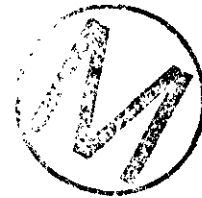# Title 40 CFR Part 191
Compliance Certification
Application
for the
Waste Isolation Pilot Plant

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INFORMATION ONLY

Conceptual Model Description for BRAGFLO Direct Brine Release Calculations to Support the Compliance Certification Application

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Model Purpose

This model has been developed to support the Direct Brine Release portion of the 1996 performance assessment (PA) of the WIPP repository site. The calculations will be performed to contribute to the complimentary cumulative distribution function (CCDF), the probability distribution of exceeding normalized cumulative radionuclide releases to the accessible environment, that will become part of the Compliance Certification Application (CCA). Direct brine releases may occur when a future driller penetrates the WIPP and contaminated brine is unknowingly brought to surface during the drilling process. These releases are not specifically accounted for in the cuttings, cavings and spallings calculations (CUTTINGS_S), as that code only models the solids removed during the drilling process. Certain conditions must exist within the waste in order for contaminated brine to flow directly to the surface during a drilling intrusion:

- Pressure in the waste must be greater than that exerted by the column of drilling mud that penetrates a waste panel. Drillers in the Delaware Basin currently use a salt saturated mud while drilling through the Salado, with a specific gravity of 1.23. This corresponds to ~8.0E+06 Pascals at the repository horizon, which is the minimum pressure needed to overcome a static column of drilling mud.

- There must be mobile brine present in the waste panels to flow to the surface. Corrosion and biodegradation processes consume brine and release gasses as by-products, and it is possible for the brine volume in the waste pores to drop below its "mobile" (residual) saturation. It is likely for gas-only flows to occur up a drill hole, but these flows are only of concern for the solids releases (Spalls).

Model Description

SWCF: A :1.2.07.1.3: CO/CCA

The model is set up as a two-dimensional finite difference mesh of 39 X 39 grid blocks to be solved using the BRAGFLO code (hereafter called DBR_BRAGFLO - see Figure 1). The mesh compares to the regional 10,000 year model (hereafter called BRAGFLO) in the following ways:

- The DBR_BRAGFLO mesh is oriented in the areal plane, with the z-dimension (height) one element thick. BRAGFLO is oriented as a cross-section, with multiple layers in height and the thickness (y-dimension) one element thick.
- DBR_BRAGFLO models flow only in the waste area. The BRAGFLO model includes the surrounding geology as well as the entire WIPP excavation (including operations, experimental, and shaft regions).
- Local scale heterogeneities are included in the DBR_BRAGFLO model, including the salt pillars, rooms, panel seals, and passageways which contain waste. These are not fully represented in the BRAGFLO mesh.
- The DBR_BRAGFLO mesh uses constant thickness, while BRAGFLO radially flares the element thickness to account for 3-dimensional volumes in 2-D space.
- The disturbed rock zone (DRZ) is included in both models, but exists above and below the excavated regions in the BRAGFLO model, whereas the DRZ surrounds the waste rooms on the sides for the DBR_BRAGFLO model.
- Both models include one degree formation dip through the excavated regions.
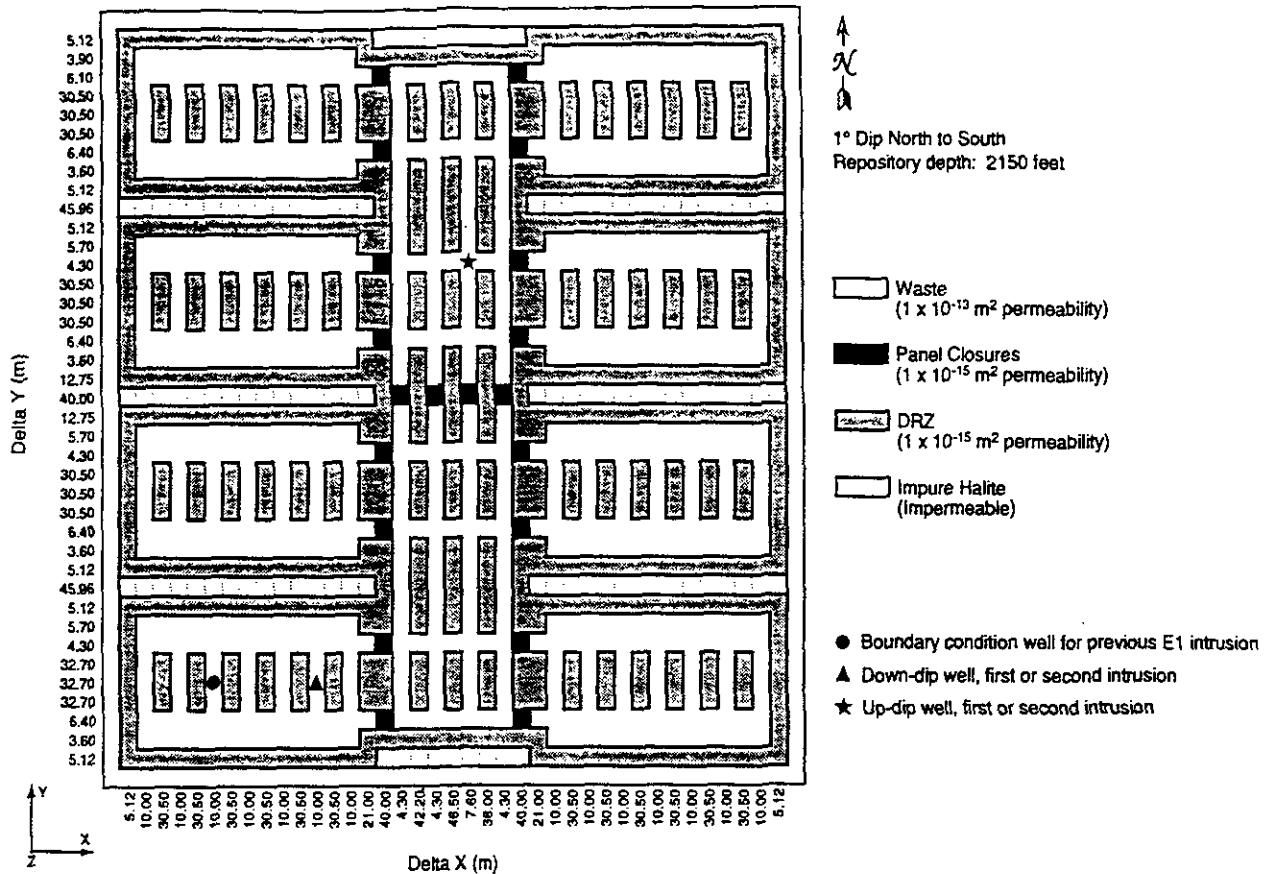
Note: Model cells are not to scale. The actual dimensions of the
grid blocks, are indicated along the edge of the diagram.

Figure 1: Direct Brine Release (DBR_BRAGFLO) Mesh

Principal Parameters Defined By Model

The pressure and saturation time-histories for each realization (3 replicates of 5 scenarios of 100 consequences) from the 10,000 year BRAGFLO calculations will provide the basic input needed for the direct brine releases. The pressure and saturation at specified times for each consequence will provide the initial conditions needed for the DBR_BRAGFLO model. These values are also used to calculate the boundary conditions which represent flow up the intrusion borehole.

The input parameters that will be used for the direct brine release calculations will come from four sources: the 10,000 year BRAGFLO output files, the CUTTINGS_S code, the WIPP database and a correlation to simulate flow up the borehole (Figure 2).
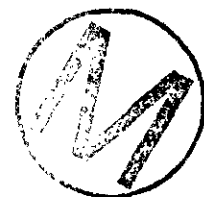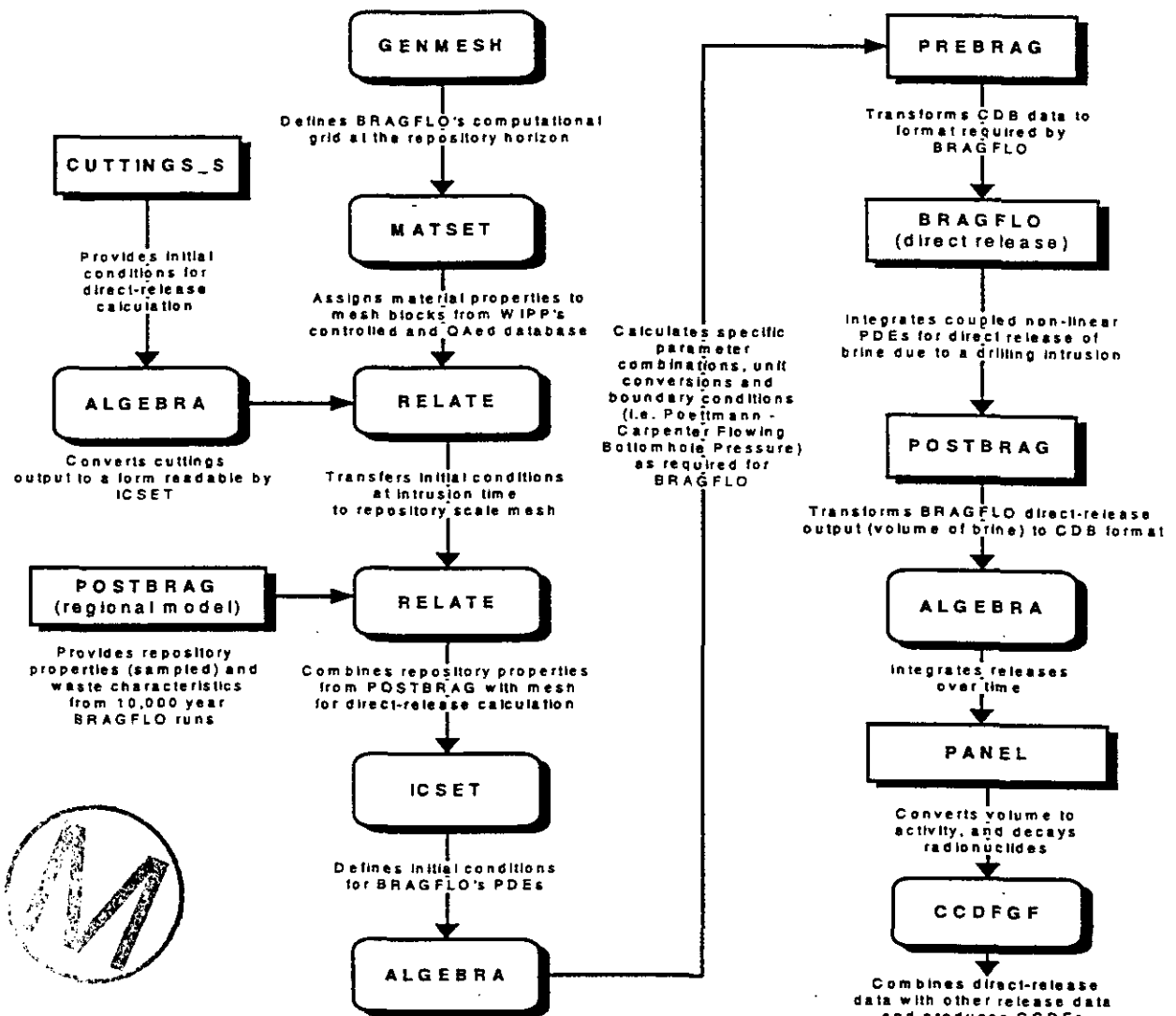
The code sequence for the BRAGFLO direct-release
calculation in the 1996 CCA PA.

Figure 2: Calculational Flowchart for DBR_BRAGFLO

- The initial brine saturation and pressure, porosity, and crushed panel height within the waste used in the direct release model are determined from the 10,000 year BRAGFLO results, and therefore vary with time. These parameters are calculated by time interpolation in the CUTTINGS_S code, and RELATEd to the direct release model. An intermediate ALGEBRACDB step is required to convert time-history variables to material properties.
- Unsampled material properties which remain constant are read directly from the parameters database (through MATSET).

- Sampled material properties are RELATEd from the 10,000 year BRAGFLO output files.
- The pressure (boundary condition) that drives the wellbore model has been developed from a commonly used petroleum industry multi-phase vertical pipe flow correlation (Poettmann-Carpenter), which is tied to the well deliverability expression used by DBR_BRAGFLO.

The two RELATE steps accomplish the same function as the LHS sequence for the 10,000 year BRAGFLO calculations. DBR_BRAGFLO does not require a separate sampling, as all needed variables are extracted from the previously run BRAGFLO and CUTTINGS_S files. Hence, important flow parameters for the waste region (such as residual brine and gas saturation) are the same for each realization in the BRAGFLO and DBR_BRAGFLO models. The DRZ, panel seal, and halite relative permeability and capillary pressure parameters are set equal to those used in the waste region. This was done to ease the DBR_BRAGFLO computation. The intrinsic permeability of the DRZ and panel seals are the median values read from the database.

The element thickness of the DBR_BRAGFLO mesh is adjusted to equal the crushed room height, which is passed on from the CUTTINGS_S code. This arbitrarily sets all elements in the mesh to the same height, therefore, the porosity in the non-waste regions (DRZ, halite, and seals) are increased proportionally to maintain equal pore volume with the corresponding 10,000 year BRAGFLO regions.

Integration with other PA codes

The DBR_BRAGFLO mesh is coupled to BRAGFLO by subdividing the waste area in BRAGFLO into four regions. Region one represents the farthest up-dip repository grid blocks in BRAGFLO which contain waste. This corresponds roughly to the up-dip quarter of the DBR_BRAGFLO mesh. Region four represents the farthest down-dip section of waste in BRAGFLO, which is the "panel" region in the 1996 CCA mesh. This corresponds to the farthest down-dip quarter of the DBR_BRAGFLO mesh. Similar subdivisions are made for the middle two sections of each grid (Figure 3). Pore-volume averaged brine saturation and pressure within each region of the BRAGFLO model are used to initialize similar regions in the DBR_BRAGFLO mesh at each intrusion time.
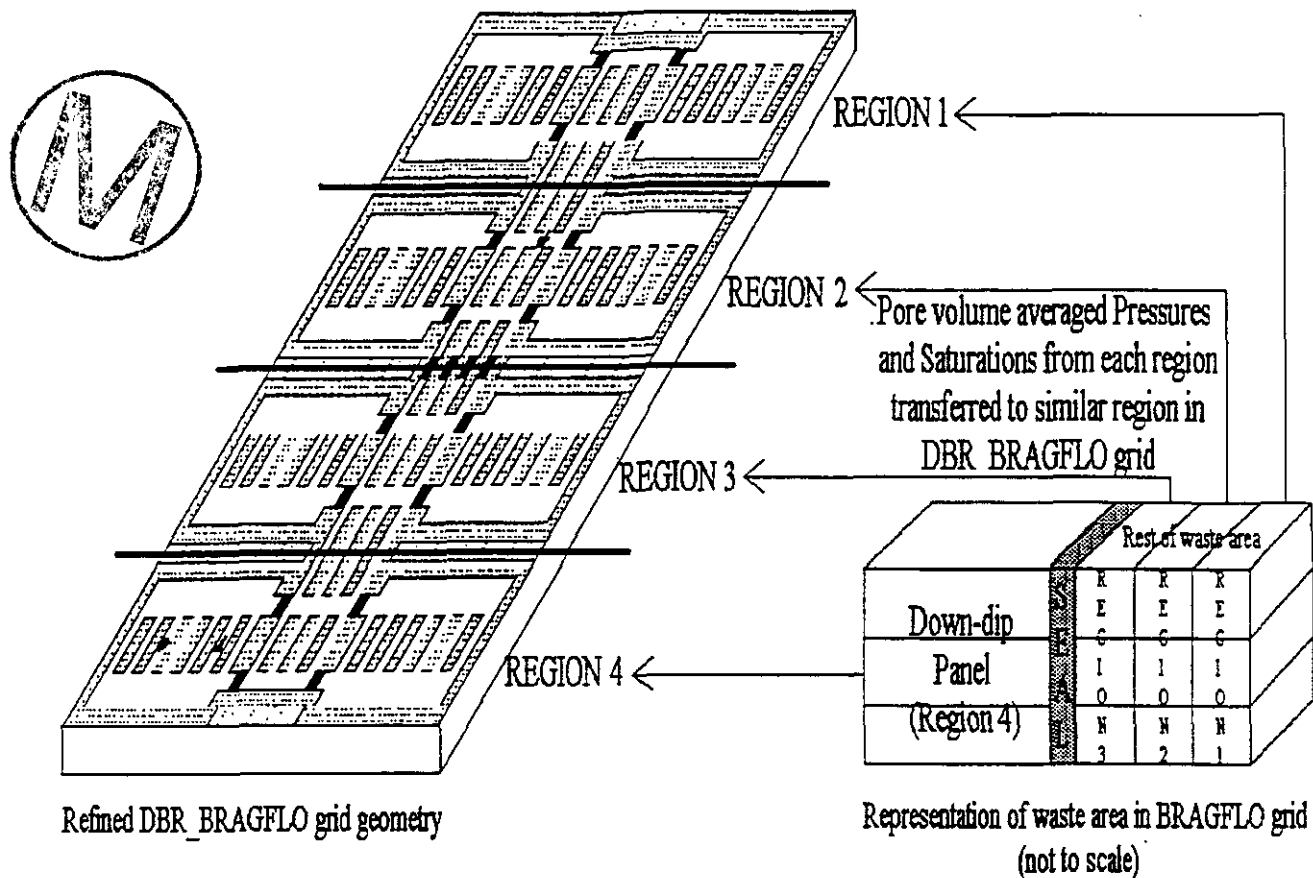
REGION 1

REGION 2

Pore volume averaged Pressures and Saturations from each region transferred to similar region in DBR_BRAGFLO grid

REGION 3

REGION 4

Rest of waste area

Down-dip

Panel

(Region 4)

Refined DBR_BRAGFLO grid geometry

Representation of waste area in BRAGFLO grid (not to scale)

Figure 3: Representation of coupling between the two grids to obtain initial conditions for the DBR_BRAGFLO mesh at each intrusion time

The DBR_BRAGFLO model uses the same intrusion times as is used by the CUTTINGS_S code to provide brine releases for the CCDF generation. Intrusion times differ for each scenario, and two calculations are performed at each time: one for an up dip intrusion, and one for a down dip intrusion. For all subsequent intrusions following an initial intrusion into the Castile brine pocket, the boundary condition well is "turned on" to simulate an abandoned borehole connection to the brine pocket (a more detailed explanation can be found in Appendix A). Since thousands of probabilistic time histories are possible for each replicate-scenario-vector, the actual releases are determined by time interpolating between the given times at which the DBR_BRAGFLO calculations were performed. A more detailed description of how this is accomplished will be provided in the CCDFG code description. A summary of the direct release calculational scheme follows:

• **Scenario 1 (From Undisturbed BRAGFLO runs):** Up dip and down dip first intrusions are modeled at 100, 350, 1000, 3000, 5000, and 10000 years (12 calculations X 100 vectors = 1200 calculations).

- **Scenario 2 (From 350 year first intrusion to brine pocket BRAGFLO runs - E1):** Up dip and down dip second intrusions are modeled at 550, 750, 2000, 4000, and 10000 years (10 calculations X 100 vectors = 1000 calculations).

- **Scenario 3 (From 1000 year first intrusion to brine pocket BRAGFLO runs - E1):** Up dip and down dip second intrusions are modeled at 1200, 1400, 3000, 5000, and 10000 years (10 calculations X 100 vectors = 1000 calculations).

- **Scenario 4 (From 350 year first intrusion, no brine pocket BRAGFLO runs - E2):** Up dip and down dip second intrusions are modeled at 550, 750, 2000, 4000, and 10000 years (10 calculations X 100 vectors = 1000 calculations).

- **Scenario 5 (From 1000 year first intrusion, no brine pocket BRAGFLO runs - E2):** Up dip and down dip second intrusions are modeled at 1200, 1400, 3000, 5000, and 10000 years (10 calculations X 100 vectors = 1000 calculations).

- A total of 5,200 calculations will be performed per replicate, or 15,600 calculations for the 3 replicates to be submitted in the CCA.

The DBR_BRAGFLO is also coupled to the CUTTINGS_S code to account for the possibility of enhanced near wellbore flow due to solids removal. This is accomplished through the use of the skin factor parameter (S) in the DBR_BRAGFLO well deliverability equation, and is included in the determination of flowing bottom-hole pressure.

Flowing bottom-hole pressure using Poettmann-Carpenter wellbore model

Flow up the intrusion borehole during drilling is governed by complex physics dependent on frictional effects and two-phase fluid properties. This phenomena is much studied in petroleum engineering, and many correlations have been developed to predict flow rates and pressures in vertical two-phase pipe flow. The Poettmann-Carpenter approach was chosen to calculate the necessary flowing bottom hole pressures (FBHP) to be used in the DBR_BRAGFLO model. The wellbore is descritized into finite delta lengths of 25 feet, each being described by the diameters of the open hole, drill pipe, drill collars, and casing(s). Note that for the DBR_BRAGFLO model, brine is assumed to flow to surface through the annular area only (between the drill string and open hole). Figure 4 shows the wellbore configuration used for the CCA calculations.

Psurface = 101.32 kPa
Tsurface = 27 C

Kelly Joint

Surface

182.88 m

Surface Casing
323 mm ID

655.32 m

289.56 m

Repository Brine & Gas

Drill Pipe
88.9 mm OD

Drill Collars
203.2 mm OD

182.88 m

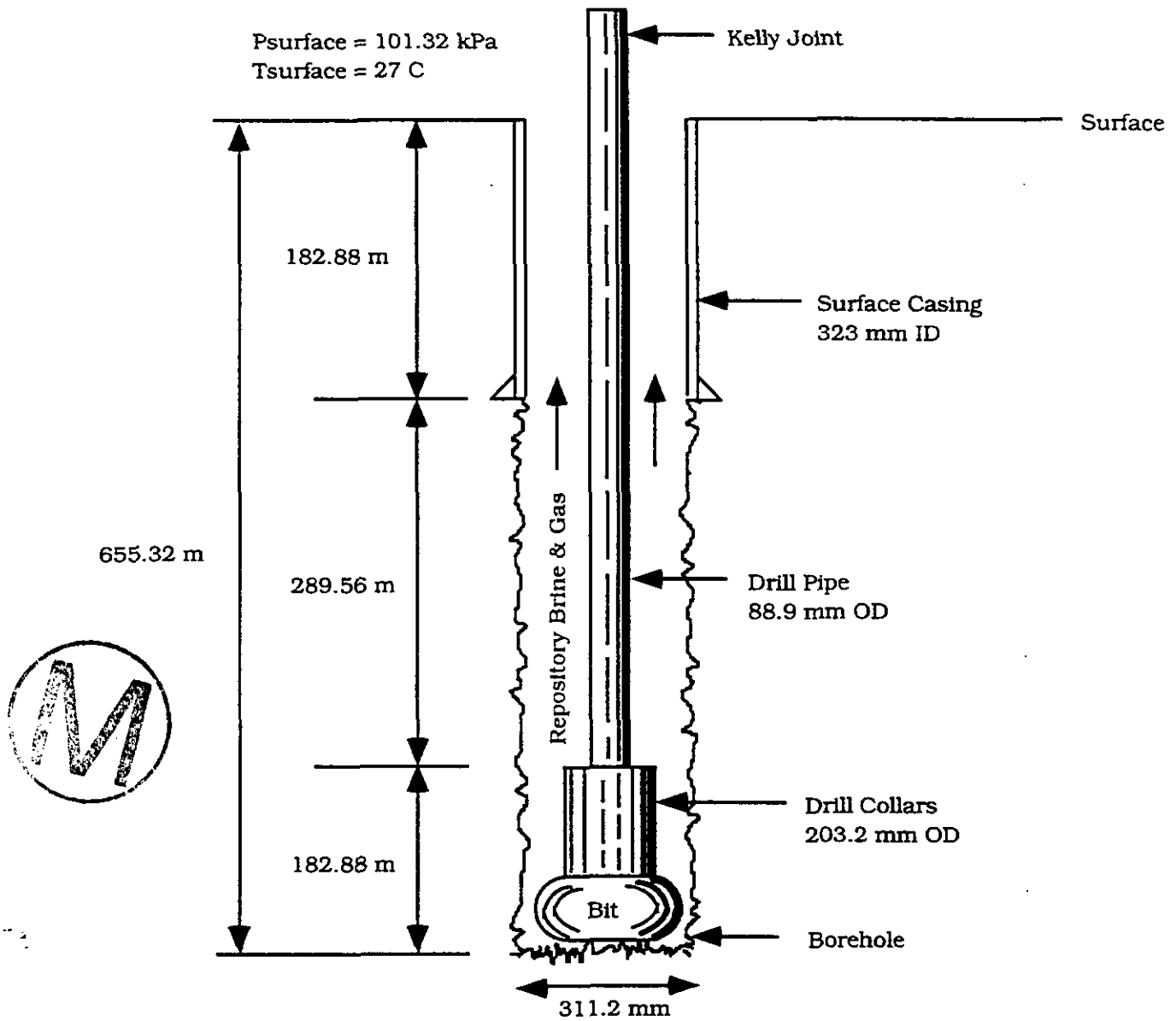Bit

Borehole

311.2 mm

Figure 4: Borehole representation used for Poettmann-Carpenter correlation

The Poettmann-Carpenter model (P-C mod) was chosen because it is easy to implement, accounts for multi-phase frictional effects based on empirical (field) data from flowing wells, and is one of the few correlations that includes annular flow data in its development. To calculate the flowing bottom hole pressures to be used in the CCA calculations, the flow rates used in P-C mod have to match those predicted by the DBR_BRAGFLO well model. Since the fluid saturations and panel pressures are known for each realization at each intrusion time, it is possible to calculate the FBHP iteratively. A starting FBHP is assumed, and the gas and brine flow rates are calculated from the DBR_BRAGFLO well deliverability equation. These flow rates are then used in the P-C mod to determine finite pressure drops up the wellbore to the surface. If the resulting surface flowing pressure does not equal atmospheric, a new FBHP is

assumed and the process repeated until the surface pressure is calculated to within 5% tolerance of atmospheric. A detailed description of the equations used can be found in Appendix B. Figure 5 shows a flowchart of this process.
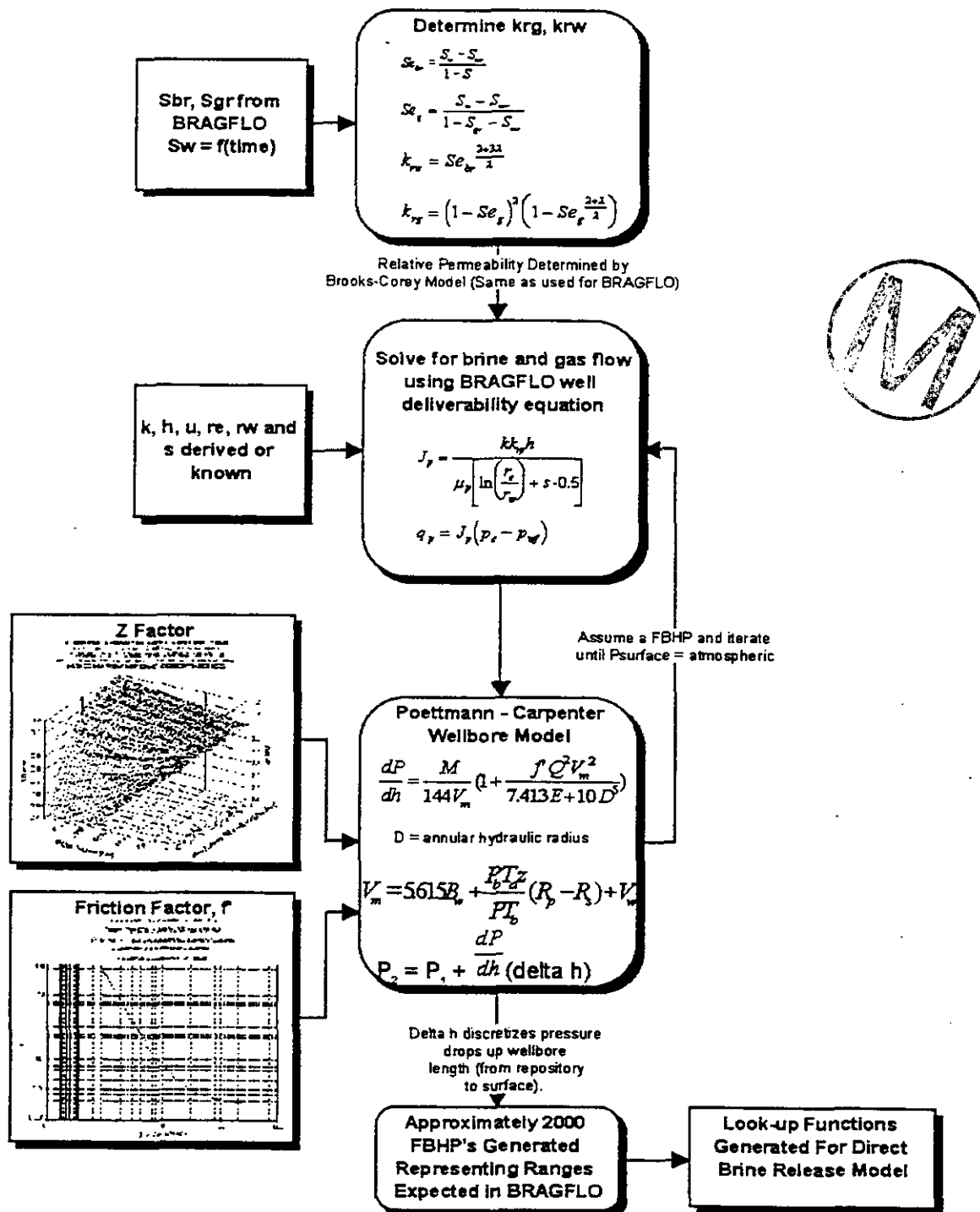
Sbr, Sgr from BRAGFLO
$Sw = f(time)$

Determine krg, krw

$$Se_w = \frac{S_w - S_{wc}}{1 - S}$$

$$Se_g = \frac{S_g - S_{gr}}{1 - S_{gr} - S_{wc}}$$

$$k_{rw} = Se_w^{\frac{2+3\lambda}{\lambda}}$$

$$k_{rg} = \left(1 - Se_g\right)^2 \left(1 - Se_g^{\frac{2+\lambda}{\lambda}}\right)$$

Relative Permeability Determined by Brooks-Corey Model (Same as used for BRAGFLO)

k, h, u, re, rw and s derived or known

Solve for brine and gas flow using BRAGFLO well deliverability equation

$$J_p = \frac{kk_{rp}h}{\mu_p\left[\ln\left(\frac{r_e}{r_w}\right) + s - 0.5\right]}$$

$$q_p = J_p(p_e - p_{wf})$$

Assume a FBHP and iterate until Psurface = atmospheric

Z Factor

Poettmann – Carpenter Wellbore Model

$$\frac{dP}{dh} = \frac{M}{144V_m}(1 + \frac{f\,Q^2V_m^2}{7.413E+10\,D^5})$$

D = annular hydraulic radius

$$V_m = 5.615B_w + \frac{PT_z}{PT_b}(R_p - R_s) + V_w$$

$$P_2 = P_1 + \frac{dP}{dh}\,(\text{delta h})$$

Friction Factor, f

Delta h discretizes pressure drops up wellbore length (from repository to surface).

Approximately 2000 FBHP's Generated Representing Ranges Expected in BRAGFLO

Look-up Functions Generated For Direct Brine Release Model

Figure 5: Flowchart of iterative process used to estimate flowing bottom hole pressure in the CCA calculations

An Excel spreadsheet was developed to perform the iterative procedure and create a table of FBHPs based on randomly generated crushed panel heights, initial panel pressures, and residual fluid saturations. These variables are expected to vary with time, or are sampled in the CCA calculations. The resulting (2,000 plus) FBHPs were curve-fitted to three look-up functions, which were used to predict the starting FBHP in the intruded grid block in each DBR_BRAGFLO calculation (the second ALGEBRA step in Figure 2). Skin factor (based on spall removed) was kept at zero and mole fraction Hydrogen was kept at 100% for development of the lookup functions, even though these may vary in the BRAGFLO runs. Ideally, the FBHP should be updated at each time step in the DBR_BRAGFLO calculation, but the current version of BRAGFLO is unable to achieve this. Therefore, the FBHP is held constant for the duration of the direct release flow time period. This is a conservative modeling constraint, since the FBHP should realistically increase with time (thereby reducing flow) as the panel pressure decreases.

Uncertainty in Conceptual Models and a Qualitative Discussion of the Relative Significance of Parameters

The DBR_BRAGFLO model uncertainties are captured in the 10,000 year BRAGFLO calculations from which the initial and boundary conditions are derived. The model parameters that have the most influence on the brine direct releases are repository pressures and brine saturations at time of intrusion. High brine saturations are influenced by many factors, including Salado and marker bed permeability and gas generation rates (for undisturbed calculations). For intrusion scenarios, Castile brine pocket pressures and volumes (E1) and abandoned borehole permeabilities (E1 and E2) influence conditions for the 2nd and subsequent intrusions. Additionally, dip in the repository (hence location of intrusions), two-phase flow parameters (residual brine and gas saturation, etc.), and time of intrusion have lesser impacts on brine releases.

Duration of flow for DBR_BRAGFLO model

The DBR_BRAGFLO model is run for 50 days for each realization that meets the blowout criteria (adequate pressure and saturation). The cumulative brine releases to contribute to the CCDF construction are determined in a post processing step (the last ALGEBRA run in Figure 2) by the following criteria:

- Every realization will accumulate brine for a minimum of three days. This is based on the estimated length of time it will take to drill through the Castile and cement the intermediate casing (see reference No. 10 for a synopsis of current drilling practices in the WIPP area). If there is little or no gas flow associated with the brine flow, current practice is to allow the brine to "seep" into the drilling mud and flow to the mud pits (the "seepage" may even go undetected), until the salt section is cased.
- If there is a significant amount of gas flow associated with the brine releases, it is possible that the driller will lose control of the well. In such cases the brine releases will accumulate until the gas rate drops below a predetermined gas "cut-off" rate. This rate is arbitrarily set by the author at 100 thousand standard cubic feet per day (MSCF/D), and represents a gas flow rate (in oil field units) at which control of the well could be easily be regained.

- Should the gas flow rate continue above the cut-off rate, the brine releases will accumulate for a maximum of eleven days. This is based on the amount of time it took to control the South Culebra Bluff Unit #1 well, which blew out in January, 1978 (see reference No. 3). Eleven days was the response time needed to gather the equipment and personnel necessary to regain control of that well

Model output and integration with CCA results

The output from the repository-scale direct release model is volume of brine (m^3) released to the surface. The number of intrusions into the waste area, location (updip or downdip), and scenario (E1 or E2) are determined stochastically in the CCDFG code for each BRAGFLO realization. The actual brine released directly for each time history is then calculated by linear time interpolation from the DBR_BRAGFLO results. This is combined with output from PANEL (expressed in EPA units) to determine the releases associated with each realization at each intrusion time.

References: Direct Brine Release Model

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APPENDIX A

A1: E1-E2 SCENARIOS

The following definitions for the E1-E2 scenarios are paraphrased from the SPM-2 Decision Aiding Tool, Prepared for the DOE's Waste Isolation Pilot Plant (WIPP) by Sandia National Laboratories, March 31, 1995, Report Volume 1, Glossary (Section 9):

E1 Intrusion Scenario - A characterization of an alternative future state of the WIPP disposal system that models an inadvertent exploratory borehole intersecting the repository and a hypothetical pressurized brine reservoir (pocket) in the underlying Castile formation.

E2 Intrusion Scenario - A characterization of an alternative future state of the WIPP disposal system that models an inadvertent exploratory borehole intersecting the repository but missing the hypothetical brine reservoir.

E1E2 Intrusion Scenario - A characterization of an alternative future state of the WIPP disposal system that models two or more inadvertent exploratory boreholes intersecting the repository, at least one of which hits an underlying brine reservoir. With robust panel seals the boreholes must intersect the same panel, one of which is a previously abandoned well through the brine reservoir. With degraded or failed seals, communication to the abandoned brine pocket well could exist across multiple panels. For the 1996 CCA, panel seals are given a 10^{-15} m^2 permeability, which is robust enough to inhibit short-term (days) brine flow between panels, but can allow significant gas flow through the waste area.

The 1996 CCA calculations treat future abandoned intrusion boreholes the following way:
- The first 200 years after abandonment are characterized by two cement plugs (5×10^{-17} m^2 permeability) across the top of the Salado and bottom of the Castile formations. Between the two plugs, the borehole is treated as corroded, brine-filled pipe open to flow between the brine pocket and WIPP panel.
- From 200 to 1,200 years after abandonment, the cement plugs are assumed to degrade and the entire borehole is filled with debris, with permeability sampled from 10^{-11} to 10^{-14} m^2.
- From 1,200 to 10,000 years after abandonment, the lower section of borehole in the Salado between the WIPP horizon and Castile is assumed to be affected by salt creep, and its permeability is reduced one order of magnitude.

The amount of brine that can flow from the brine pocket, through an abandoned borehole, into a WIPP panel (E1 scenario), and out a nearby (blowout) well in the same panel (E2 scenario) is a function of the following, assuming steady-state flow for the duration of the blowout:
- Castile brine reservoir properties:
  1. Height (h_{BP}) is assumed to be 12.34 meters for all calculations, which is equivalent to that used in the BRAGFLO model
  2. Areal extent expressed as external drainage radius ($r_{e\,BP}$), set equal to 114 meters for all calculations, which corresponds to the highest brine pocket size possible that could fit underneath a single waste panel.
  3. Brine pocket pressure (P_{BP} - Pascals), which is taken from BRAGFLO at the blowout well intrusion time.
  4. The brine pocket permeability (K_{BP} - m^2), which is a sampled parameter obtained from BRAGFLO.
  5. Flowing pressure at the wellbore in the brine pocket ($P_{wf\,BP}$ - Pascals).
- Waste panel properties:
  6. Flowing pressure at the wellbore in the abandoned borehole grid block for boundary condition treatment ($P_{wf\,BC}$ - Pascals).

7. Equivalent radius representing area of abandoned borehole grid block ($r_{e\,BC} = [(delx \cdot dely)/\pi]^{0.5}$, meters)

8. Flowing pressure at the wellbore for the intrusion well ($P_{wf\,BO}$ - Pascals), which is calculated separately using the Poettmann-Carpenter correlation.

9. Wellbore radius (r_w - meters, from bit size parameter off the database) is assumed to be equal for the abandoned wellbore and intrusion borehole.

10. Flow up the abandoned borehole from the brine pocket (Q_{BP} - m³/s) is assumed to be equal to flow "injection" into the panel (Q_{BC} - m³/s), for steady state conditions.

E1-E2 Illustrations/Terminology
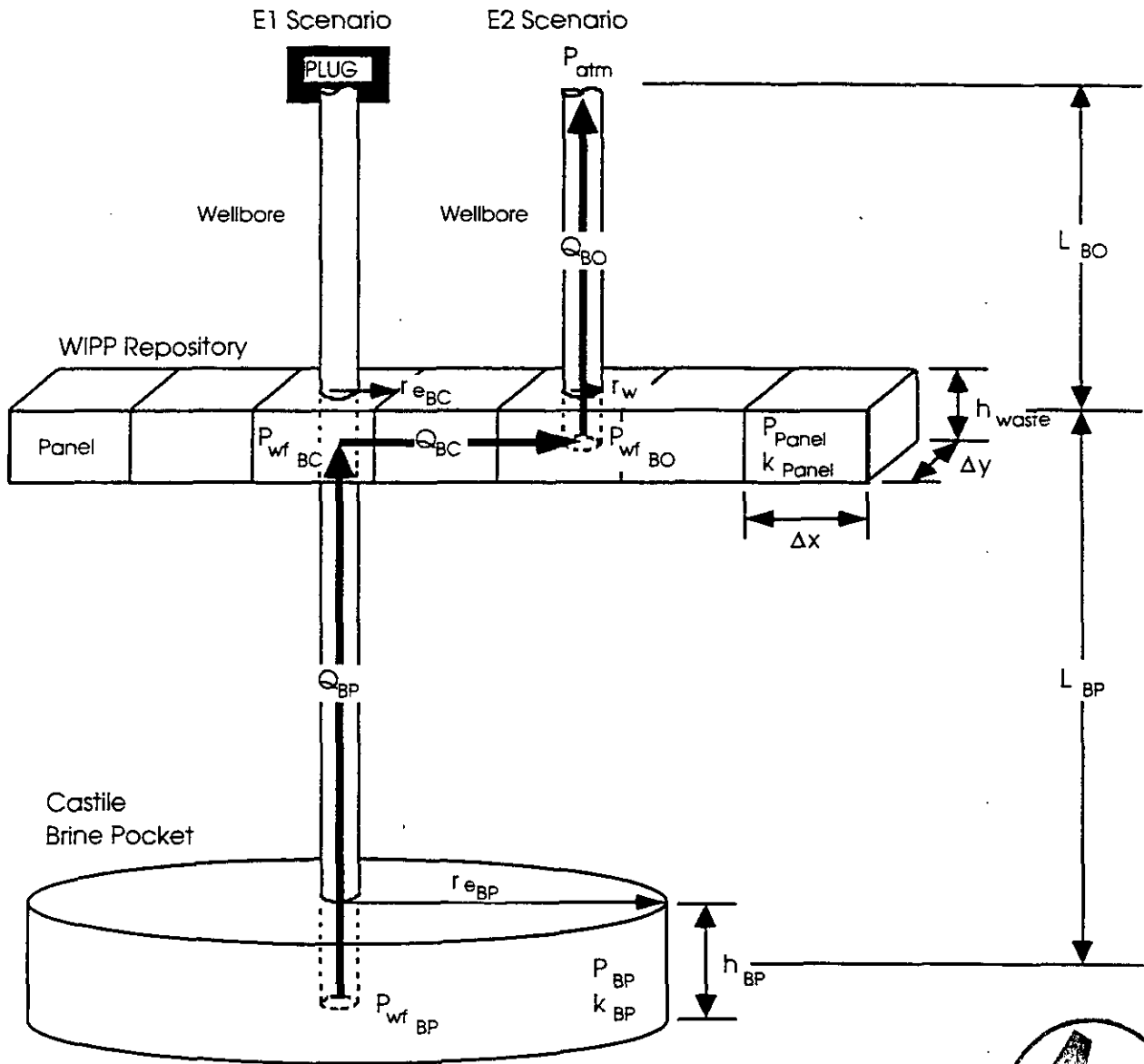
Figure A1: Representation of assumed flow path for E1E2 scenario
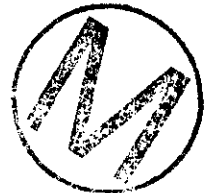
A2: THEORETICAL CONSIDERATIONS

A. Frictional Effects

Consider the flow rate necessary to achieve laminar flow from the brine pocket to the repository as depicted by the following:
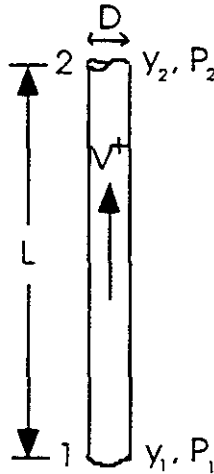
Assuming the flow is positive between location 1 (brine pocket) to 2 (repository panel), the following equation describes linear flow according to Poiselle's Law:

$$\left(\frac{P_1}{\gamma} + y_1\right) - \left(\frac{P_2}{\gamma} + y_2\right) = \frac{32\mu V L_{BP}}{\gamma D^2}$$ [Equation A1]

$$Q = VA, V = \frac{Q}{A} = \frac{4Q}{\pi D^2}$$ [Equation A2]

$$\left(\frac{P_1}{\gamma} + y_1\right) - \left(\frac{P_2}{\gamma} + y_2\right) = \frac{128\mu Q L_{BP}}{\gamma \pi D^4}$$

or by separating and combining terms:

$$(P_1 - P_2) + \gamma(y_1 - y_2) = \frac{128\mu Q L_{BP}}{\pi D^4}$$ [Equation A3]

Using the following WIPP properties:

$$\gamma = 9.8\frac{m}{sec^2} * 1230\frac{kg}{m^3} = 12,054\frac{kg}{sec^2 m^2} = 12,054\frac{Pascal}{m}$$

$$L_{BP} = y_1 - y_2 = -247m$$

$$\mu = 1.8E - 03\,Pascal - sec$$

For 9 5/8 inch OD casing (8.921 inch ID):

$$D = 0.2266m$$

Substituting these values into Equation A3 results in the following relationship for P_2 as a function of P_1 and Q as follows:

$$P_2 = P_1 - 2.9773E06 - 6.8705E03Q \qquad \text{[Equation A4]}$$

where:
P_1 = Pressure at the brine pocket end of the wellbore (Pa)
P_2 = Pressure at the repository end of the wellbore (Pa)
Q = Poiselle laminar flow rate from the brine pocket to the repository (m³/sec)

Since Q must be $\geq$ 100 m³/sec for frictional forces to have an effect on flow, frictional forces will be neglected in the remainder of the equations developed (6.8705E03*Q = 0).

B.   Open Borehole Connection Between Brine Pocket and Repository Panel

For open borehole flow where Q_{BC} is negative for injection:

$$P_{wf_{BC}} = P_{wf_{BO}} - Q_{BC}\left[\frac{\mu \ln\left(\dfrac{r_{e_{BC}}}{r_w}\right) - 0.5}{k_{waste}h_{waste}(1)}\right] \qquad \text{[Equation A5]}$$

$$P_{wf_{BP}} = P_{wf_{BC}} + 2.9773E06 - 6870Q_{BC} \qquad \text{[Equation A6]}$$

$$Q_{BP} = -Q_{BC} \qquad \text{[Equation A7]}$$

$$Q_{BP} = \left[\frac{k_{BP}h_{BP}(1)}{\mu \ln\left(\dfrac{r_{e_{BP}}}{r_w}\right) - 0.5}\right](P_{BP} - P_{wf_{BP}}) \qquad \text{[Equation A8]}$$

Substituting Equations A6 and A7 into Equation A8:

$$-Q_{BC} = \left[\frac{k_{BP}h_{BP}}{\mu \ln\left(\dfrac{r_{e_{BP}}}{r_w}\right) - 0.5}\right](P_{BP} - P_{wf_{BC}} - 2.9773E06) \qquad \text{[Equation A9]}$$

Substituting Equation A9 into Equation A5:

$$P_{wf_{BC}} = P_{wf_{BO}} + \left[\frac{k_{BP}h_{BP}\left(P_{BP} - P_{wf_{BC}} - 2.9773E06\right)}{\mu \ln\left(\frac{r_{e_{BP}}}{r_w}\right) - 0.5}\right]\left[\frac{\mu \ln\left(\frac{r_{e_{BC}}}{r_w}\right) - 0.5}{k_{waste}h_{waste}}\right]$$

or by separating and combining terms:

$$P_{wf_{BC}} = P_{wf_{BO}} + \left[\frac{k_{BP}h_{BP}\ln\left(\frac{r_{e_{BC}}}{r_w}\right) - 0.5}{k_{waste}h_{waste}\ln\left(\frac{r_{e_{BP}}}{r_w}\right) - 0.5}\right]\left(P_{BP} - P_{wf_{BC}} - 2.9773E06\right) \qquad \text{[Equation A10]}$$

Now define the following to be a constant:

$$Const1 = \left[\frac{k_{BP}h_{BP}\ln\left(\frac{r_{e_{BC}}}{r_w}\right) - 0.5}{k_{waste}h_{waste}\ln\left(\frac{r_{e_{BP}}}{r_w}\right) - 0.5}\right] \qquad \text{[Equation A11]}$$

Substituting Equation A11 into Equation A10 and rearranging gives:

$$P_{wf_{BC}} = \left[\frac{P_{wf_{BO}} + Const1 P_{BP} - Const1(2.9773E06)}{(1 + Const1)}\right] \qquad \text{[Equation A12]}$$

Equation A12 is the defining equation for open borehole flow between the brine pocket and repository panel.

C.   Sand-filled Connection Between Brine Pocket and Repository Panel

For the sand-filled connection between the brine pocket and repository the borehole flow rate (for linear flow, neglecting drawdown in the brine pocket) according to Darcy's Law is:

$$Q_{BH} = \left\{\frac{k_{BH}A_{BH}\left[\left(P_{wf_{BC}} - P_{BP}\right) + 2.9773E06\right]}{\mu L}\right\} \qquad \text{[Equation A13]}$$

Rearranging terms and solving for Pwf_{BC} gives:

$$P_{wf_{BC}} = \frac{Q_{BH}\mu L}{k_{BH}A_{BH}} + P_{BP} - 2.9773E06 \qquad \text{[Equation A14]}$$

$$Q_{BH} = Q_{BC} \qquad \text{[Equation A15]}$$

Substituting Equation A15 into Equation A14 and rearranging:

$$Q_{BC} = \left(P_{wfBC} - P_{BP} + 2.9773E06\right)\left(\frac{k_{BH}A_{BH}}{\mu L}\right)$$

[Equation A16]

Substituting Equation A16 into Equation A5:

$$P_{wfBC} = P_{wfBO} + \left[\frac{k_{BH}A_{BH}\ln\left(\frac{r_{eBC}}{r_w}\right) - 0.5}{Lk_{waste}h_{waste}}\right]\left(P_{BP} - P_{wfBC} - 2.9773E06\right)$$

[Equation A17]

Now define the following to be a constant:

$$Const2 = \frac{k_{BH}}{h_{waste}}\left[\frac{\pi r_w^2 \ln\left(\frac{r_{eBC}}{r_w}\right) - 0.5}{Lk_{waste}}\right]$$

[Equation A18]

Substituting Equation A18 into Equation A17 and rearranging gives:

$$P_{wfBC} = \left[\frac{P_{wfBO} + Const2P_{BP} - Const2(2.9773E06)}{(1 + Const2)}\right]$$

[Equation A19]

Equation A20 is the defining equation for sand-filled borehole flow between the brine pocket and repository panel.

A3:   CONCLUSIONS

Equations A12 and A19 are the expressions that are used to determine the boundary condition pressure that represents abandoned E1 wells. This "injection" pressure simulates flow into the panel from the brine pocket, and is a function of brine pocket properties and abandoned borehole permeabilities at blowout well intrusion time.

APPENDIX B

B1. FLOWING BOTTOMHOLE PRESSURE ISSUE AND THEORY

The driving force behind expulsion of brine and gas from the WIPP repository to the surface via a wellbore during an uncontrolled blowout is determined by the static panel pressure and flowing bottomhole pressure at the time of intrusion. The flowing bottomhole pressure, defined as the dynamic pressure at the inlet to the wellbore adjacent to the point of entry into the repository, is less than the static pressure due to elevation, friction and acceleration effects. The ability of the well to produce brine and gas is governed by the drop in panel pressure and the productivity index (assuming steady-state flow) by the following well deliverability equation:

$$q_p = J_p \left(p_e - p_{wf} \right)$$

[Equation B1]

where:

q_p = well flow rate of the produced phase (brine or gas)
J_p = phase productivity index
p_e = phase pressure at the outer boundary of the well drainage area (panel pressure)
p_{wf} = flowing bottomhole pressure

In a radial drainage area where saturation is uniform over the drainage region (which is valid throughout the assumed blowout period), the productivity index, J_p can be determined from Darcy's law:

$$J_p = \frac{kk_{rp}h}{\mu_p \left[\ln\left(\frac{r_e}{r_w}\right) + s + c \right]}$$

[Equation B2]

where:

k = absolute permeability (assumed to be constant through time at 1.7E-13 m²)
k_{rp} = relative permeability to phase (based upon the modified Brooks-Corey KRP = 4 model)
h = crushed panel height (calculated from porosity surface)
μ_p = viscosity of fluid phase (assumed to be constant through time for brine, μ_{brine} = 1.8E-03 Pa-sec, and for gas μ_{gas} = 8.92E-06 Pa-sec)
r_e = external drainage radius (which for rectangular gridblock dimensions, r_e is taken as the equivalent areal radius, i.e. for panel dimensions of 10 m by 32.7 m:

$$r_e = \sqrt{\frac{(10)(32.7)}{\pi}} = 10.2023 \text{ m})$$

r_w = wellbore radius (assumed to be constant through time at 0.1556 m)
c = -0.50 for pseudosteady-state flow
s = skin factor, incorporating well stimulation caused by spallings release

The CUTTINGS_S model can be coupled through the skin factor according to the petroleum engineering well testing relationship:

$$s = \left(\frac{k}{k_{skin}} - 1 \right) \ln\left(\frac{r_{skin}}{r_w} \right)$$

[Equation B3]

where:
s =   skin factor
k =   absolute permeability
k_{skin} =   permeability of an open channel as a result of CUTTINGS_S releases (assumed to be infinite)
r_w =   wellbore radius
r_{skin} =   effective radius of the wellbore with CUTTINGS_S volume removed

The effective radius of the wellbore can be determined using the total area removed from the CUTTINGS_S model (AreaTotal) by assuming a radius (r_{skin}) such that:

$$AreaTotal = \pi r_{skin}^2$$

[Equation B4]

Rearranging Equation B4 to solve for r_{skin} gives:

$$r_{skin} = \sqrt{\frac{AreaTotal}{\pi}}$$

[Equation B5]

Substituting Equation B5 into Equation B3 and assigning infinity to k_{skin} gives the desired relationship between skin (s) and total area removed according to the CUTTINGS_S model (AreaTotal):

$$s = -1 \ln\left(\frac{\sqrt{\dfrac{AreaTotal}{\pi}}}{r_w} \right)$$

[Equation B6]

The relative permeability to a phase (k_{rp}) using the modified Brooks-Corey model (KRP = 4) shown in Equation B2 is defined using the following expressions for brine (br) and gas (g) respectively:

Calculate an effective saturation (Se) for each phase as follows:

$$Se_{br} = \frac{S_w - S_{wr}}{1 - S_{wr}}$$

[Equation B7]

$$Se_g = \frac{S_w - S_{wr}}{1 - S_{gr} - S_{wr}} \quad \left(0 \leq S_{gr} \leq 0.15\right)$$

[Equation B8]

where:
S_w =   brine saturation in panel at time of intrusion
S_{wr} =   residual brine saturation (sampled parameter, from 0% to 40%)
S_{gr} =   critical gas saturation (sampled parameter, from 0% to 15%)

Calculate the relative permeability for each phase as follows:

$$k_{rw} = Se_{br}^{\frac{2+3\lambda}{\lambda}}$$

[Equation B9]

$$k_{rg} = \left(1 - Se_g\right)^2 \left(1 - Se_g^{\frac{2+\lambda}{\lambda}}\right)$$

[Equation B10]

where:

k_{rw} =   relative permeability to brine

k_{rg} =   relative permeability to gas

λ =   pore size distribution parameter (assumed constant at 2.89 for the waste region)

Sampled parameters in combination with Equations B6, B9 and B10 when used in Equation B2, yield the productivity index for brine and gas. These values are available with the panel pressure at the time of intrusion. The only variable unknown is the flowing bottomhole pressure which when used in the well deliverability equation (Equation B1) gives the expelled brine and gas flow rates. To determine the flowing bottomhole pressure, an iterative procedure is used based upon a petroleum engineering industry multiphase flow correlation developed by Poettmann and Carpenter (for a discussion of the Poettmann and Carpenter technique, refer to section B3). The method begins by assuming a gas composition comprised of hydrogen and carbon dioxide (CO_2 is assumed to be 0 because of its adsorption in the backfill) and a flowing bottomhole pressure less than the panel pressure. With the productivity index computed from Equation B2, flow rates for brine and gas are computed using Equation B1. Using the Poettmann and Carpenter method which takes into account elevation, friction and acceleration impacts on the flowing pressure gradient, a surface pressure is computed. If the surface pressure is equal to atmospheric pressure (101.32 Pa, for a blowout scenario), the iteration ceases using the last flowing bottomhole pressure used. If the surface pressure is not equal to atmospheric pressure, another flowing bottomhole pressure is assumed and the process of computing the brine and gas flow rates and subsequent surface pressure is repeated until the surface pressure is at atmospheric pressure.

B2. RESULTS

Flowing bottomhole pressures (FBHP) were generated using the method described in Section B1 of this report to represent expected ranges of panel pressures, brine saturation, critical gas saturation, panel permeability, crushed panel height and skin factor due to spall releases. These results were then developed into correlations based upon relationships between FBHP versus panel pressure and log of well productivity index (as shown in Figure B1) and FBHP versus panel pressure and log (krg/krw) (as shown in Figures B2 and B3 for brine dominated and gas dominated flow, respectively). The linear fit equations (shown in Figures B1-B3) are used as a "look-up" function in the BRAGFLO Direct Brine Release model to determine FBHP. Figures B4 and B5 demonstrate how the FBHP changes with log (krg/krw) and brine saturation, respectively.
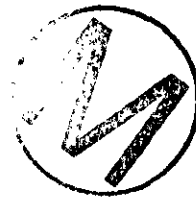
FIGURE B1

FBHP as a Function of Brine Well Index and Panel Pressure (Krg=0, Brine only)
Rank 36 Eqn 1001 $z=(a+bx+cy)/(1+dx+ey)$
$r^2=0.98189816$ DF Adj $r^2=0.98103617$ FitStdErr=1284.2129 Fstat=1437.4399
a=8002577.4 b=821379.75 c=0.024916096
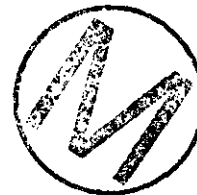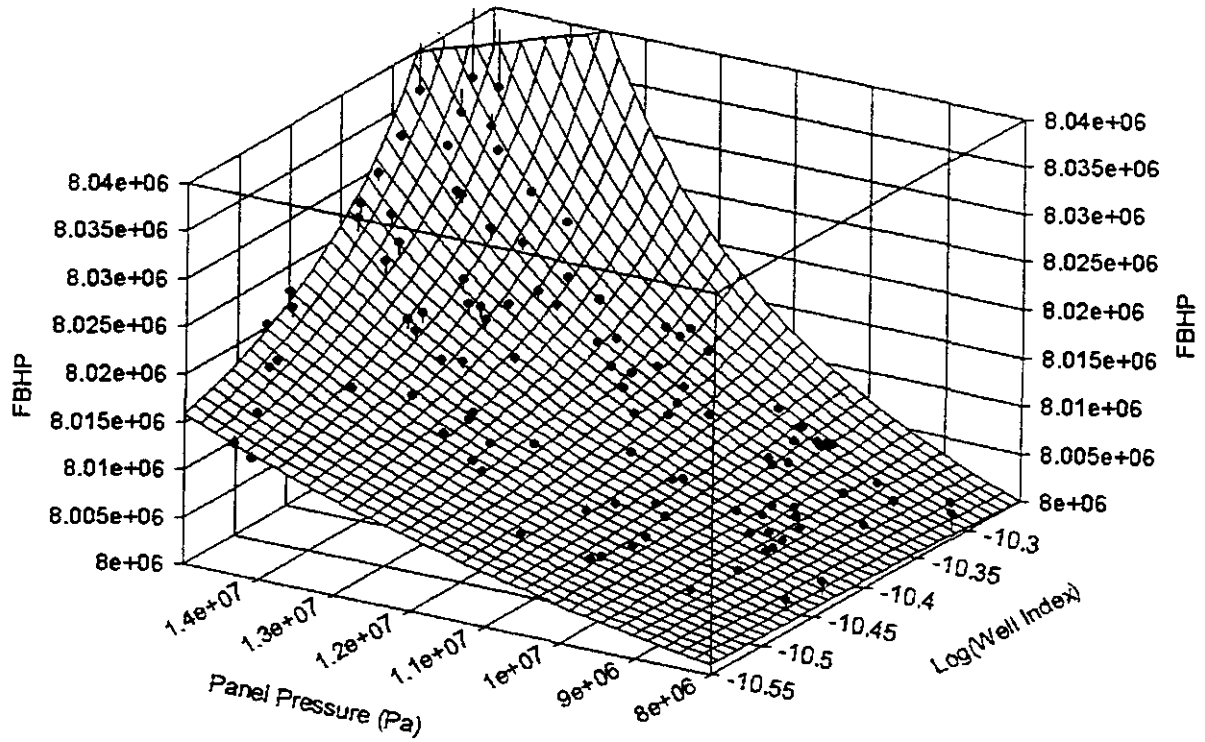d=0.10264807 e=3.1235777e-09

FIGURE B2

FBHP as a Function of Rel Permeabilities and Panel Pressure (brine dominated)

Rank 3 Eqn 1100 $z=(a+bx+cx^2+dx^3+ey)/(1+fx+gx^2+hy)$
$r^2=0.99785338$ DF Adj $r^2=0.99782216$ FitStdErr=147128.98 Fstat=36590.213
a=847082.65 b=2788147.9 c=3451058.3 d=-54884.388
e=-0.017079483 f=0.8953597 g=0.54041532 h=-4.9369107e-09
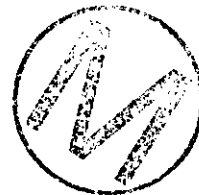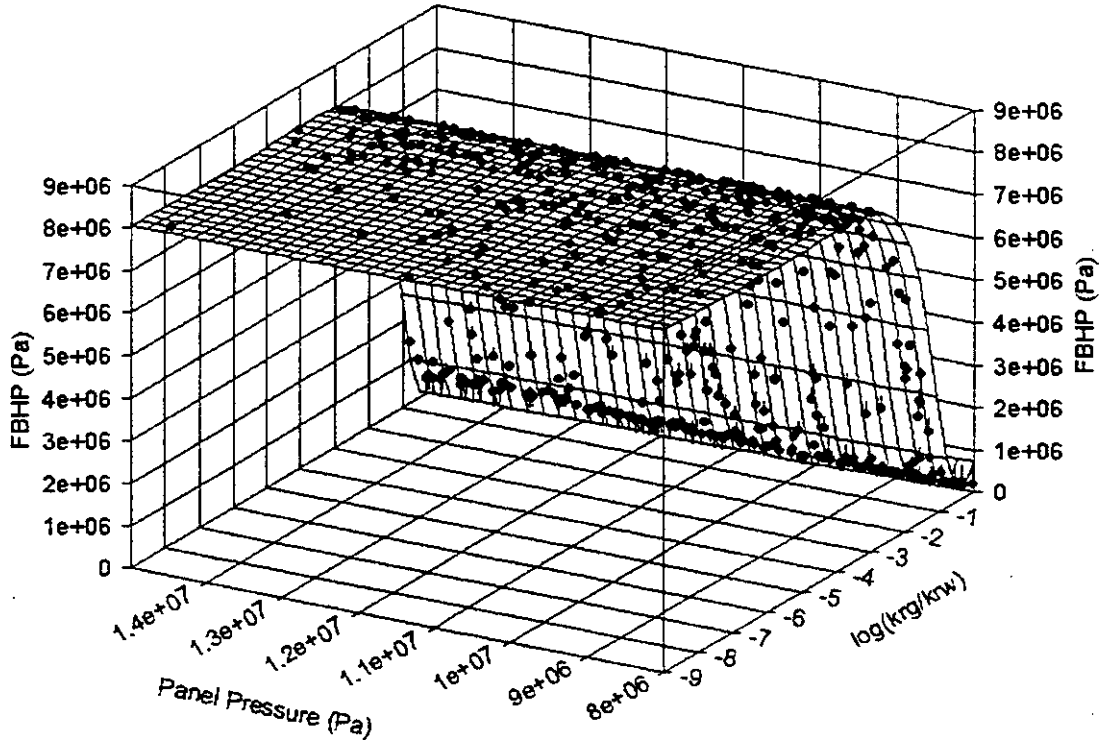
FIGURE B3

FBHP as a Function of Rel Permeabilities and Panel Pressure (gas dominated)

Rank 54 Eqn 151250960 lnz=a+bx+cx$^{0.5}$+de^{-x}+ey$^{0.5}$

r^2=0.94539889 DF Adj r^2=0.94520677 FitStdErr=11520.361 Fstat=6155.3571

a=8.9214635 b=-0.2274279 c=1.3680586
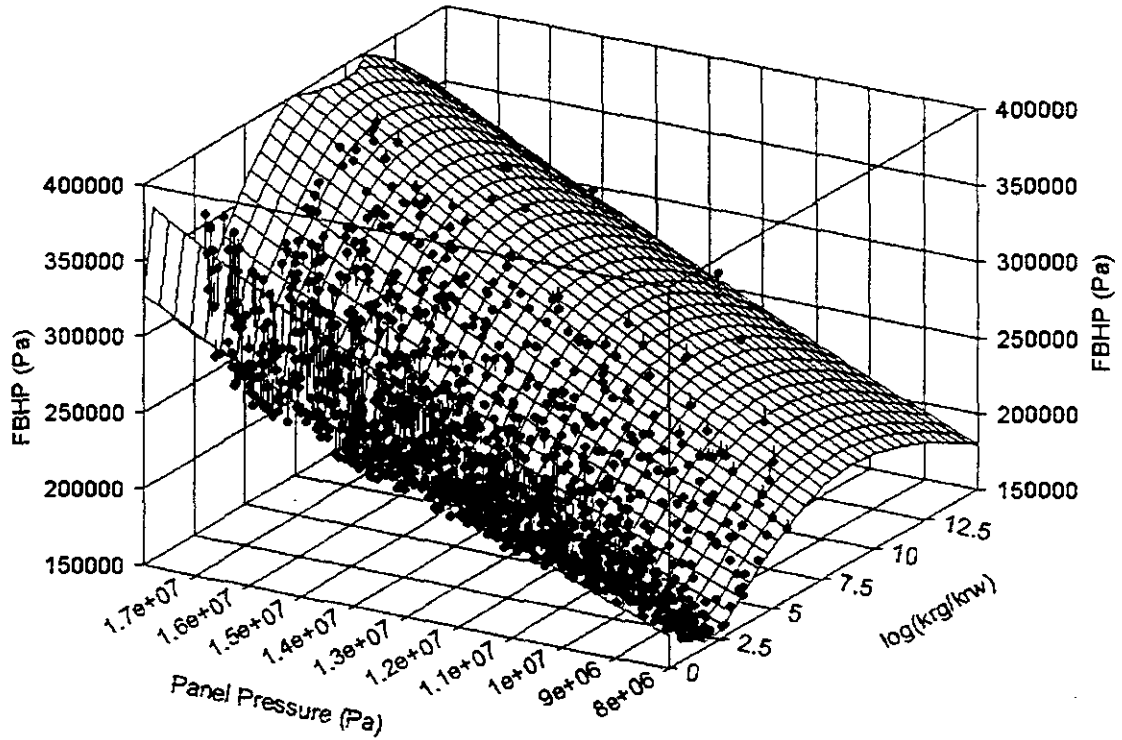
d=1.8350086 e=0.00045726223
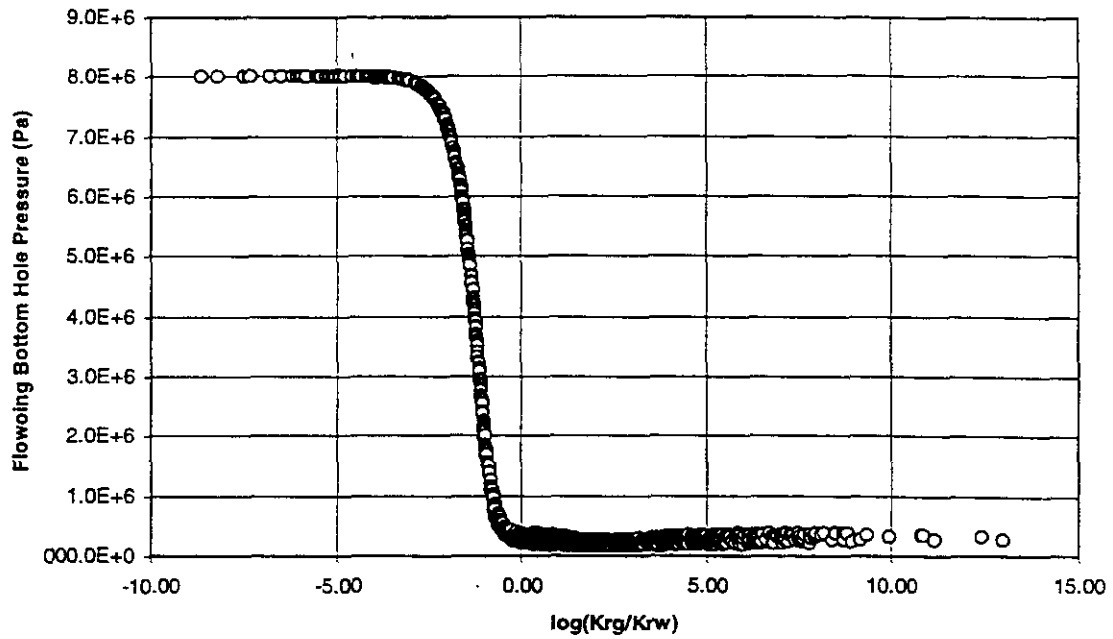
FIGURE B4
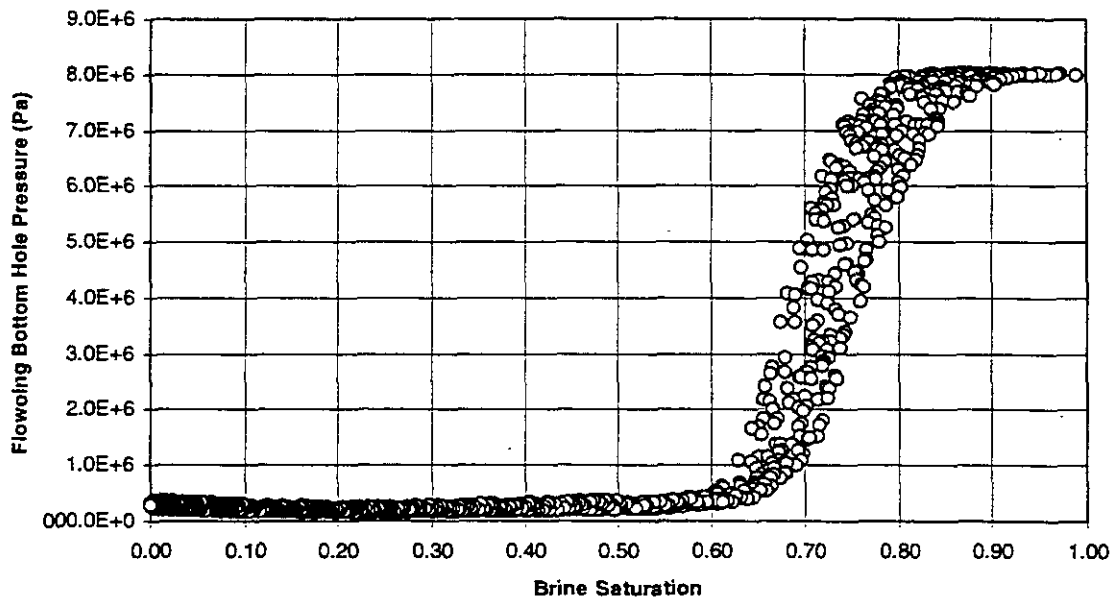### FBHP as a Function of log(Krg/Krw)

FIGURE B5
FBHP as a Function of Brine Saturation

B3. Poettmann and Carpenter Equations

For vertical flow, the general pressure gradient equation can be written as:

$$\frac{dp}{dz} = \left(\frac{dp}{dz}\right)_{el} + \left(\frac{dp}{dz}\right)_{f} + \left(\frac{dp}{dz}\right)_{acc}$$

The total pressure drop is the sum of the pressure drops due to elevation, friction and acceleration, respectively. The pressure drop caused by elevation change depends on the density of the mixture. The pressure drop caused by friction losses requires evaluation of a friction factor. The pressure drop caused by accelerating the fluids is especially important for cases of high flow velocities as would be expected with high pressure gas. The empirical correlations differ in the manner used to calculate the three components of the total pressure gradient.

To calculate the bottom-hole flowing pressure using the method of Poettmann and Carpenter, the following information is required:

$$\frac{dP}{dh} = \frac{M}{144V_m}(1 + \frac{f'Q^2V_m^{\,2}}{7.413E+10D^5})$$

where:

$\dfrac{dP}{dh} = $ pressure gradient (psia/ft)

$D = $ annular diameter [using "hydraulic radius" concept] (ft)

$\qquad D^5 = (d_i + d_o)^2(d_i - d_o)^3$

$$V_m = 5.615B_w + \frac{P_bT_a z}{PT_b}(R_p - R_s) + V_w$$

$V_m = $ volume of mixed gas and brine at pressure P per barrel of stock-tank liquid, based on the ratio of fluids flowing into and out of the flow string (ft³/stbl)

$R_p = $ producing gas-liquid ratio (scf/stb)

$B_w = $ formation volume factor of brine $=$ 1 (rbl/stb)

$P_b = $ base pressure at which gas is measured (101.32 Pa)

$T_a = $ average temperature of flow (300.1 °K)

$T_b = $ base temperature at which gas is measured (300.1 °K)

$z = $ compressibility factor of the gas in the annulus at temperature T_a (300.1 °K) and pressure P

Component	Pc (psia)	Tc (deg R)	Tr = Ta/Tc
H2	187.52	59.29	8.94
CO2	1070.23	547.51	0.97
Methane	667.00	342.93	1.55
N2	491.68	227.09	2.33
O2	731.43	278.17	1.90
H2S	1296.64	671.69	0.79

Z Factor as a Function of Mole Fraction H2 and Panel Pressure

Rank 2 Eqn 1301 $z=(a+cx+ey+gx^2+iy^2+kxy)/(1+bx+dy+fx^2+hy^2+pxy)$
$r^2=0.99503132$ DF Adj $r^2=0.99483038$ FitStdErr=0.0089438965 Fstat=5467.1154
a=0.96953278 b=-0.53291978 c=-0.42234014 d=-0.00052606629 e=-0.0006826474 f=1.9968523
g=1.9224323 h=1.2470738e-07 i=1.3716083e-07 j=0.00025630877 k=0.00054053362
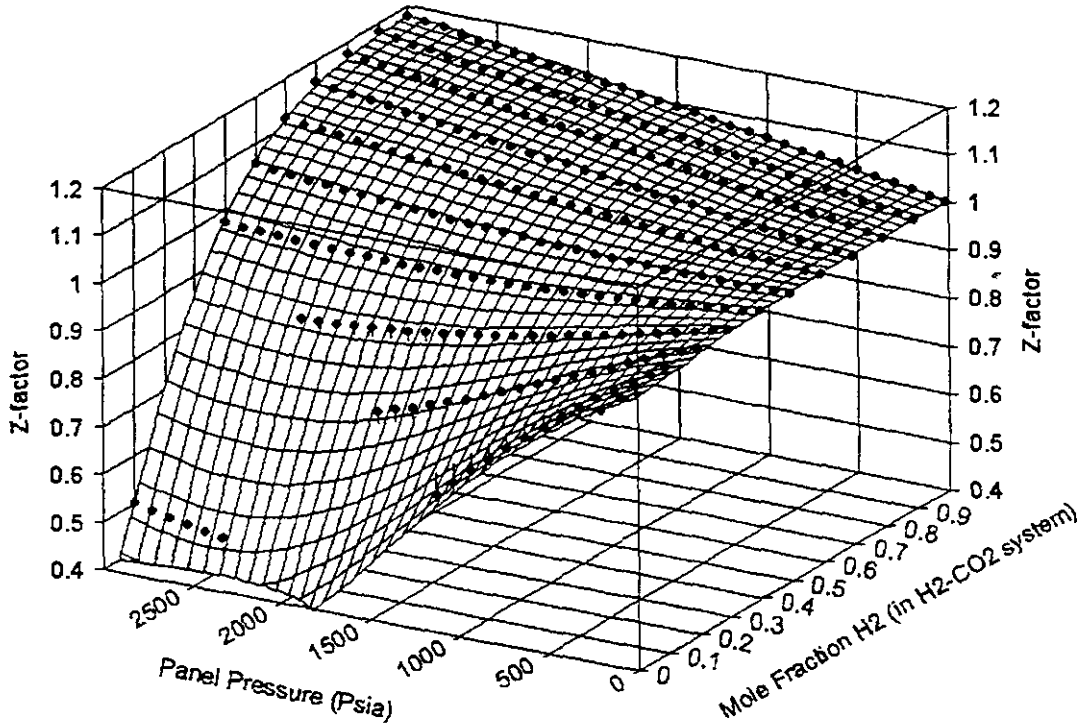
R$_s$ = solution gas-liquid ratio at pressure P (scf/stb) [assumed to be 0]
V$_w$ = cubic feet water produced (scf/stb) [assumed to be 0]
Q = bbl of stock-tank liquid produced per day (bbl/day)
M = $(5.615)(62.4)(G_{sto}) + 0.0764(G_g)(R_p) + 62.4(G_b)(V_w)$
M = total mass of gas and brine, lb, associated with 1 bbl stock-tank liquid
    flowing into and out of flow string.
G$_{sto}$ = specific gravity of stock-tank oil = 0
G$_g$ = separator gas gravity (air = 1.0) [function of the gas composition, determined with SUPERTRAPP
    program developed by NIST]
G$_b$ = specific gravity of produced water = 1.23
M will remain constant at any point in the annulus
Defining the flowing density as follows:

$$\rho = \frac{M}{V_m}(lb/ft^3)$$

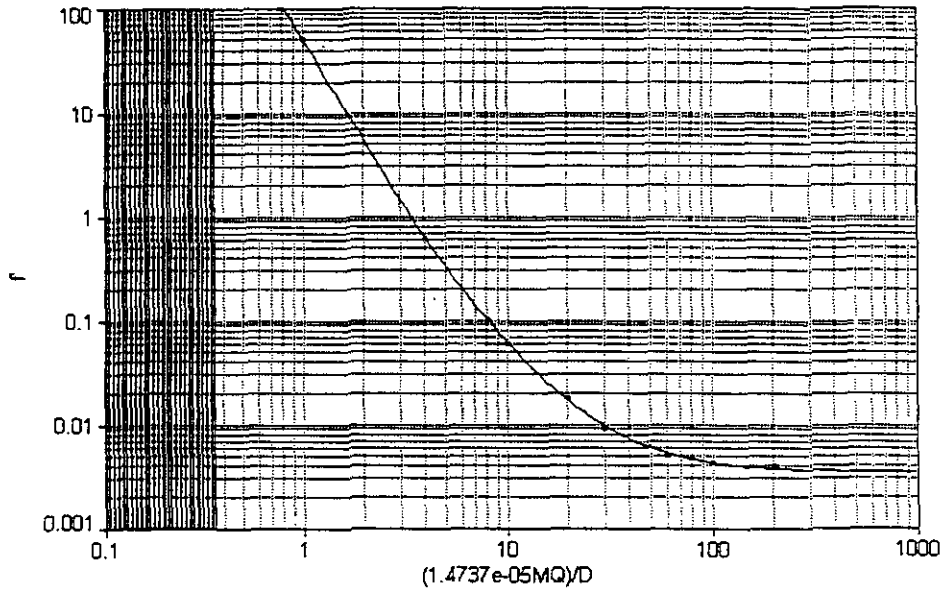f = determined empirically from the work of Poettmann and Carpenter as a function of M, Q & D

SWCF: A :1.2.07.1.3: CO/CCA

Friction factor (f) as function of M, Q, & D

Rank 2 Eqn 6503 y=a+b/x+c/x²+d/x³+e/x⁴+f/x⁵

r²=1 DF Adj r²=1 FitStdErr=0.00080805987 Fstat=3.1276393e+09

a=0.0034152139 b=0.05040896 c=3.8265844

d=8.0204911 e=62.225962 f=-24.126862

$$\frac{dP}{dh}$$ is determined from the original expression above so that the new pressure may be obtained by the following:

For delta h increments up the wellbore, $P_2 = P_1 + \frac{dP}{dh}$(delta h)