Figure 1. In cross section, the two-dimensional panel configuration is modeled as shown in Figure 2, which gives all of the necessary dimensions.

The model boundaries extended 500 m beyond the top, bottom, and barrier pillar side of the repository. The left boundary represents the symmetry plane of the repository. Horizontal displacements were prescribed to be zero on the left symmetry plane and on the right boundary. Vertical displacements were prescribed to be zero along the bottom boundary. The finite element mesh contains 20,740 four-node, isoparametric quadrilateral elements with increased refinement near the excavations. Elements were included in the room regions to accommodate the gas generation model. The finite element program, **SPECTROM-32** [Callahan et al., 1989], was used to perform the calculations. For the current simulations, it was assumed that the deformations and strains are sufficiently small that they can be predicted using the infinitesimal strain assumption.

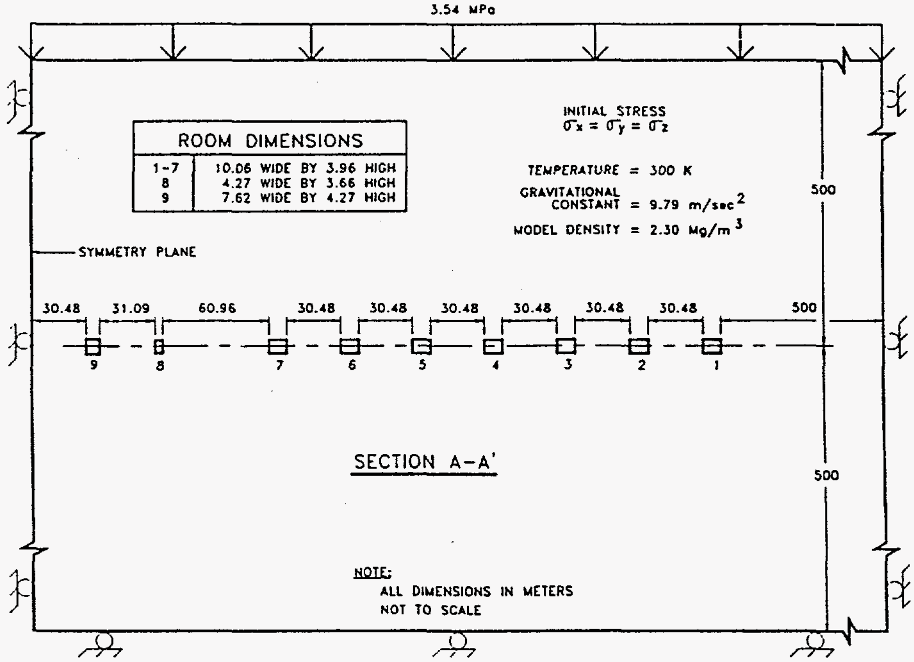

Figure 2. Two-Dimensional Geomechanical Model of a WIPP Storage Panel.

A lithostatic stress state was assumed that varies linearly with depth based on an average material density within the calculational model. The stress at the repository horizon, which is approximately 655 m below the surface of the ground, was taken to be –14.8 MPa. The computed overburden pressure at the upper boundary of the model is –3.54 MPa.

Material Model for Salt

The extreme size of this configuration requires that the geological setting of the WIPP facility be simplified. Thus, even though the actual bedded stratigraphy around the facility horizon is composed of halite, argillaceous halite, anhydrite, and polyhalite layers and clay in the form of clay stringers [Munson et al., 1989], a simplified stratigraphy consisting only of halite is used for these calculations.

The Modified Multimechanism Deformation (M-D) steady-state creep model with work-hardening/recovery transients for clean salt [Munson et al., 1989] was used to predict the behavior of the rock mass surrounding the rooms. The model contains three mechanisms corresponding to the three regions identified by the deformation mechanism map where unique mechanisms dominate steady-state creep at the stress and temperature conditions expected for WIPP salt. The M-D model, together with the Tresca flow potential, has been successfully used in a number of validation calculations to simulate large-scale in situ tests, which include isolated heated and unheated rooms, multiple room complexes, and shafts (e.g., Munson and DeVries [1991]). The accuracy of these validation calculations suggests that the constitutive model can be used to predict the response of salt under a variety of stress, loading, and geometrical conditions for the WIPP.

Gas Generation Rates

Gas generation rates are difficult to establish since they depend on a number of unknown factors, including the availability of brine. Brush [1995] gives a range of gas generation rates per drum of waste from a maximum of 155 to a minimum of 1.5 moles/drum/year. In addition, the Engineering Alternatives Task Force (EATF) has defined a baseline case which is representative of the current WIPP design (e.g., Labreche et al. [1995 (E-41)]). The EATF baseline case specified that the gas production from anoxic corrosion is 1,050 moles/drum with a production rate of 1 mole/drum/year, and the estimated gas production from microbial activity is 550 moles/drum with a production rate of 1 mole/drum/year. This means that the microbial activity ceases after 550 years while the anoxic corrosion ceases after 1,050 years. Gas production from radiolysis is expected to be negligible compared to the potential amount of gas produced from decomposition and corrosion. Without further knowledge of the actual gas production, it is assumed that the gas generation rates given by the EATF are adequate for the purpose of these calculations.

Room Contents Characterization

Based on the current design, each 91.4-m-long disposal room will contain 6,804 drums of unprocessed waste [Butcher et al., 1995]. The contents of the rooms were not modeled; thus, the closure resistance provided by the room contents (compacting waste and backfill) was ignored. Whether or not the room contents are modeled explicitly is not expected to significantly alter the predicted stress state in the salt because the closure resistance provided by the room contents is small [Butcher and Mendenhall, 1993 (A-218)] compared to gas pressures generated. Nevertheless, the initial porosity of the gas generating regions was specified as 0.6382 [Butcher et al., 1995], which accounts for the actual solid mass content within the rooms.

The waste which will be emplaced in the entry drifts was assumed to have the same waste-to-room volume ratio as the disposal rooms and was assumed to have the same initial porosity as that of the disposal rooms. In this manner, the additional mass of gas generated in the entry drifts was included in the simulations. The computed gas pressure was represented by a surface traction of the same magnitude applied to the room periphery. For the calculation that assumes a fracture within the confines of the repository, a surface traction equal to the gas pressure was prescribed along the interfaces between the fractured material and the salt, as well as along the periphery of the rooms.

CALCULATIONS AND RESULTS

Gas Pressure

The full WIPP disposal panel was simulated for 1,500 years after excavation, with several different gas generation rates. Gas generation was assumed to begin immediately after excavation and continue until materials were depleted by chemical and microbial activity. The gas pressure in the perfectly sealed repository will increase as gas is generated. Without creep closure, the maximum gas pressure predicted to develop in the repository, assuming 1,600 moles/drum of gas, is 11.6 MPa. This value was determined from a relatively simple linear-elastic finite element analyses of the WIPP panel configuration. Therefore, gas generation alone is not sufficient to obtain a gas pressure greater than the overburden pressure of 14.8 MPa. However, if the creep closure of the rooms is modeled, the gas pressure can exceed the overburden pressure because of the diminished volume available to the gas.

The gas generation rates specified by the EATF for the baseline case were used in the first calculation. These results are shown in Figure 3 (curve identified as 2:1 moles/drum/year) and indicate that the creep closure decreases room volume at a rate sufficiently high that the relatively slow gas generation rate eventually results in pressurization of the repository above lithostatic pressure. This result is consistent with Butcher and Mendenhall [1993] with the peak pressure of 22.1 MPa at 550 years. The pressure at longer times decreases because the overpressure causes creep-induced expansion of storage rooms. To determine the relative effect of gas generation and creep closure rates, additional calculations were performed with total production rates of 155, 30, and 5 moles/drum/year spanning the range of possible rates. For consistency, all calculations assume that 1,600 moles of gas are produced by each waste container. The gas generation rate was assumed to be constant and to begin immediately after excavation. These results are compared in Figure 3 and indicate that gas generation rates greater than 30 moles/drum/year will not produce an overpressurization. For the higher generation rates, the loss of volume in the repository from creep is insufficient to reduce the gas expansion volume since the increased pressures reduce the deviatoric stress and slow the creep process.

An additional calculation was made to determine the influence of the nonstorage-mined volume on the amount of overpressurization. As shown in Figure 1, the repository storage volume in the southern part of the facility contains some 406,000 m^3, and the nonstorage region to the north contains another 146,000 m^3, which is available to accommodate gas. The availability of the additional volume can be examined by assuming average facility values for void space and gas production per unit volume. The calculated results are expected to be conservative since this modeling procedure assumes that the void volume in the northern portion of the facility closes at the same rate as the panel cross section, which has a higher extraction ratio. The average porosity of the WIPP facility, including the northern experimental area, was estimated to be 0.734. For the two-dimensional model, the corresponding change in the amount of gas generated per unit depth of the calculation model is approximately 26 percent less than the panel calculations previously presented. The repository response, including aspects of the nonstorage volume, was calculated using the gas generation rates specified by the EATF for the baseline case, resulting in the pressure generation shown in Figure 3. Interestingly, the result of additional gas storage volume tends to delay the pressure rise, but decreases the peak overpressurization by only 1 MPa.

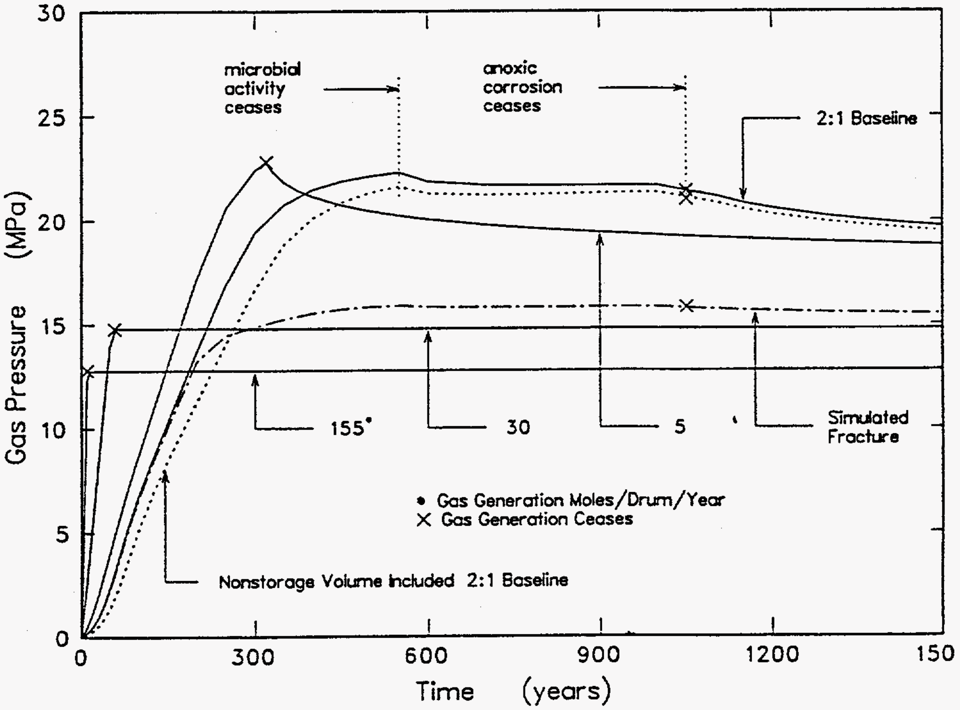

Figure 3. Predicted Gas Pressures Assuming Different Gas Generation Rates.

Pillar Stresses

While pressurization may lead to the breakdown of the formation and the development of fractures and to stress concentrations at crack tips requiring detailed fracture mechanics studies, it is not possible to examine these processes with the large numerical models used in this work. Rather, we can examine only the limiting conditions of fracture; i.e., the conditions of no fracture or predefined gas permeable fractures. For the preexisting fracture condition, opening of the fracture will result in altered repository responses including repository overburden uplifting. For the no-fracture condition, possible failure events can be postulated based on the calculated stress fields within the repository structure. Geotechnical engineers have traditionally used a comparison of induced stresses in the rock to rock strength to evaluate the potential for structural failure. In general, as long as the pillar stresses remain compressive or less than the tensile strength of the rock, development or propagation of fractures will be difficult in the absence of an existing crack.

For the calculation noted previously with baseline gas generation rates, the vertical stresses induced in the repository pillars at 1, 100, and 1,000 years are given in Figure 4. Stresses shown are those calculated in the horizontal row of elements at the room midheight, where negative values indicate compression. Obviously, the gaps in stress correspond to the rooms, where there is no vertical stress at the room midplane. As illustrated in Figure 4a, after relaxation of the high initial elastic compressive stresses, the least compressive vertical stresses occur at the pillar surfaces early in time. However, to maintain vertical equilibrium, the compressive stress near the center of the pillar is actually greater than the overburden stress, conforming to the tributary stress principle. Before significant gas pressures are generated, the vertical stresses near the room surfaces are typically between –8 and –10 MPa and decrease to approximately –20 MPa in the center of the pillars separating the rooms. As the gas pressure increases from 4 MPa to 18 MPa between 50 and 200 years, the stresses become more uniformly distributed across the pillars, as shown in Figure 4b. Continued pressurization results in expansion of the rooms and subsequent narrowing of the pillars. This process continues with the stresses near the rib becoming more compressive, eventually resulting in an inversion of the vertical stress profiles when the pressure exceeds the lithostatic stress as shown in Figure 4c. As the gas pressure in the rooms becomes great enough to support some of the overburden, the pillars unload and the stress near the center of the pillars becomes less compressive. These effects are most pronounced in the pillars between the entry drifts; however, at no time does the stress become tensile.

Preexisting Fracture

Based on the results discussed above, the stresses remain compressive in the no-fracture condition, suggesting that the compressive stress field could restrict the propagation of existing fractures. However, it is unlikely that the repository can sustain internal pressures significantly greater than the overburden stress without failure processes intervening. The consequences of gas generation, which produces pressures in excess of the lithostatic stress, is potentially significant. There are at least two possible responses of the repository. First, as the gas pressure in the repository increases, it is possible that the inflow of brine will be markedly inhibited and perhaps forced from the room back into the salt formation [Butcher and Mendenhall, 1993]. In this event, gas production may be limited since sufficient quantities of brine would not be available for decomposition and corrosion of the metallic drums and waste constituents. Second, the stress conditions may make the salt formation and interbeds candidates for local hydraulic fracture [Beauheim et al., 1993; Xie et al., 1994].

Although the first condition appears to be the most likely, it requires a hydrological analysis which is beyond the structural analysis examined in this work. The mechanical aspects of the second possibility are examined here.

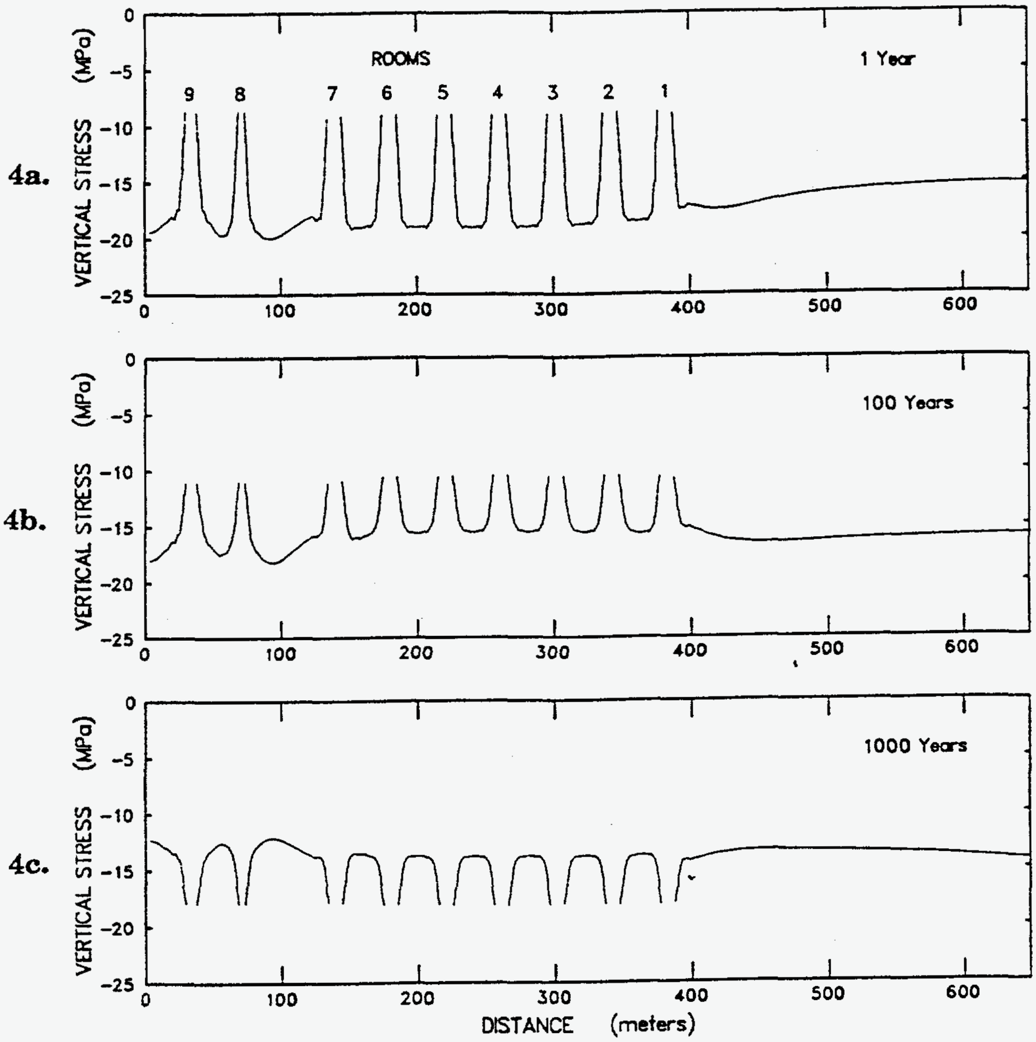

Figure 4. Vertical Stress Profiles Through the Repository at Room Midheight.

Recent results [Xie et al., 1994] using a finite element solution assuming linear elastic fracture mechanics have been used to argue that existing fractures will propagate into the far-field around the repository. However, the linear elastic fracture mechanics solution potentially overpredicts the crack length because it does not take into account the time-dependent relaxation of salt with the possibly large fracture process zone at the crack tip and the potential for fracture development within the confines of the repository.

Field data for hydraulic-fracturing tests indicate that as the gas pressure increases, the breakdown stress for initiation of a fracture can be exceeded in the salt and interbeds. This breakdown stress for interbeds is on the order of 1.8 to 6.0 MPa with a fracture-extension pressure of 1.4 MPa above the in situ stress [Beauheim et al., 1993]. Moreover, this breakdown pressure does not necessarily have to exceed the overburden stress. This is because the altered stress field adjacent to the underground openings results in a minimum principal stress state markedly less than the overburden stress [Beauheim et al., 1993]. Based on the computed stress field, the conditions for fracture development would certainly be met first in the pillars between rooms of the panel or entries where the compressive stresses are the smallest. Additionally, the perturbed stress state resulting from excavation and gas pressurization could allow fracture development at gas pressures below the lithostatic stress. It is postulated that the gas pressure will become sufficient to propagate a fracture through the pillars, if the preexisting fractures do not already extend through the pillars, before a fracture will develop in the massive salt barrier pillar. Possible sites for preexisting fractures would be the anhydrite/clay interbeds between major salt layers.

To examine the event of a fracture produced in the creeping repository environment, the equivalent of a preexisting plane of separation is introduced over portions of the repository postulated to have fractured. The preexisting fracture was modeled as a very thin material from the left symmetry plane through all of the pillars in the panel at midheight. The fracture was assumed to be permeable to gas and pressurized along its entire length. The preexisting fracture was not extended into the massive salt barrier pillar outside the repository. The preexisting fracture was modeled as a limited tension material, which strains without resistance when the stress in the material reaches a given tensile value (zero in this case) [Callahan et al., 1989]. Whenever the stress in the limited tension material becomes tensile, the material separates, adding to the void volume created by expansion of the rooms. In the calculation, gas was generated at the baseline rates given by the EATF.

Figure 3 shows the results of this calculation and indicates that the predicted gas pressure is essentially the same for the first 100 years as the earlier calculation without the preexisting fracture. However, since the gas is accessible to the fracture surfaces, the preexisting fracture begins to open as the pressure approaches lithostatic. As the gas generation continues, the fracture opens further and the gas pressure, although it increases, does not exceed 15.8 MPa. Thus, the overpressurization for a preexisting or created fracture through the barrier pillars surrounding the repository is limited to about 1.0 MPa. The magnitude of the fracture opening or pillar separation at several discrete times is given in Figure 5. Considerable detail can be seen in the plot, with greater fracture opening nearer the excavations than at pillar centers. For the entire repository, fracture opening is greatest between Rooms 4 and 5. Fracture opening near the center of the repository is less pronounced because the compressive stress is greater here than over the disposal rooms. Although this trend continues with time, it becomes less pronounced. The maximum uplift at the center of the repository is about 0.3 m.

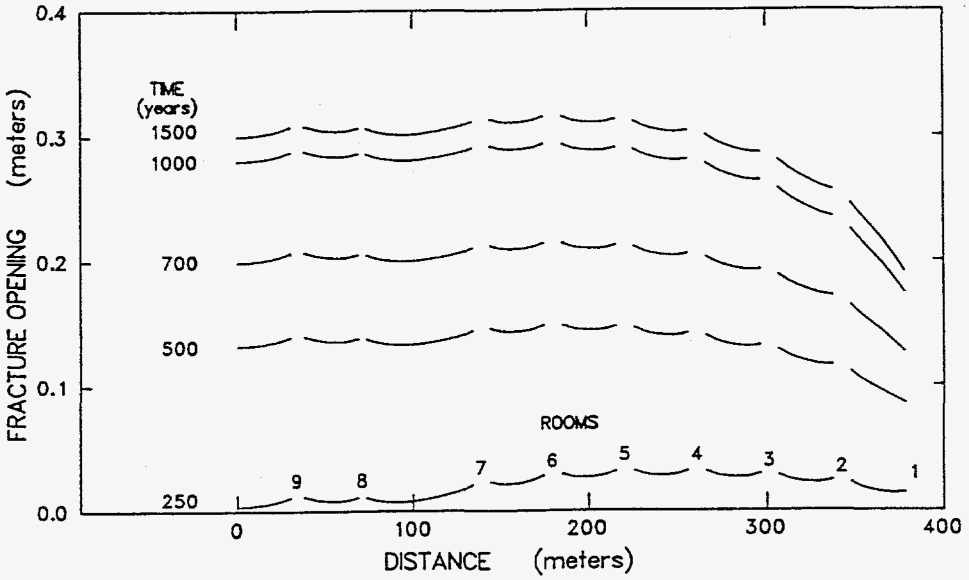

Figure 5. Opening of a Fracture Through the Repository at Room Midheight.

The implications of these calculations are that the fracture expansion within the confines of the repository provides for expansion of gas and effectively limits the gas pressure. In fact, the excess pressure is less than the experimentally determined fracture-extension pressure given by Beauheim et al. [1993]. This suggests that the fracture process makes additional volume available for gas expansion within the confines of the repository and reduces the pressures, which decreases the potential for fractures to propagate away from the repository.

The three-dimensional geometry of the repository will affect the fracture opening results. If all the pillars within the repository are fractured, the total available fracture area is approximately 1.38 times the total area of the panels. Although no calculation was made, the additional fracture area available suggests that the actual uplift over the repository may be approximately 0.2 m. Although the overpressure is probably not decreased much by this additional fracture area, the increase in fracture area will further assure that the overpressure remains less than 1 MPa.

CONCLUSIONS

Finite element demonstration calculations were performed using a plane-strain model of a WIPP storage panel cross section. Because estimates of the type and amounts of gases produced within the repository are uncertain, calculations were performed for a range of gas generation rates. The results of this parametric study suggest that a gas generation rate less than 30 moles/drum/year will potentially result in gas pressures within the repository that exceed the overburden pressure, assuming 1,600 moles or fewer of gas will be produced per waste drum. Even though the gas pressure exceeds lithostatic, the stresses in the pillars remain compressive, which strongly implies that fractures would have difficulty forming or propagating in the compressive stress field, in the absence of existing pressurized cracks.

On the basis of hydraulic fracture tests at the WIPP, the potential appears to exist for a fracture to develop or propagate if the gas pressure becomes significantly greater than the overburden pressure. When the conditions of the complete repository are simulated, as was possible in these demonstration calculations, the results suggest that fracture development, if it occurs, will take place within the confines of the repository. The most likely place for the fracture to occur is along interbeds through the pillars of the repository where the compressive stress is the least. This condition can be modeled as a preexisting gas-filled fracture over the repository area, which was determined to have a significant influence on the repository response. The calculation shows that the fracture opens to about 0.3 m over the repository and effectively limits the over-pressurization to about 1.0 MPa. Inclusion of the nonstorage region of the repository would undoubtedly result in an even lower calculated pressure and smaller fracture opening.

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