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# Evaluation of Brine Inflow at the Waste Isolation Pilot Plant

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## ABSTRACT

The Waste Isolation Pilot Plant (WIPP) is a mined, geologic repository operated for the U.S. Department of Energy. Ongoing technical programs at the facility support requirements regarding continued demonstration of compliance with regulations and improvements to operational efficiency. One factor that can be important to performance measures at WIPP is the volume of fluid flowing into the repository. The objective of the analysis presented in this paper is to address those processes which influence liquid inflow into the waste disposal areas. Simulations focus on the coupling between brine inflow and properties of the proximal damaged zone in the host rock. Calculations show that significant reduction in predicted brine inflow results when two-phase flow properties of the damaged zone are modified relative to baseline values. The results warrant further investigation regarding these properties. The study also indicates that only nominal improvement to predictive capabilities would result from implementation of a fully coupled transient approach to simulate development of damage in the host rock.

KEYWORDS: brine inflow, nuclear repository, transuranic, waste disposal, WIPP

## OBJECTIVE

The Waste Isolation Pilot Plant (WIPP) is a mined, geologic repository operated for the U.S. Department of Energy (DOE). In 1998 the U.S. Environmental Protection Agency (EPA) certified WIPP for acceptance of transuranic waste generated as a consequence of nuclear weapons research and production. Waste packages are shipped from DOE sites

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across the United States to the disposal facility, which is located in the southeastern corner of New Mexico.

The underground facilities are excavated approximately 650 m below the surface in the Permian Salado Formation—a thick, predominantly halite evaporite sequence. Within this paper, the terms "halite" and "salt" are used interchangeably; the term "salt" is commonly used in geomechanical analyses, while the term "halite," more commonly used in hydrological analyses, is used to describe the mineralogy of a specific lithologic unit.

Shaft sinking at the WIPP began in 1980, and most of the existing excavation was complete in 1984. Design of the repository consists of a series of eight wing panels, with seven rooms in each panel and two central equivalent panels. The underground rooms and drifts of the WIPP facility were excavated by continuous-mining techniques, thus minimizing excavation damage to the formation. Blasting techniques are not used for the WIPP underground.

Experimental programs conducted in the underground include measurement of geomechanical, geochemical, and hydrological parameters (Knowles et al., 1996; Beauheim et al., 1993; Munson, 1991; Borns and Stormont, 1988). Results from the field, coupled with theoretical developments and laboratory studies, provide the technical basis supporting the WIPP facility as a permanent disposal site.

Prior to certification and receipt of waste, the DOE was required to demonstrate that transport of contaminants from the repository to the biosphere remains below regulatory limits for 10,000 years. Demonstration of compliance with regulations was achieved through quantitative calculations of fluid flows and contaminant transport within a region extending from several hundred meters below the disposal area horizon to the surface, and an area extending approximately 40 $km^2$ around the repository footprint. To account for uncertainties in parameter values, quantitative analysis of the repository consisted of a set of probabilistic performance assessment calculations. The results of a set of calculations performed for the certification application were submitted to the EPA in 1996 (US DOE, 1996).

Ongoing technical programs at WIPP are designed to support site monitoring requirements, to allow continued demonstration of compliance with regulations, and to improve operational efficiency. One factor shown to be potentially important to the performance of WIPP is the volume of in situ fluid flowing into the repository. This fluid will be brine from the surrounding Salado Formation.

The volume of Salado brine inflow during disposal operations is very small, and is insufficient to warrant any preventive measures. Brine inflow is of significance only with respect to its influence on the long-term, post-closure behavior of the disposal system over the 10,000-year regulatory period. Prior sensitivity studies show that predictions of brine inflow are influenced by the conceptual models of the host rock and their assumed parameters (Helton et al., 1998).

Compared to crystalline rocks, salt will creep readily in response to stress differences (Munson et al., 1991). Creation of a mined opening alters the stress field, resulting in formation of a disturbed rock zone (DRZ) consisting of microfractures in the salt around the excavation. Compared to the intact salt, the DRZ will have an increased porosity because of the microfracturing, increased permeability as a result of interconnected microfractures, and a decreased load-bearing capacity or strength. Over time, the DRZ properties will change as salt creep continues.

Full-scale probabilistic performance assessment calculations demonstrate that the quantity of predicted brine inflow to the repository is tied to the existence of a DRZ around the waste disposal regions. As will be discussed in this paper, the evolution of this DRZ entails coupled interactions between hydrological and geomechanical processes. However, the large-scale, system-wide performance assessment calculations do not capture the details of these processes. The analysis presented in this paper addresses processes that relate brine inflow into the waste disposal areas to the DRZ and examines the sensitivity of this inflow to a number of parameters. Uncertainty exists with regard to the rate and volume of the inflow. Current laboratory and theoretical studies support efforts to reduce this uncertainty. The numerical studies of predicted brine inflow presented here have been designed to identify the most sensitive parameters and processes and to focus programs to quantify these. Because numerical tools coupling salt creep and fluid flows are not currently available, these calculations use a partially coupled approach to assess sensitivity of brine inflow to the characteristics of the DRZ.

## METHODOLOGY

### Physical Setting

Stratigraphic units associated with the WIPP repository are depicted in Figure 1. From the surface downward, principal stratigraphic units are the Dewey Lake Red Beds, Rustler Formation, and the Salado Formation. The Dewey Lake Red Beds consist of alternating layers of sandstone and siltstone. The Rustler Formation consists of carbonates and is the youngest of the Late Permian evaporite sequence. The 250-millionyear-old Salado Formation is more than 600 m thick and lies below the Rustler. Depositional models for the Salado have been presented by Lowenstein (1988) and Holt and Powers (1990). These models assume cyclical deposition of thin claystones and sulfates (anhydrites) through flooding of a large basin; halite beds are precipitated from standing water bodies. Complete depositional cycles are typically a few meters thick. Anhydrite layers above and below the repository horizon are designated as marker beds and are numbered, starting at 100, with numbers increasing as a function of depth. Marker beds 138 and 139 reside approximately 12 m above and 2 m below the waste disposal horizon, respectively.

The Salado stratigraphy is continuous over horizontal scales of hundreds of meters to kilometers and dips slightly to the southeast. The thickness of the Salado between the repository horizon and Rustler Formation isolates the repository horizon from any known water-bearing units. Lithology at the repository horizon consists of clear to argillaceous halite.

Salt deforms viscoplastically (creeps) in response to stress differences, so that disposal rooms will eventually close. For example, Figure 2 shows typical closure curves for a WIPP room (Callahan and deVries, 1991). As seen from this plot, vertical closure occurs rapidly, resulting in room height reduction from 4m to 2m (50%) within 50 years after excavation. Because the closure rate depends on the deviatoric stresses in the incumbent host rock (Munson et al., 1991), creep slows as the stresses equilibrate. As described by Stone (1997a), backstresses imposed by structural stiffness of the waste or increasing room pressure from gas generation also reduce room closure rates. Evaluation of these coupled processes for purposes of WIPP performance calculations entails numerical simulations of closure using a geomechanics code (Stone, 1997b) with the effects of waste stiffness and variable pressures approximated. Results are post-processed to produce a table of room void volume as functions of time and waste room pressure (Bean et al., 1996). The processes of salt creep and development of DRZ are governed by the geomechanical response of the Salado, excavation depth, and geometry.

As the mining machine creates an opening, traction-free surfaces are produced, and a stress difference between the maximum stress and the minimum stress (zero at the free surface) develops instantly. At the depth of the repository, these stress conditions, and the resulting deformations, are sufficient to initiate grain boundary separation in salt, which is the initial stage of DRZ development.

Since initial documentation of the existence of the DRZ (Borns and Stormont, 1988; Holcomb, 1988) investigators have proposed a variety of stress criteria to quantify the onset and extent the DRZ. The experimental database suggests that dilatant zones can be predicted from stress conditions. Van Sambeek et al. (1993) empirically determined a simplified damage factor, *D,* written in terms of stress invariants from laboratory data. If *D* is greater than one, then conditions favor dilation in the following equation:

$$D = \frac{\sqrt{J_2}}{0.27 I_1} \qquad (1)$$

where $J_2$ and $I_1$ are stress invariants, which can be readily evaluated computationally. This damage measure corresponds to the region expected to show a measurable permeability (i.e., $>10^{-21}$ m$^2$) based on laboratory experiments. The corresponding increase in porosity, or dilatancy, remains small, with damage strains of less than 2% (Knowles et al., 1996). Figure 3 depicts a schematic of DRZ development around a WIPP panel access drift. The plot shows that dilation is likely between the clay seam and the roof of the waste room and between the underlying Marker Bed 139 and the floor. The criterion for $0.8 < D < 1.0$ is also plotted such that the transition to non-dilational stress conditions can be ascertained in the figure. When load is reapplied to the salt, the DRZ tends to heal. However, because of the time needed to compact the waste and heal large fractures, reversal of the DRZ process around the disposal rooms will take centuries.

Field measurements indicate that dilatancy may extend farther than predicted using Equation 1, but the magnitude of the effect on permeability outside this region is unknown. This is partly caused by the lack of quantitative definition relating DRZ damage to permeability. As noted by Roberts et al. (1999), permeability of the Salado increases as a function of pore pressure, as would be expected from the effective stress principle. To date, developmental work has not led to successful coupling between salt deformation, DRZ evolution, and permeability. Therefore, other means have been employed to capture these effects in performance assessment calculations. Performance assessment capabilities for WIPP have evolved over a period of 10 years (Knowles et al., 1999). Within this time the need to consider complex, coupled processes in WIPP performance evaluations has become increasingly clear. This paper evaluates possible advantages of using a fully coupled approach for calculation of brine inflow.

The water content of the Salado is approximately 1.0 to 1.5% by weight, with a similarly low porosity (about 1.0 to 1.5%). Possible mechanisms for fluid flow in the Salado have been debated for a number of years (Howarth et al., 1995). Proposed mechanisms include fluid flow from the far field in response to potentiometric gradients, redistribution of fluids in interconnected networks formed due to fracture processes, and drainage from clay layers and pockets within the Salado. Transient brine seepage has been noted on excavation faces, at a number of anhydrite/polyhalite marker beds, and into holes drilled into the repository horizon. These and other field and laboratory data support a conceptual model for flow in the Salado that combines the far field flow and redistribution mechanisms (Domski et al., 1996; Roberts et al., 1999). Table 1 summarizes permeability, porosity, and pore pressure of the bedded units of the Salado. These values represent the technical baseline approved by the regulator for use in WIPP calculations, as well as data acquired subsequent to the certification application. All units exhibit low permeability, low porosity, and high pore pressure.

The disturbed zone may connect the more permeable marker beds above and below the waste rooms to the repository horizon. These marker beds are thought to contribute a significant percentage of the total predicted brine inflow to disposal areas during the regulatory period. In general, if a permeable pathway exists, pore pressures significantly different than hydrostatic will tend to be dissipated by flow processes. The presence of high pore pressures in the Salado remains a topic of technical discussion. However, the rate at which fluid flow dissipates in salt is extremely slow, even on geologic time scales.

The pore fluid in undisturbed Salado interbeds is brine. Creation of the DRZ associated with an excavated opening results in partial desaturation of the pores, so that two-phase conditions exist near the opening, and flow of brine is governed by the relative permeability.

Relative permeability is defined as:

$$k_{rl} = \frac{k_l}{k} \tag{2}$$

where $k_l$ is the permeability to the liquid phase (brine) and $k$ is the intrinsic, or absolute, permeability of the formation. Relative permeability is a function of the phase saturation. It can be written in terms of the effective saturation, where effective saturation is defined as:

$$S_e = \frac{S - S_r}{1 - S_r} \tag{3}$$

Residual saturation, $S_r$, is regarded as the lowest obtainable saturation under flow conditions, i.e., the saturation at which the phase becomes discontinuous and advective fluid flow within that phase is no longer possible. The relationship between relative permeability and saturation can be described, for example, in the Brooks-Corey model. In this model, movement of a fluid in phase $l$ between pore spaces requires that two conditions be met: (1) a continuous path of fluid must exist between the adjacent pores, characterized by effective saturation given in Equation 3, and (2) capillary pressures must exceed a minimum value, defined as a threshold pressure. In the Brooks-Corey model, threshold pressure is defined as:

$$P_{ct} = P_c(S_e^{1/\lambda}) \tag{4}$$

The pore-size distribution index in this equation, $\lambda$, lumps together the influence of pore size, shape, and tortuosity (Brooks and Corey, 1966).

## Numerical Model

The analysis presented in this section consists of a numerical sensitivity study of the processes and parameters considered likely to influence brine seepage into the WIPP disposal areas. Issues related to brine inflow pertain to DRZ geometry relative to the waste panel volumes, as well as selected fluid flow parameters. A baseline DRZ model geometry and parameter set are defined. Results are compared to variations in DRZ properties, as well to an alternative geometry and conceptual model of the damaged zone. The modeled region is a single WIPP disposal room.

A numerical two-phase flow code, BRAGFLO (BRine And Gas FLOw) was used in the calculations for this study. This code does not include geomechanical processes such as salt creep. Salt creep is accommodated within the BRAGFLO architecture as a look-up table generated for WIPP-specific conditions, as previously described. Additional details regarding architecture and theory can be found in Appendix BRAGFLO of US DOE (1996). Other assumed properties for the disposal room properties are consistent with laboratory studies on the permeability of compacted waste drums (Luker et al., 1991). The waste and packages will contain metals. Corrosion of iron occurs when regions surrounding waste packages become brine-saturated. This process generates hydrogen gas and consumes liquid; it is accommodated in the BRAGFLO code through a stoichiometric equation that is coupled to brine inflow. Microbial degradation of organic material is also likely. Because current models for microbial degradation are not coupled to brine inflow into the waste areas, this process is not considered in the present analysis.

The numerical model was run on a two-dimensional $19 \times 35$ grid. Hydraulic no-flow boundary conditions were set at the exterior grid blocks. Fluid pressure for exterior and interior cells were functions of elevation, brine density, and compressibility. Atmospheric pressure was initially assigned to the waste room. Simulations were initialized with a five-year conditioning run to allow waste room pressures and saturation to equilibrate under the initial and boundary conditions. Following the initialization run, conditions in the waste room are re-set so that (1) at the start of the 1000-year simulation period the waste room is dry and at atmospheric pressure, and (2) the DRZ partially desaturated. A 1000-year simulation period was selected because creep closure (Figure 2) will largely cease by this time and healing of the DRZ could occur.

Mean values from the technical baseline are applied for hydraulic properties of the undisturbed Salado Formation, as presented in Table 1. For the baseline simulations, the DRZ is extended about 12 m above the repository rooms to Marker Bed 138, and about 2 m below the repository floor to the bottom of Marker Bed 139. This geometry represents the maximum possible extent of a damaged zone around a WIPP room, based on both field and theoretical studies. Representation of the DRZ in WIPP analyses has evolved from a large zone extending laterally around room pillars to this baseline geometry (Sandia National Laboratories, 1992).

Of interest within this analysis is the effect on brine inflow if the extent of the DRZ is assumed to be less than the baseline and more representative of a "vaulted" damage zone above the waste area. This geometry represents an additional reduction in the assumed areal extent of the DRZ for purposes of analysis and is not intended to optimize the DRZ model. Instead, it is used as a tool to perform sensitivity studies as compared to the baseline model. Damage in the vaulted geometry extends through a thin zone to the overlying marker bed. Field measurements taken in the overlying marker beds suggest that perturbation in these beds extends to Marker Bed 138, 12 m above the room (Roberts et al., 1999). Although additional geomechanical analysis may screen out the possibility of damage to the intervening halite units, the present study assumes that a DRZ exists in the halite as well. Schematics of the baseline and alternative geometries are shown in Figure 4.

The first set of calculations assessed the influence of DRZ flow properties on the volume of brine inflow using the baseline geometry. Transient creep processes cause variations in porosity and permeability of the DRZ both spatially and temporally. To assess the relative importance of DRZ permeability and porosity, these properties are reduced from the baseline model. The baseline permeability of the DRZ ($10^{-15}$ $m^2$) selected is within the range of measured values for the DRZ, but is sufficiently high so that a flow path exists between the waste rooms and marker beds. The reduced DRZ permeability ($10^{-19}$ $m^2$) is based on recent interpretation of flow testing in the Salado (Roberts et al., 1999). Porosity is modified by multiplying the intact halite porosity by a constant value (1.04), which results in a DRZ porosity of about 1.6%. Lower permeability and porosity are assigned to the DRZ in a deterministic fashion so that comparisons can be made to the baseline simulation.

DRZ two-phase properties for baseline simulations permit minimum interference between brine and gas. As noted by Davies (1991) and Knowles et al. (1996), two-phase effects are expected in the DRZ. An appropriate range of two-phase models and parameters is difficult to define, since no laboratory or field data exist for the DRZ in halite at WIPP. Values selected for threshold pressure in the DRZ range from 0.0 MPa for baseline calculations, to 0.5 and 1.0 MPa; residual brine and gas saturation range from 0.0 (baseline) to 0.1 and 0.2 in the sensitivity study. These are consistent with literature values and with models and parameters applied to undisturbed Salado halite and anhydrite.

The vaulted model is subjected to an identical set of parameter variations as the baseline model so that the influence of DRZ geometry can be ascertained. To accommodate the effects of fracture and separation at Clay Seam G, shaded grid blocks in Figure 4 are assigned a lower permeability ($10^{-20}$ $m^2$) than the remainder of the damaged zone ($10^{-19}$ $m^2$) in some simulations.

## RESULTS

Brine inflow volumes through the upper DRZ region for the baseline geometry and parameter variations are depicted in Figure 5. Brine inflow through the lower DRZ is relatively insensitive to any changes in hydraulic parameters. This is attributed to the relatively short distance to the underlying Marker Bed 139, which maintains high DRZ brine saturation. The volume of brine inflow to the disposal room calculated in all cases results in brine saturations of <15% within the waste area. Current models of waste evolution, as described in Hansen et al. (1997), correlate any degradation of the waste or waste packages to brine inflow. The analyses presented in this section focus only on the relative volumes of brine predicted to flow into the waste areas. Processes relevant to waste evolution are not addressed.

Reduction in the DRZ porosity results in a concomitant reduction in brine flow from the upper DRZ by approximately 20%. Modification of any other flow parameter reduces brine inflow through this region by more than 80%. Differences in brine inflow volumes relative to the baseline calculated using reduced DRZ permeability or alternative two-phase parameters produce the most significant effects, as can be deduced from the plots. The volume of brine inflow through the upper DRZ using the alternative geometry is depicted in Figure 6. Differences in parameter variations for this geometry are less marked than those predicted using the baseline geometry, but the trends are similar.

Results shown in Figures 5 and 6 demonstrate the significance of hydraulic parameters on predicted brine inflow volumes. Comparison of the influence of geometry on brine inflow is shown in Figure 7. Results are shown using the baseline parameters, reduced DRZ permeability, non-zero residual saturations and a threshold pressure of 1.0 MPa. Results of other parameter combinations will provide a similar comparison. With the exception of the first 600 years using baseline parameters, the vaulted geometry results in a higher cumulative brine inflow to the waste disposal room. This result is most pronounced when non-zero saturations and threshold pressures are applied to the DRZ.

## DISCUSSION

Discussion will focus on the influence of geomechanical processes on predicted brine inflow. While it is certain that transient creep processes alter porosity in the DRZ, these simulations demonstrate that brine inflow is sensitive to this parameter, but to a lesser degree than other parameters evaluated. This is likely due to the relatively small changes in porosity in the dilatant zone as compared to intact salt. Clear differences exist in simulation results when hydraulic parameters other than porosity are modified. Implementation of an alternative geometry also produces significant changes to the brine inflow predictions.

Salt creep will compact the waste areas in a manner consistent with that depicted in Figure 2. A consistent application of geomechanical processes in the flow model supports a less contiguous geometry, with a transient reduction in DRZ permeability and porosity occurring over a period of several hundred years. Modification of the DRZ using the vaulted geometry does not necessarily reduce the cumulative volume of brine inflow. As can be deduced from Figure 6, calculated brine inflows using this geometric configuration model will, for most cases, be higher than those predicted using the baseline model. As compared to the vaulted geometry, the only baseline geometry calculation predicting a larger volume of brine inflow to the waste room over the simulated period implements a high value for the DRZ permeability.

The increased brine inflow using the vaulted geometry is interpreted as follows. The vaulted geometry sustains high brine saturation in the DRZ and the proximal intact salt. Consequently, the effective brine permeability to brine in this instance is greater than it would be for a region that is approaching residual brine saturation. The baseline geometry, as compared to the vaulted geometry, experiences higher gas saturation because of the smaller ratio of surface area to volume of DRZ in contact with the intact Salado. These results indicate that further investigation of approximating two-phase flow in a fractured dilatant media with an equivalent porous media two-phase flow code is warranted.

Predicted brine inflow could also be reduced through implementation of reduced DRZ permeability. A rigorous treatment of a transient DRZ permeability in the flow model requires coupling of this parameter to an evolutionary stress regime. As Figure 2 shows, room closure is rapid for approximately 50 years following excavation. During this period, the host rock will contact the waste, reducing differential stresses in the salt, with a concomitant reduction in the extent of the dilatant zone. It is assumed that microfractures will be eliminated as the dilatant zone is reduced in size. The timing of this process significantly influences any potential reduction in brine inflow to the waste room. As seen in Figure 5, the slopes of the cumulative brine inflow curves for the different cases are essentially parallel after about 200 years. This implies that the rate of brine inflow stabilizes at this time. Modification of flow properties after the first 200 years is therefore likely to have only nominal influence on the cumulative inflow. Consideration should also be given to the modeling assumption of a homogeneous DRZ. Field data suggest that dilatant effects are non-uniform within the DRZ, with a transition to nearly intact conditions expected within 2 to 3 m of the excavation surface (Knowles et al., 1996). Implementations of a zoned, or layered, disturbed region are likely to significantly reduce predicted brine inflow volumes relative to the baseline. Comparatively, inclusion of transient, coupled effects, if they can be successfully implemented, is likely to result in minimal reduction to the cumulative predicted inflow, with a reduction in uncertainty that is similarly minimal. Additional numerical studies can assist in determination of a proper course of action. Verification of the spatial transition to intact conditions in the roof of disposal rooms can be obtained with a limited field test program.

Comparison of results obtained by either reducing the constant DRZ permeability or using non-zero saturation and threshold pressures produces consistently lower cumulative brine inflows. This suggests generation of additional experimental data regarding two-phase models and parameters are less valuable than additional permeability data in reduction of overall problem uncertainty. Consequently, this finding suggests that determination of the DRZ permeability will provide sufficient information such that quantification of brine inflow volumes is adequately constrained.

## CONCLUSIONS

Site and laboratory studies on features and processes that influence brine inflow into a WIPP waste disposal area are reviewed so that an appropriate sensitivity study on these processes can be conducted. The data suggest that the cumulative brine inflow is coupled to the existence and hydrological properties of a DRZ in the incumbent salt formation. Considerable uncertainty exists regarding the extent and properties of the DRZ, which are a consequence of uncertainties in the geomechanical processes, including creep and fracture. A baseline numerical model is constructed so that meaningful comparisons can be made when problem parameters and assumptions are varied. The objective of the analysis presented in this paper is to ascertain whether additional theoretical or experimental studies will significantly reduce the uncertainty in brine inflow. Evaluation of the variation in predicted brine inflows suggests that this performance measure is closely tied to assumptions regarding permeability and geometry of the DRZ. However, reduction in the size of the DRZ does not necessarily correlate to reduction in predicted brine inflows. Development of complex models for coupled processes may produce additional insight into these DRZ properties. However, this information can also be derived through rigorous geomechanical analyses followed by a limited field program. Coupled numerical tools are considered unlikely to significantly reduce problem uncertainty. Similarly, implementation of further studies on two-phase effects in the DRZ will only nominally reduce uncertainty in predictions. Additional numerical studies are recommended to further constrain the problem of geomechanical effects on brine inflow to a WIPP waste disposal room.

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## NOMENCLATURE

$\lambda$ = pore-size distribution index

$D$ = damage criterion

$I_1$ = first invariant of the stress tensor

$J_2$ = second invariant of the stress tensor

$k$ = absolute permeability of formation ($m^2$)

$k_l$ = effective permeability of formation to phase l ($m^2$)

$k_{rl}$ = relative permeability of formation to phase l

$P_c$ = capillary pressure (Pa)

$P_{ct}$ = threshold displacement pressure (Pa)

$S$ = absolute saturation to fluid phase l

$S_e$ = effective saturation to fluid phase l

$S_r$ = residual saturation to fluid phase l

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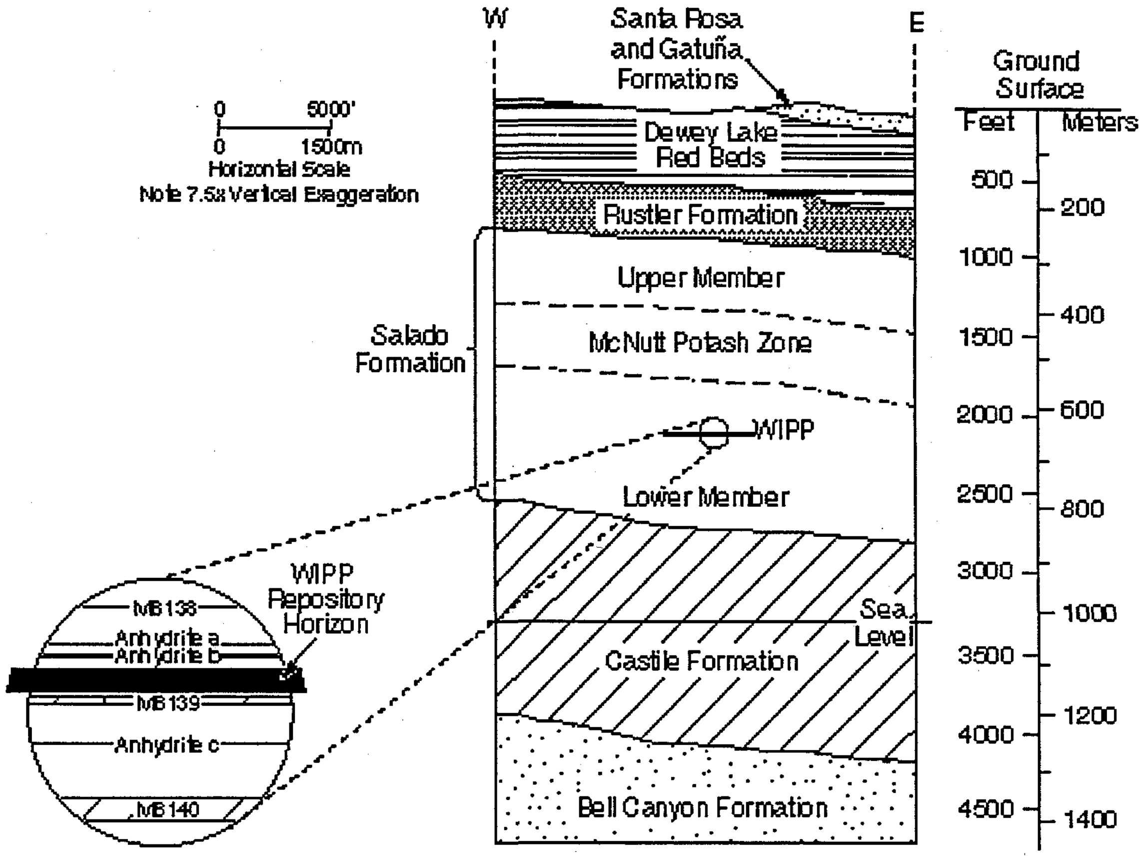


Figure 1. Waste Isolation Pilot Plant (WIPP) stratigraphy.

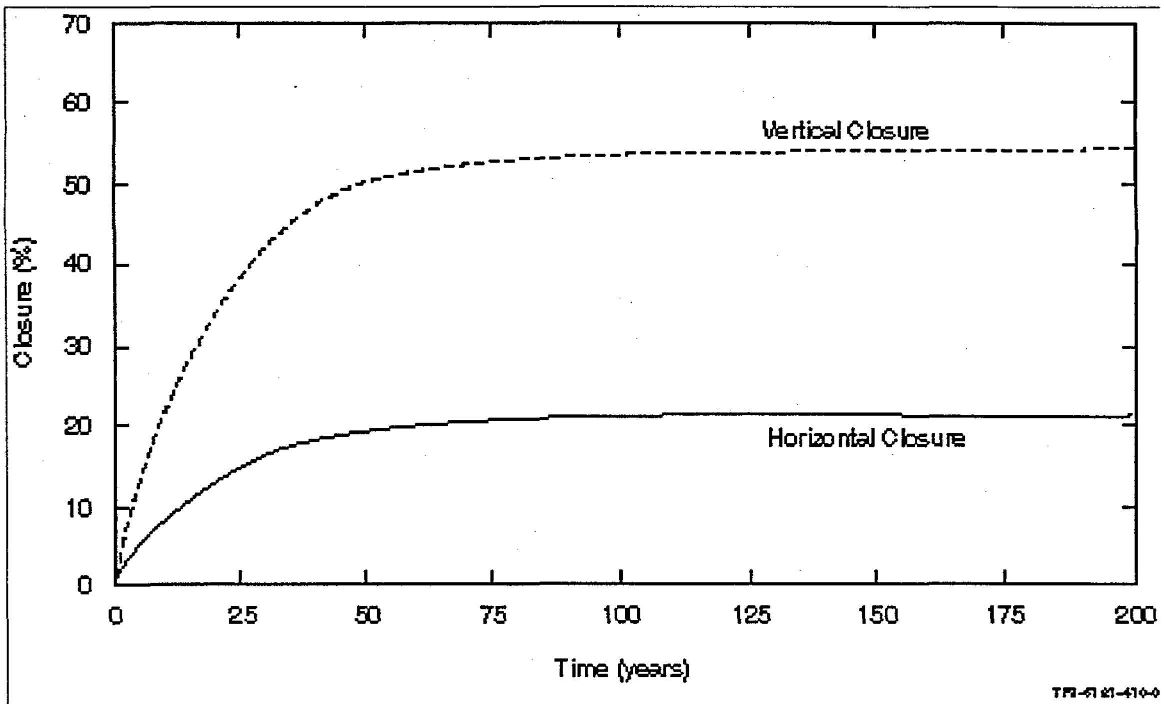


Figure 2. Classic creep-deformation behavior of salt.

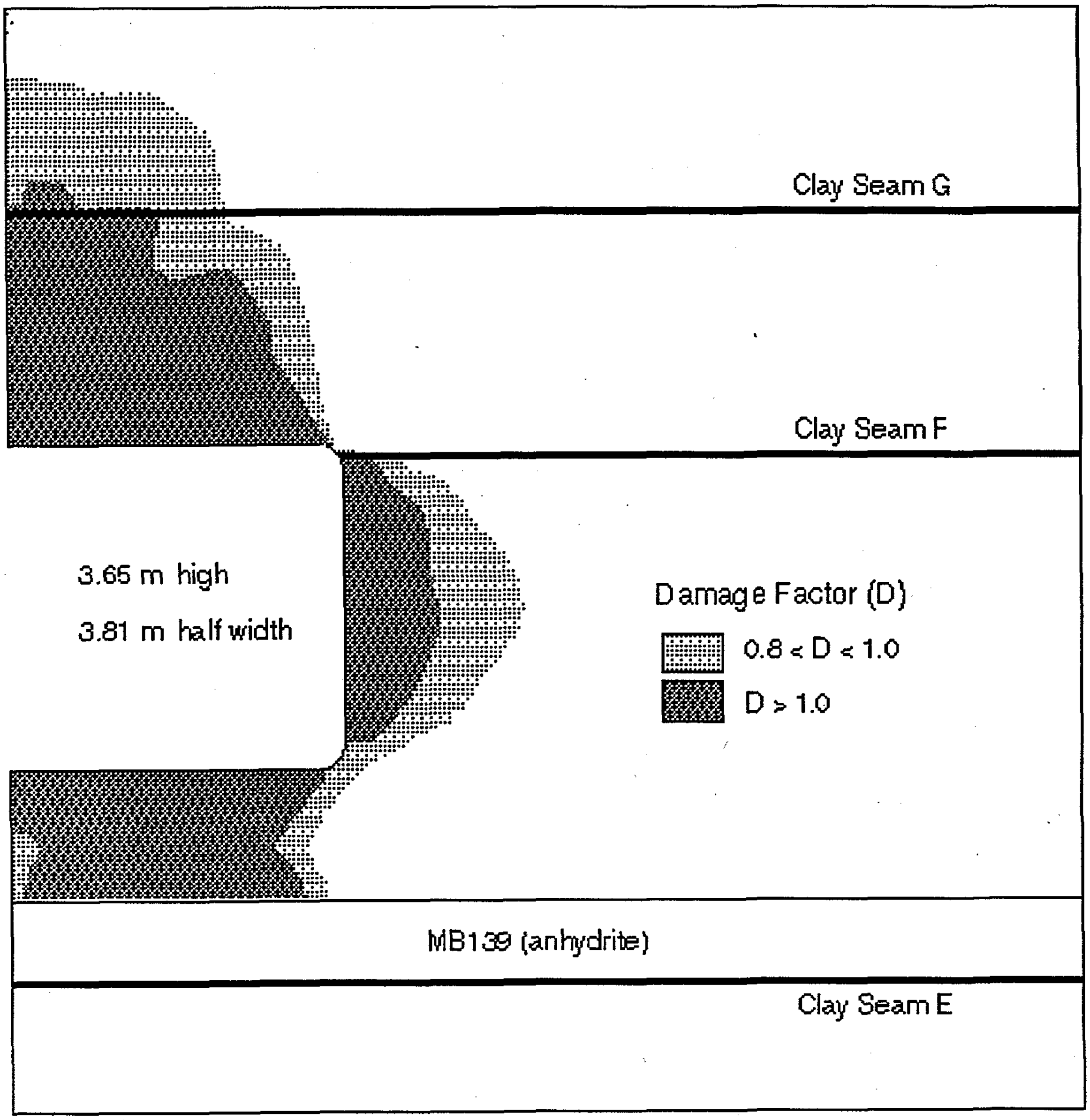


Figure 3. Schematic of dilatant zone in the vicinity of a WIPP waste room (after Francke et al., 1994).

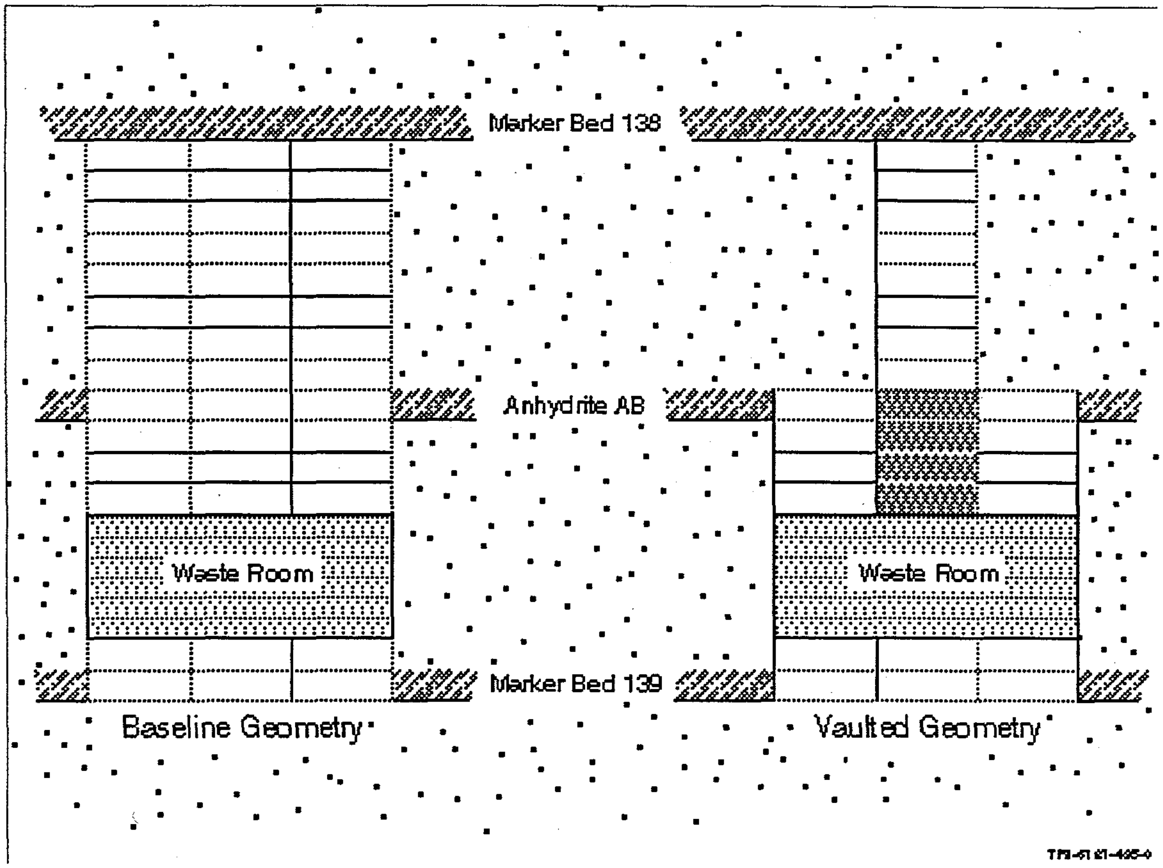


Figure 4. Schematics for baseline and alternative DRZ geometries. Not drawn to scale.

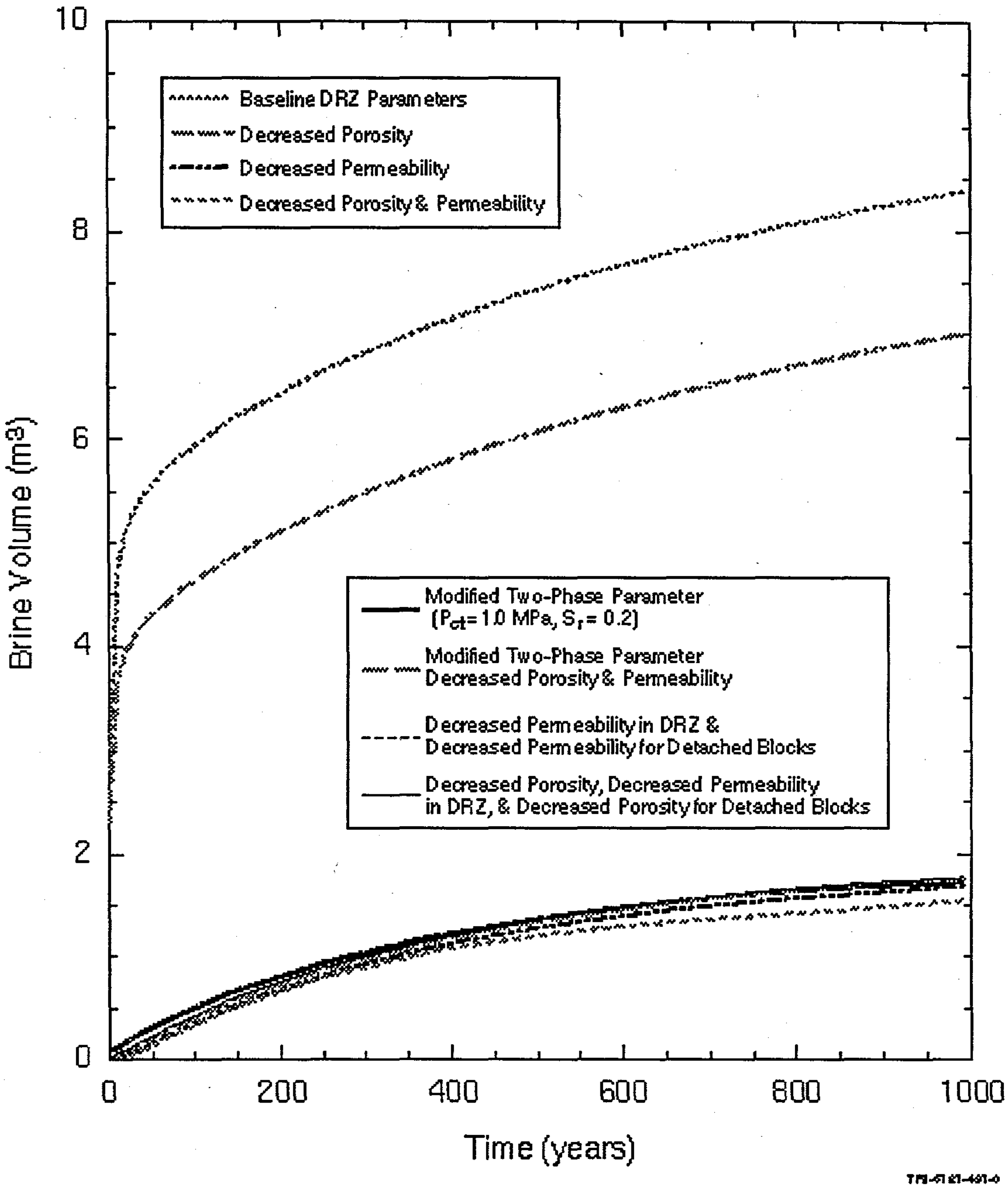


Figure 5. Brine inflow from the upper DRZ for simulations using the baseline geometry.

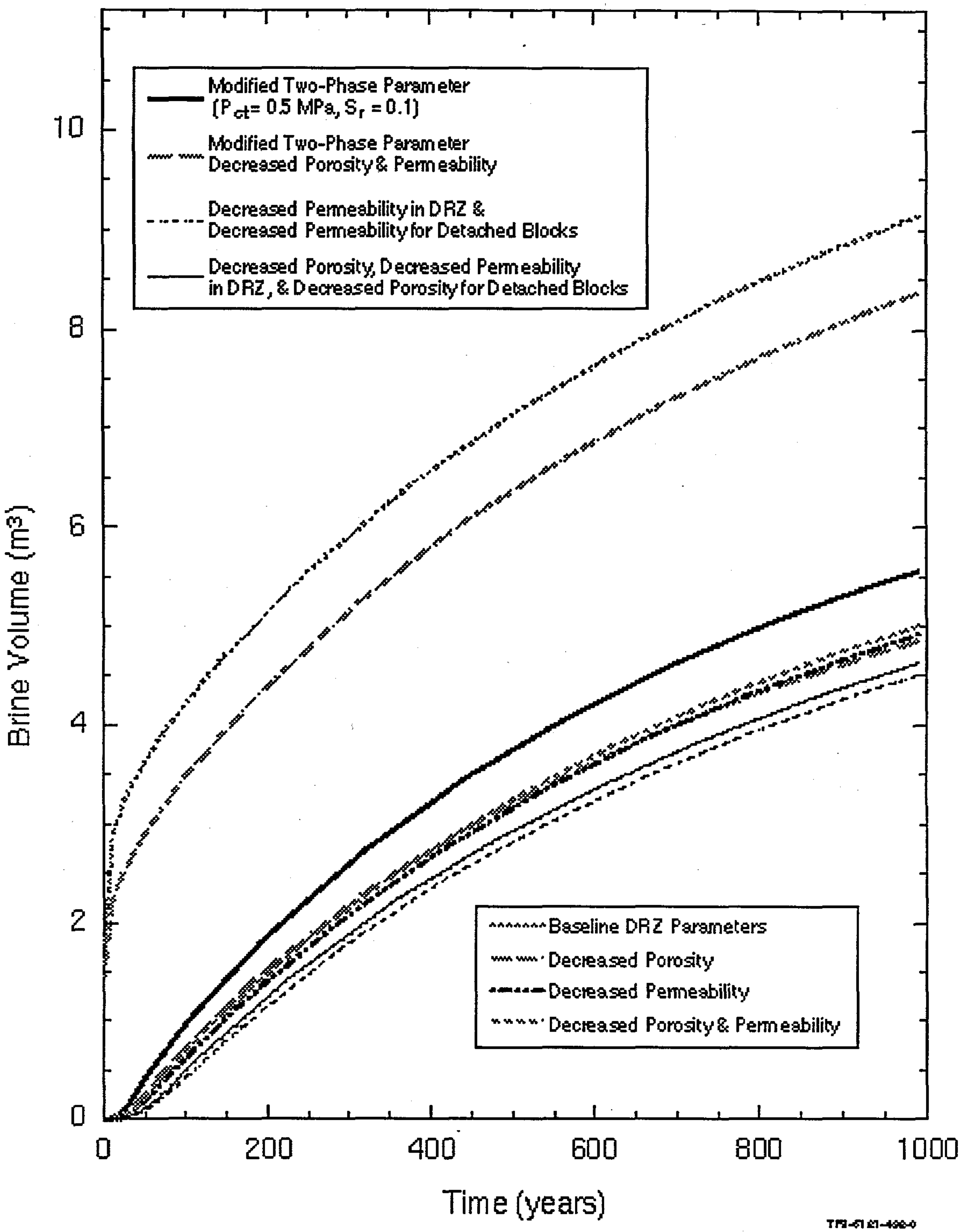


Figure 6. Brine inflow from the upper DRZ for simulations using the alternative geometry.

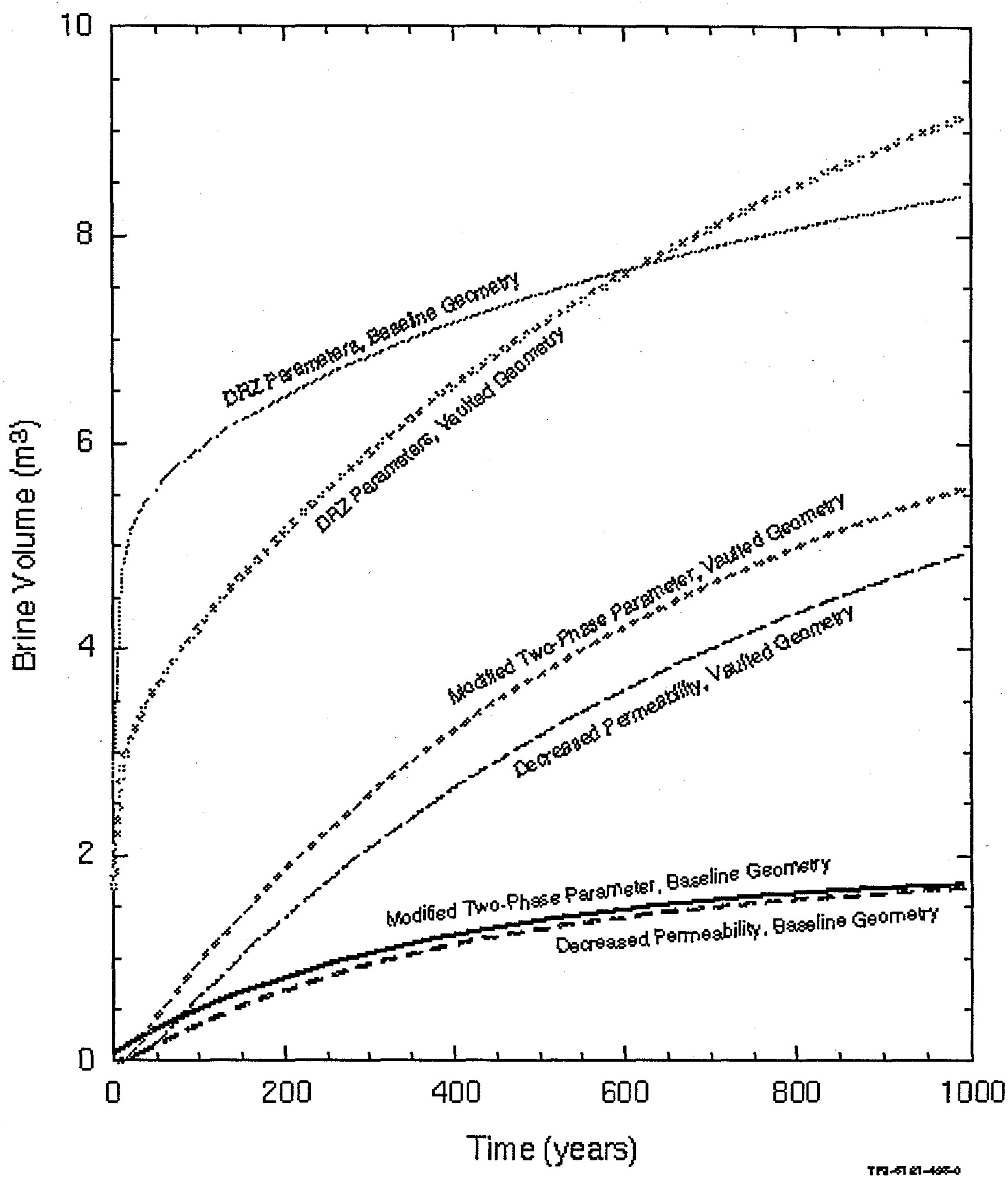


Figure 7. Comparison of baseline and vaulted geometry predictions.

Table 1. Material hydrologic and simulation parameters.

| Model Material and Parameters | Range of Values | Value Used in Simulation |
|---|---|---|
| Undisturbed halite | | |
| Permeability | $10^{-21} - 10^{-24}$ m$^2$ [a] | $3.16 \times 10^{-23}$ m$^2$ |
| Porosity | 0.003 – 0.01 [a] | 0.013 |
| Pore size distribution index | | 2.9 |
| Residual brine saturation | | 0.3 |
| Residual gas saturation | | 0.2 |
| Threshold pressure | | 100 MPa |
| DRZ | | |
| Permeability | $10^{-12} - 10^{-21}$ m$^2$ [b] | |
| Permeability for $0 < t < 5$ yrs | | $1.0 \times 10^{-17}$ m$^2$ |
| Permeability for $t > 5$ yrs | | $1.0 \times 10^{-15}$ m$^2$ |
| Porosity | 0.006 – 0.01 [c] | 0.0133 |
| Pore size distribution index | | 0.7 |
| Residual brine saturation | | 0.0 |
| Residual gas saturation | | 0.0 |
| Threshold pressure | | 0 MPa |
| Anhydrite | | |
| Permeability | $10^{-18} - 10^{-20}$ m$^2$ [a] | $1.28 \times 10^{-19}$ m$^2$ |
| Porosity | 0.001 – 0.01 [a] | 0.011 |
| Pore size distribution index | | 6.44 |
| Residual brine saturation | | 0.084 |
| Residual gas saturation | | 0.0771 |
| Threshold pressure | | 100 MPa |
| Waste room | | |
| Permeability for $0 < t < 5$ yrs | | $1.0 \times 10^{-10}$ m$^2$ |
| Permeability for $t > 5$ yrs | | $1.7 \times 10^{-13}$ m$^2$ |
| Porosity $0 < t < 5$ yrs | | 1.0 |
| Porosity $t = 0$ | | 0.848 |
| Pore size distribution index | | 2.89 |
| Residual brine saturation | | 0.0276 |
| Residual gas saturation | | 0.075 |
| Threshold pressure | | 0 MPa |
| All units | | |
| Pore pressure | >12.5 Mpa [d] | |

[a] Roberts et al. (1999)
[b] Knowles et al. (1996)
[c] Christian-Frear (1996)
[d] Beauheim (1987)

Captions List

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