# DESIGN ANALYSIS OF ENGINEERED ALTERNATIVES FOR THE WASTE ISOLATION PILOT PLANT*

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## ABSTRACT

The effectiveness of several engineered alternatives, designed to enhance the performance of the Waste Isolation Pilot Plant (WIPP), were evaluated relative to the performance of the baseline design. This evaluation was performed using a computer program referred to as the Design Analysis Model which couples salt creep closure, brine inflow, gas generation and dissipation to realistically simulate these interrelated processes over a 10,000 year period following the decommissioning of the repository. Analyses of the baseline design and nine alternative designs were performed for the undisturbed repository conditions, as well as three human intrusion events. Improvements in repository performance of up to four orders of magnitude were predicted for various engineered alternative waste forms.

## INTRODUCTION

The Engineered Alternatives Task Force (EATF) was established by United States Department of Energy (DOE) in September 1989 to evaluate the relative effectiveness and implementation feasibility of selected performance enhancements for the WIPP. The purpose of this paper is to summarize the methodologies and initial evaluation of the relative effectiveness of selected engineered alternatives.

The Waste Isolation Pilot Plant in southeastern New Mexico is a proposed underground repository designed and constructed for the storage and disposal of transuranic (TRU) radioactive wastes. The majority of TRU waste is material that is contaminated with alpha emitting radionuclides with half-lives greater than twenty years. The underground storage area of the WIPP repository is located 2,150 feet below the surface in a bedded salt (halite) formation of Permian age. The WIPP rooms and panels (which consist of seven rooms and associated access drifts) will be excavated in the salt beds of the Salado Formation. Detailed descriptions of the geology and hydrology of the WIPP site can be found elsewhere (1,2,3). The rooms and the panels are to be filled with the waste containers. A backfill material (salt, for example) is used to fill the space around and between the waste containers. The combination of waste and backfill is assumed to be a homogeneous composite material referred to as the waste/backfill composite. The purpose of adding the backfill is to reduce the permeability of the materials in the room. Reduced permeability results in lower releases of radionuclides in the case of human intrusions into the repository, which are described below.

TRU waste to be disposed of at the WIPP is presently generated and/or stored in drums or boxes at ten major DOE facilities across the United States. Examples of processes that generate the waste are plutonium recovery operations, glove box operations, and the operation of on-site analytical and R&D laboratories. The waste destined for the WIPP site is either solid or solidified material, and can be grouped under three major waste forms:

- Sludges which are predominantly inorganic solidified wastes with some form of solidifying or stabilizing agent, usually a cement-based material. A small percentage of sludges designated as "organic sludges" may contain organic solvents in greater than trace (> 1 weight percent) quantities (4).
- Solid Organic Waste consists of organic materials (sometimes referred to as "combustible" waste) such as paper, plastic, tissues, plywood, etc.
- Solid Inorganic Waste consists of metals, glass, and a small percentage of other non-combustible material.

All of the types of waste are in a chemically stable and non-reactive form, and have been safely stored and handled at the waste generator and storage sites for up to four decades. The waste generated at the different sites are comparable (due to the similar processes in operation), and can all be grouped under the waste forms discussed above with few exceptions.

Analyses of the long-term performance of the WIPP disposal system performed by Sandia National Laboratories (SNL) have identified two potential problems with demonstrating compliance with applicable regulations (3,5). The first potential problem relates to gas generation. A large number of moles of gas may be generated from anoxic corrosion of metals, microbial degradation of organic materials, and radiolysis. Although processes exist to dissipate excess gas pressure, these processes are currently believed to be slow relative to the current estimates of gas generation

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* Work supported by the U.S. Department of Energy Assistant Secretary for Defense Programs, Office of Defense Waste and Transportation Management, under DOE Contract No. DE-AC04-86AL31950 DOE/WIPP 90-024C

rates, resulting in peak gas pressures in storage rooms that may temporarily exceed lithostatic pressure.

A second potential problem with demonstrating regulatory compliance relates to the consequences predicted from future inadvertent human intrusion events. Some of the preliminary evaluations of compliance with the containment requirement of 40 CFR Part 191 performed by SNL suggest that some of the current waste forms may not be acceptable for disposal at the WIPP. This may be due to either actual problems with current waste forms or uncertainties in key performance parameters. Key parameters that control the release of radionuclides during human intrusion scenarios are permeability of the waste storage rooms and radionuclide solubilities.

The primary goal of the EATF is to develop and evaluate engineered alternatives that can mitigate any potential problems associated with the long-term performance of the WIPP repository. These include alternatives that eliminate any adverse consequences of excess gas pressure in the storage rooms and reduce the releases of radionuclides during human intrusion scenarios, should that be necessary.

The effectiveness of several engineered alternatives relative to the performance of the baseline design have been evaluated using a computer program developed by the EATF. This program is referred to as the Design Analysis Model, and is described below.

## DESCRIPTION OF THE DESIGN ANALYSIS MODEL

The Design Analysis Model simulates the processes expected to occur following waste emplacement in the WIPP facility. The program is used to analyze the relative effectiveness of various modifications to the facility and waste forms when compared to the WIPP baseline design and current waste forms. The primary processes considered in the Design Analysis Model include:

- Creep Closure

The repository starts to close by creep of the surrounding halite. This creep is plastic flow of salt in response to the pressure gradient between the far-field lithostatic pressure, and the sum of fluid pressure in the repository and the mechanical resistance stress of compacting the waste/backfill composite. The Chabannes equation was coupled with measured creep closure rates to predict closure rates in the repository as a function of time.

- Gas Generation and Consumption

Four processes related to gas generation and consumption were simulated: anoxic corrosion of iron with water to generate amakanite, microbial gas generation, radiolysis and dissolution of gases in brine.

- Brine Inflow

The rate of brine inflow was assumed to linearly decrease as fluid pressure in the room increases, and approaches zero when the pressure in the room reaches lithostatic pressure. Thus, brine inflow is coupled with creep closure and gas generation since all of these processes affect fluid pressure in the repository.

- $CO^2$/Brine/Cement Interactions

Gaseous $CO^2$ generated by microbial *or radiolytic processes* will partition into any brine present in the repository. This results in a net reaction forming a stable carbonate phase (for calcite, aragonite or dolomite) and water. The reaction requires brine as a medium, and $CA(OH)^2$ (portlandite) as a reactant. The water which is generated by the reaction of carbon dioxide and portlandite to form calcite and water is added to the total number of moles of water in the repository.

- Consolidation of the Shaft/Seal System and Advection of Fluid Across this System

The permeabilities of the repository panel seals and shaft seals were obtained as a function of time. The advection of gases and brine across these seals was modeled at each time step.

- Diffusion and Advection of Gases into Surrounding Formations

The Salado Formation and the underlying and overlying anhydrite layers are modeled as parallel routes for the diffusion of gases (due to a concentration gradient) and advection of gases (due to pressure gradients).

- Gas Compressibility

The Lee-Kessler Equation of State (6) was used to estimate the compressibility of the gas mixture in the repository at each time step. The fluid pressure was updated based on the compressibility value and was then used to estimate molar advection rates of gases, rate of brine inflow, creep closure, and gas solubilities in brine at each time step.

- Waste/Backfill Composite Compaction and Resulting Mechanical Resistance to Closure

The density of the waste/backfill composite varies as a function of time due to consolidation caused by salt creep. The stress of waste/backfill compaction corresponding to this density was evaluated from physical property data and supplied to the creep equation as the mechanical resistance to creep closure.

- Development of a Zone of Enhanced Porosity Surrounding the Repository

The creep of the surrounding host rock creates an additional void volume within a zone of enhanced porosity which the generated gases may occupy. The rate and extent of creep closure will govern the magnitude of this void volume which is assumed to contain no brine and to be interconnected.

- Radionuclide Releases Caused by Three Types of Inadvertent Human Intrusion Scenarios Into the Repository

The two main performance parameters that are used to compare the relative merits of each engineered alternative are; (1) the peak index pressure reached in the storage rooms during undisturbed conditions (no human intrusion), and (2) a measure of the cumulative release of radionuclides caused by human intrusion events.

For undisturbed conditions, the program estimates fluid pressure (brine and/or gas) within a typical waste storage room environment, as a function of time. Coupling of creep closure, brine inflow and gas generation is incorporated into the model to simulate these interrelated processes over a 10,000-year period following the decommissioning of the repository.

For human intrusion events, three scenarios are considered (5) (Fig. 1):

- A borehole that penetrates a waste-filled room and continues into or through a pressurized brine pocket assumed to exist in the underlying Castile Formation (E1 scenario).
- A borehole that penetrates the repository and stops (E2 scenario).
- Two boreholes that penetrate storage rooms in the same panel. One of these boreholes also penetrates a pressurized Castile brine pocket (E1E2 scenario).

For the analysis of human intrusion events, a "Measure of Effectiveness" (ME) is calculated for each alternative design based on the cumulative flux of twelve radionuclides into an overlying water-bearing strata (the Culebra Dolomite) over a 10,000-year period, plus the activity associated with the direct release of contaminated drill cuttings to the surface. "Measure of Relative Effectiveness" (MRE) values are then calculated for each alternative by dividing the ME for that alternative by the ME for the baseline design. Thus an MRE greater than one indicates a decrease in performance and an MRE less that one indicates an increase in performance. These measures provide a convenient means of comparing the improvements offered by alternative designs. While preliminary PA studies do indicate that some form of alternatives may be necessary (3), these can be formalized only after the potential problems associated with the baseline design are quantified by Performance Assessment. As such, the peak index pressures and MREs are not performance measures.

## DESIGNS ANALYZED

Quantitative estimates of chemical and physical properties for the combination of waste and backfill are required by the Design Analysis Model to determine the relative effectiveness of an engineered alternative. The term "properties" refers to chemical and physical properties of the waste/backfill composite. Properties of the composite such as density, porosity, hydraulic conductivity, and effective waste volume are quantified as a function of compaction stress level. The effective waste volume is the volume of the waste/backfill composite minus the volume of the backfill along the sides of the waste stack. This parameter was used in the Design Analysis Model to calculate radionuclide releases to the surface due to removal of drill cuttings. In addition, gas generation rates and potentials are provided to the Design Analysis Model.

Analyses of the baseline design plus nine alternative designs were performed for undisturbed conditions, as well as the three human intrusion events described above. The baseline design and engineered alternatives that were analyzed are summarized in Table I.

## ANALYSES PERFORMED

Specific analyses that were performed for undisturbed conditions include:

- Prediction of room pressurization for the baseline design (Fig. 2)

The partial pressure of hydrogen reaches a peak that coincides with the total pressure reaching lithostatic. When lithostatic pressure is reached, brine inflow ceases so there is no longer any brine available for anoxic corrosion to proceed. Hydrogen generation is thus self-limiting as a result of the assumed coupling between brine inflow, room pressure, and anoxic corrosion. Brine is required, and is also consumed, by anoxic corrosion. Based on these assumptions, when lithostatic pressure is reached, brine inflow and, hence, anoxic corrosion rates approach zero. Microbial generation on the other hand, is assumed to proceed at a constant rate that is independent of brine availability (3). Aerobic conditions are assumed to persist for 100 years after closure during which oxygen is converted to carbon dioxide via microbial activity with no significant change in pressure. Anaerobic degradation of organic materials occurs from 100 to approximately 815 years after closure when the substrate is depleted and microbial gas generation is assumed to stop. These assumptions are reflected in the partial pressure curves for microbial gases in Fig. 2 which shows a small rise during the first 100 years caused by the conversion of oxygen to carbon dioxide, followed by a linear increase in the partial pressures of these gases from 100 years to approximately 815 years.

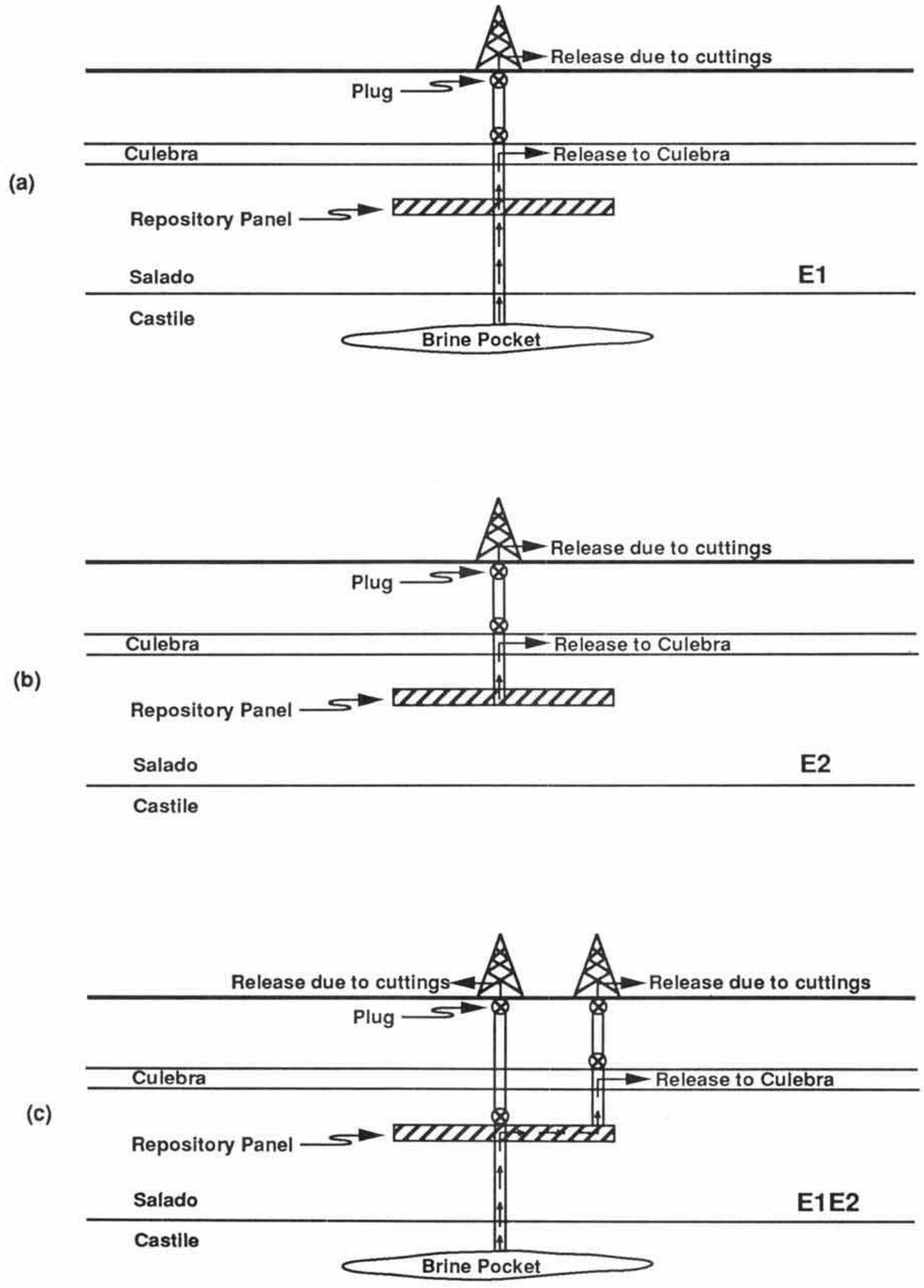

Fig. 1. Human intrusion scenarios.

## TABLE I

### Alternatives Analyzed

| DESIGN | SLUDGES | SOLID ORGANICS | SOLID INORGANICS | BACKFILL |
|---|---|---|---|---|
| Baseline | As Received | As Received | As Received | Salt |
| Alternative 1 | As Received | Shred/Cement | Shred/Cement | Salt |
| Alternative 2 | Cement | Shred/Cement | Shred/Cement | Salt |
| Alternative 3 | Cement | Shred/Cement | Shred/Cement | Grout |
| Alternative 4 | Cement | Incinerate/Cement | Shred/Cement | Salt |
| Alternative 5 | Cement | Incinerate/Cement | Shred/Cement | Grout |
| Alternative 6 | Vitrify | Incinerate/Vitrify | Melt Metals* | Salt |
| Alternative 7 | Vitrify | Incinerate/Vitrify | Melt Metals* | Grout |
| Alternative 8 | Vitrify | Incinerate/Vitrify | Melt Metals** | Salt |
| Alternative 9 | Vitrify | Incinerate/Vitrify | Melt Metals** | Grout |

*Metals are melted into transuranic (TRU) waste ingots.

**Metals are melted with glass/glass frit; radionuclides partition into the slag and metals are eliminated from the WIPP inventory, including metal containers that may produce gas by corrosion.

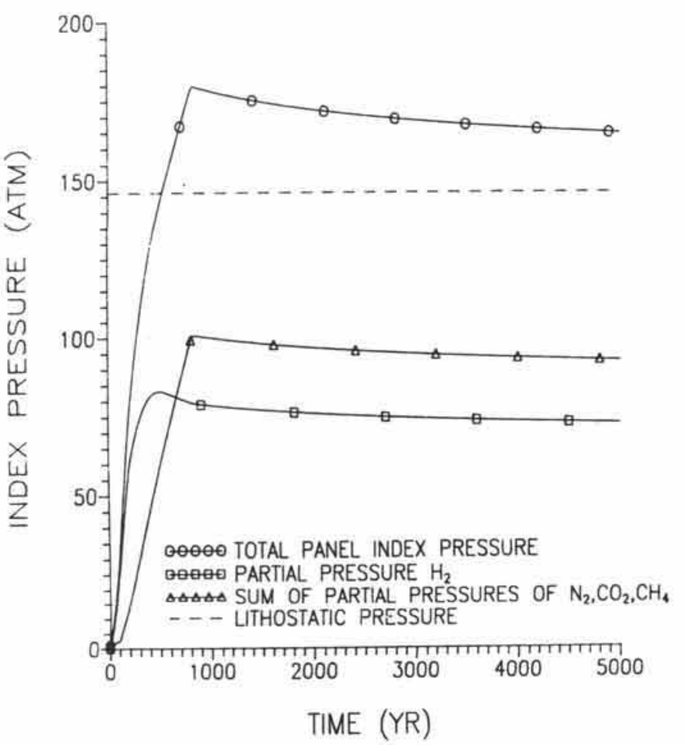

Fig. 2. Index pressure versus time curves for the baseline design.

- **Effects of supercompaction of waste on room pressurization (Fig. 3)**

Figure 3 clearly shows that a room filled with supercompacted waste reaches a peak index pressure that is roughly twice as high as a room filled with baseline waste. There are two reasons in the marked increase in predicted peak index pressures. The first reason is the decrease in initial void volume. Moles of gas that are generated occupy a smaller volume resulting in rapid pressurization. This rapid pressurization minimizes brine inflow, resulting in a decrease in the total moles of hydrogen generated by anoxic corrosion. However, these fewer moles of hydrogen occupy a smaller void volume. In addition, microbial gas generation, which is assumed to be independent of brine availability, continues and is also pressurizing a smaller volume. Even though fewer moles of hydrogen are generated, the pressures still remain high. The second reason for the increase in peak index pressure is the roughly two-fold increase in the mass of organic materials on a per-room basis, resulting in an assumed factor of two increase in the microbial gas generation rate and gas generation potential per room.

- **Effects of venting the repository for 100 years on subsequent room pressurization (Fig. 4)**

A period of 100 years was chosen because it was assumed that some type of active controls would be required to maintain an open vent from the repository to the surface and 40 *CFR* Part 191 requires that active institutional controls cannot be assumed for longer than this period of time. To evaluate the effectiveness of venting the repository, a simulation was performed that maintained a room pressure of 1 atmosphere during the first 100 years after decommissioning the repository. After 100 years, the storage rooms were allowed to pressurize in accordance with the baseline assumptions regarding gas generation, creep closure, brine inflow, etc. These results show that the peak index pressures which occur at approximately 815 years are higher in the vented case than in the baseline case. In the vented case, fluid pressure in the room does not build up during the first 100 years, providing no resistance to closure during this period. This results in lower storage room porosity at 100 years. When the vent is closed at 100 years, microbial gas generation continues for approximately 715 years and is pressurizing a smaller void volume, resulting in higher pressures.

- Effects of varying the rate and duration of microbial gas generation on room pressurization (Fig. 5)

Index pressure versus time curves for four cases are shown in Fig. 5. These results show that both the peak index pressure and the timing of the peak are very sensitive to variations in the assumed microbial gas generation rate and duration even though the total number of moles generated was held constant. In general, lower rates (with proportionally longer durations) result in higher and later peak index pressures. This is caused by the coupled nature of creep closure and gas generation. When the generation rate is assumes to be low, creep closure proceeds faster and results in rapid establishment of low room porosity. Continued gas generation then pressurizes a smaller volume, yielding higher pressures. The lowest peak index pressures were achieved in the case where the rate was doubled. *In this* case the room rapidly pressurized with gas which props open voids and reduces the amount of creep closure required to bring the room to lithostatic pressure. This also allows the room to retain a larger percentage of the initial void volume, providing a lager volume for gas to occupy.

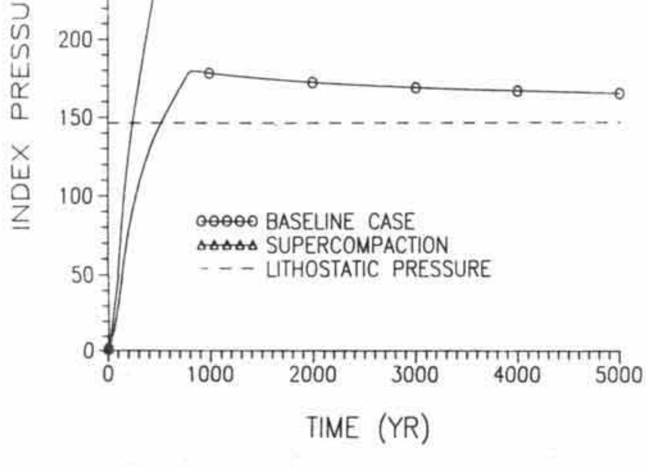

**Fig. 3. Index pressure versus time curves for supercompacted and baseline waste forms.**

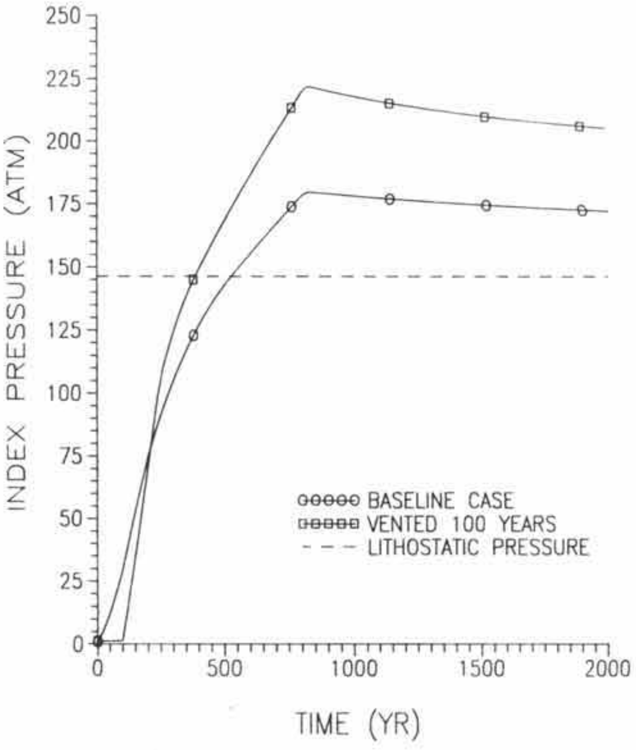

**Fig. 4. Index pressure versus time curves evaluating the effectiveness of venting the WIPP repository.**

- Effects of varying the anhydrite layers' hydraulic properties on room pressurization (Fig. 6 and 7)

The two major properties evaluated were the permeability and the far field pore pressure of the intact anhydrite layers. A set of runs of the Design Analysis Model were completed varying the permeability over three orders of magnitude ($10^{-17}$ to $10^{-20}$ $m^2$). Figure 6 shows the results of these sensitivity runs in terms of index room pressure versus time curves for the assumed permeabilities of the anhydrite layers. This figure shows that only for the most extreme case (a permeability of $10^{-17}$ $m^2$) does the peak index room pressure change slightly. The second set of sensitivity runs

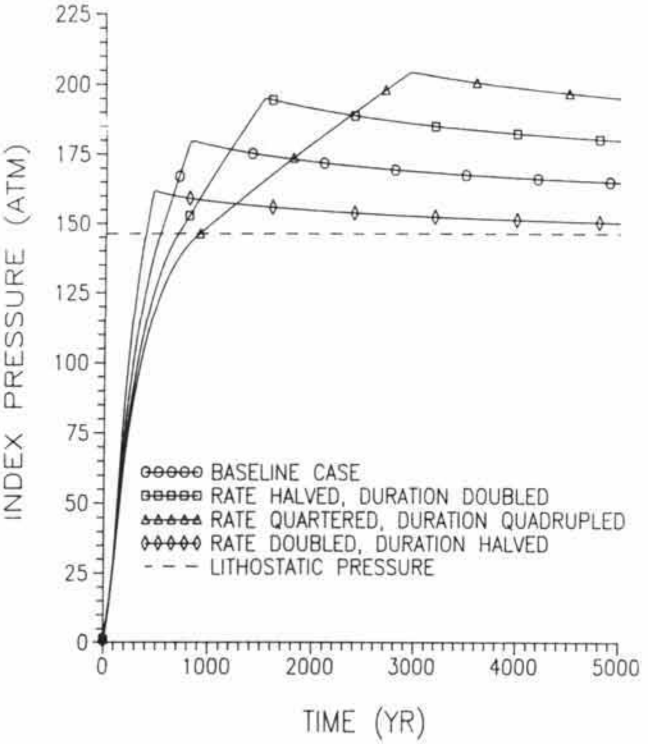

Fig. 5. Index pressure versus time curves varying rates and duration of microbial gas generation.

performed considered the effects of varying the far field pore pressure of the intact anhydrite layers. For this analysis, the far field pore pressure was varied from 60% to 90% of lithostatic pressure in 10% increments. Figure 7 shows the results of these sensitivity runs in the same format as the permeability sensitivity. This figure shows that while the rate of pressure decay changes with the assumed far field pore pressure, the overall peak index pressures are not significantly affected by this parameter.

- **Effects of varying initial brine inflow rate on room pressurization (Fig. 8)**

The results of this analysis are shown in Fig. 8. Five initial flow rates were chosen; the baseline rate, one half of the baseline rate, one quarter of the baseline rate, twice the baseline rate, and four times the baseline rate. These results indicate that the peak index pressure reached assuming the baseline rate, one half of the rate, and one quarter of the rate are all similar. Only when the baseline rate is doubled or quadrupled does the peak index pressure increase. This phenomena is due to the assumed coupling between brine inflow and anoxic corrosion.

- **Predicted peak gas pressures for the baseline design and nine alternative combinations of waste forms**

The two principal factors that affect peak index pressures are the mass of organic materials present in the room

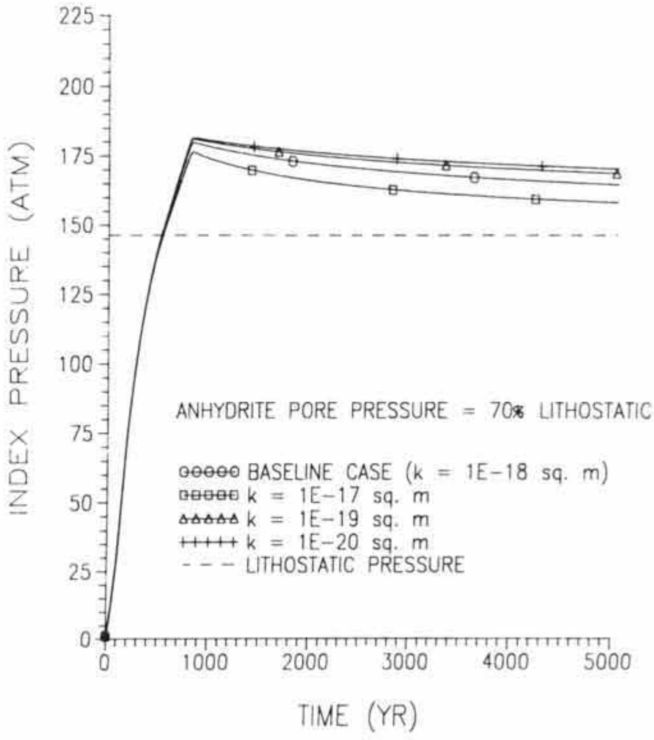

Fig. 6. Index pressure versus time curves varying anhydrite permeability.

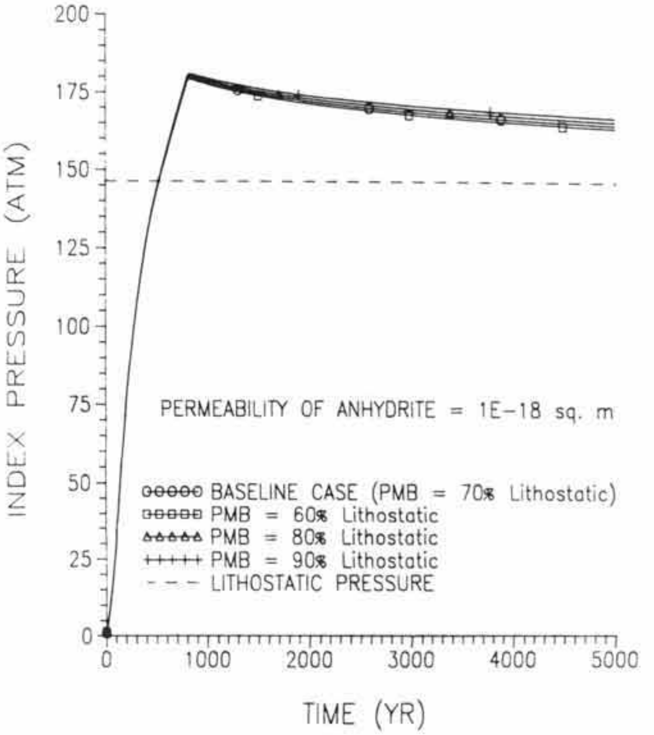

Fig. 7. Index pressure versus time curves varying far-field pore pressure in anhydrite.

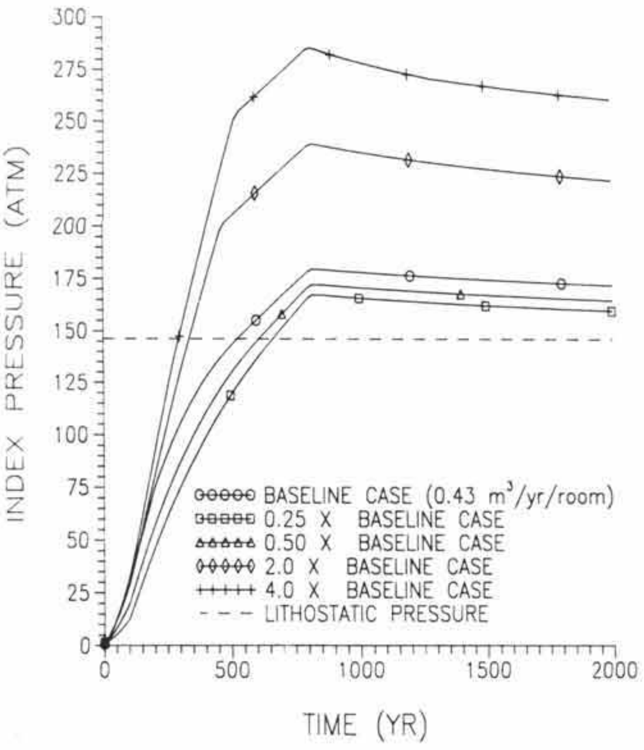

Fig. 8. Index pressure versus time curves varying the initial brine inflow rate.

and the void volume available in the room for pressurization. The alternatives that involve thermal treatment of solid organics (alternatives 4-9) show peak index pressures which correspond to lithostatic pressure. For these alternatives, thermal treatment has completely eliminated microbial gas generation so that the main gas generation process is the production of hydrogen from the anoxic corrosion of ferrous metals and aluminum in the room. This assumed coupling between anoxic corrosion and brine inflow provides a self-limiting mechanism for hydrogen generation where the generation rate approaches zero as the fluid pressure in the room approaches lithostatic. Although anoxic corrosion contributes to room pressurization, the process halts when lithostatic pressure is reached.

Analyses of human intrusion events include the calculation of MRE for nine alternative combinations of waste forms (listed above) including shredded and cemented, incinerated, and vitrified waste.

## RESULTS OF ANALYSES

*Results* of design analysis modeling for the undisturbed scenario suggest the following:

- Gas pressures in storage rooms are predicted to exceed lithostatic pressure for the baseline design using current SNL assumptions for gas generation rates.
- Supercompaction of waste results in higher peak gas pressures than the baseline (uncompacted) waste. This is due to a decrease in initial room void volume and a factor of three increase in the mass of organic materials per room.
- Venting the storage rooms will only be effective in reducing peak gas pressures if the vent remains open for the entire gas generating period. Venting for 100 years results in higher peak gas pressures than the baseline (non-vented) design.
- Predicted peak index pressures are quite sensitive to the rate and duration of microbial gas generation.
- Predicted peak index pressures are only sensitive to the initial brine inflow rate if that rate exceeds some critical value. This critical value is higher than current estimates.
- Alternatives that involve thermal treatment of organic materials are not predicted to develop gas pressures in excess of lithostatic.
- Factors that affect peak index pressures are the mass of organic materials present in the room and the void volume available for pressurization.

Results of design analysis modeling for the three human intrusion scenarios suggest the following:

- Improvements in performance of one order of magnitude (relative to the baseline design) are predicted for the Castile Brine (E1) scenario for shredded and cemented waste forms and two orders of magnitude for incinerated or vitrified waste forms. Critical parameters for this scenario are waste/backfill permeability, borehole radius and permeability, and radionuclide solubilities.
- Improvements of up to two orders of magnitude are predicted for the repository breach (2) scenario for shredded and cemented waste forms. Critical parameters for this scenario are waste/backfill permeability, volume of contaminated brine in the repository after repressurization, and radionuclide solubilities.
- Up to four orders of magnitude improvement can be gained for the dual borehole (E1E2) scenario using shredded and cemented, or incinerated, vitrified, or melted waste forms. Critical parameters for this scenario are waste/backfill permeability and radionuclide solubilities.

The conclusions presented here are derived from the preliminary results of ongoing investigations into the effectiveness and feasibility of a wide range of engineered alternatives. These conclusions are subject to change as on-going laboratory experiments, site characterization and modeling activities yield additional data that may alter the current understanding of the complex interrelated processes that will occur in the WIPP repository. The results of additional analyses will be incorporated into a final DOE report.

## REFERENCES

1. U.S. DEPARTMENT OF ENERGY, 1990 "Waste Isolation Pilot Plant No-Migration Variance Petition" DOE/WIPP 89-003 U.S. Department of Energy, WIPP Project Office, Carlsbad, New Mexico.
2. A. R. LAPPIN, 1988 "Summary of Site-Characterization Studies Conducted from 1983 through 1987 at the Waste Isolation Pilot Plant (WIPP) Site, Southeastern, New Mexico," SAND88-0157, Sandia National Laboratories, Albuquerque, New Mexico.
3. A. R. LAPPIN, R. L. HUNTER, EDS., D. P. GARBER, P. B. DAVIES, ASSOC. EDS., 1989 "Systems Analysis, Long-Term Radionuclide Transport, and Dose Assessments, Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico; March 1989," SAND89-0462, Sandia National Laboratories, Albuquerque, New Mexico.
4. U.S. DEPARTMENT OF ENERGY, 1989, "TRUPACT-II Content Codes (TRUCON)," DOE/WIPP 89-004, Rev. 3, U.S. Department of Energy, WIPP Project Office, Carlsbad, New Mexico.
5. K., M. C., S. G. BERTRAM-HOWERY, D. R. ANDERSON, K. F. BRINSTER, R. V. GUZOWSKI, H. IUSSOLINO, and R. P. RECHARD, 1989, "Performance Assessment Methodology Demonstration: Methodology Development for Evaluating Compliance With EPA 40 CFR 191, Subpart B, for the Waste Isolation Pilot Plant," SAND89-2027, Sandia National Laboratories, Albuquerque, New Mexico.
6. R. C. REID, J. M. PRAUSNITZ, and B. E. POLING, 1987, The Properties of Gases and Liquids. 4th ed., McGraw-Hill Book Co., New York, New York, p. 741.