Comparison of Effects of Brine Pocket Size

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July 19, 1996

SWCF: A :DRAFT: CO/CCA

BACKGROUND

The existence and size of a Castile Brine Pocket below the WIPP repository is uncertain. Brine pockets have been found in the northern Delaware Basin but there is little information on their size. The producibility of brine from these pockets is believed to be related to the interconnectedness of a fracture system. Analysis of WIPP-12 data have led to estimates for the areal extent of several hundred meters (drainage radius as small as 230 m -- dimension smaller than the WIPP waste-area footprint) to several kilometers (drainage radius as large as 19,000 m -- dimension larger than the land withdrawal boundary). DOE does not consider the 19 km radius brine pocket a realistic size, never the less it is included for comparison to other sizes. Because of the interconnectedness of the fracture system, the thickness of the brine pocket has been estimated to be from 7 m to 24 m with a maximum possible of 133.6 m (recent estimate based upon the total thickness of the Castile formation and NOT considered in the 1996 CCA calculations).

Each time a well penetrates the brine pocket, the pressure in the surrounding drainage area depletes. This pressure depletion will extend to those portions of the brine pocket which are interconnected. Passive Institutional Controls shield a region of the Castile from exploratory drilling directly under the waste panels. The 1996 CCA calculations assume that the Castile Brine Pocket under the waste panels is weakly interconnected hydraulically (with vertical and areal extents similar to the lower estimates from WIPP-12, i.e. total brine volume between 32,000 and 160,000 m^3 [Larson & Freeze, 1996]), and is not much affected by penetrations occuring outside the waste-area footprint. Therefore, the pressure underneath the waste panels in the brine pocket is assumed to not deplete until penetrated by a borehole drilled within the panel area. If the brine pocket has an extensive fracture system (and hence is strongly interconnected), the area beneath the waste panels can be depleted by penetrations outside the waste-area footprint.

This study looks at the consequences of assuming that the brine pocket is hydraulically interconnected such that borehole penetration depletion impacts are felt throughout a larger drainage area. The total brine volume which migrates from the Castile Brine Pocket to the Culebra aquifer with depletion impacts (large drainage area) is compared against the brine volume migration without depletion (small drainage area).

THEORETICAL CONSIDERATIONS

For the 1996 CCA calculations, an abnormally pressured Castile Brine Pocket is assumed (i.e. the brine pocket pressure exceeds the anticipated hydrostatic pressure). The brine pocket is assumed to be bounded (i.e. of limited thickness and areal extent) rather than infinite acting (such as the Culebra aquifer). Consistent with DOE regulatory criteria regarding the rate of future drilling activity, it is assumed that 47 boreholes will be drilled per square kilometer over the next 10,000 years (or 0.47/100 yrs/km^2). Each penetration of the abnormally pressured brine pocket will result in flows according to the following time horizons:

1) Time of intrusion to 72 hours - brine flows from the brine pocket, past the Culebra all the way to the surface during active drilling through an open borehole (assuming steady-state flow conditions). A computation to determine the length of time during which steady-state is valid (i.e. infinite acting period when the pressure sink caused by flow into the borehole has reached the extent of the drainage area) as computed by the following [Lee, 1982]:

$$t < \frac{\phi \mu c_t A t_{DA}}{k} \quad \text{[Equation 1]}$$

where:

t = Time (for a bounded cylindrical system is infinite acting) (sec)
ϕ = Porosity (fraction)
μ = Viscosity (Pa-sec)
c_t = Total compressibility (Pa^{-1})
A = Drainage area (defined as the land withdrawal boundary area/avg. no. of boreholes/200 years where 19.5 boreholes is taken as the average in 200 years) (m^2)
t_{DA} = Dimensionless time (which for a bounded cylindrical system = 0.10, [Lee, 1982])
k = Brine pocket permeability (m^2)

The solution to Equation 1 is approximately 7 hours. Although the steady-state flow assumption is valid only within 7 hours after penetration, a flow period of 72 hours was used. This is consistent with the 1996 CCA blowout time period to obtain direct brine releases from the WIPP repository. For the purposes of this investigation, pressure depletion during the 72 hour open flow period was not taken into account.

During the 72 hour flow period, flowrate is computed from the following (see nomenclature section for definition of variables):

$$Q_{bp} = \left\{ \frac{k_{bp} h_{bp}}{\mu \left[\ln\left(\frac{r_{e_{bp}}}{r_w} \right) - 0.5 \right]} \right\} \left(P_{bp} - P_{atm} - \rho g L_{surface} \right) \qquad \text{[Equation 2]}$$

2) 72 hours to 200 years - no brine flows from the brine pocket since the 1996 CCA calculations assume a 200 year time period immediately following intrusion during which the borehole is plugged at the Rustler and Castile formations.

3) From 200 years to 1200 years - cement plugs are no longer active. Flow occurs between the Castile Brine Pocket and the Culebra aquifer via "silty sand" abandoned boreholes with median permeabilities of 3.16E-13 m^2.

4) 1200 years to 10000 years - median abandoned borehole permeabilities are reduced one order of magnitude (3.16E-14 m^2) due to salt creep.

Abandoned Borehole Connection Between Castile Brine Pocket and Culebra Aquifer

Consider the flow rate necessary to achieve flow from the Castile Brine Pocket to the Culebra Aquifer through an abandoned borehole as depicted in Figure 1:

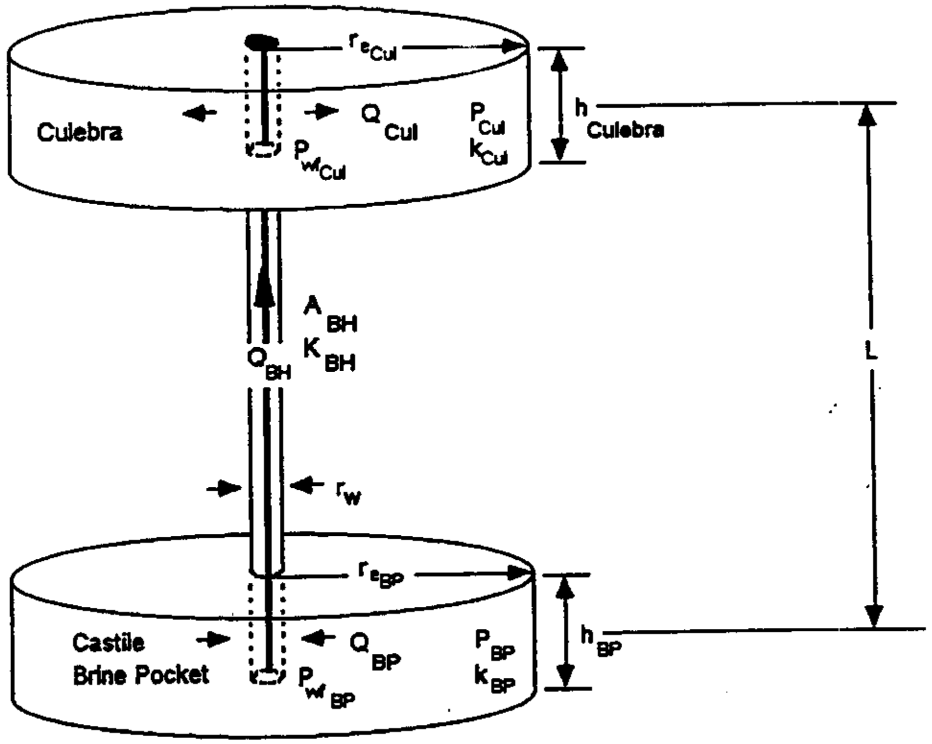


Figure 1: Representation of assumed flow path for Castile Brine Pocket to Culebra Aquifer

NOMENCLATURE

Define the following variables by:

Q = Flowrate (m^3/sec)
k = Permeability (m^2)
h = Thickness (m)
μ = Brine viscosity (Pa-sec)
ρ = Brine density (kg/m^3)
g = Acceleration due to gravity (m/sec^2)
L = Borehole length (m)
r = Radius (m)
A = Cross sectional area (m^2)
P = Pressure (Pa)
$\overline{P}$ = Average pressure between r_e and r_w (Pa)
c = Compressibility (Pa^{-1})
ϕ = Porosity (fraction)
V = Bulk volume (m^3)
ΔN = Brine volume producted between time 1 and 2 (m^3)

Define the following subscripts by:

cul = Culebra
bh = Borehole
bp = Brine pocket
e = External drainage per borehole (brine pocket area divided by number of boreholes)
w = Wellbore
wf = Abandoned wellbore flowing
atm = Atmospheric
b = Rock bulk
f = Pore volume
br = Brine
t = Total
R = Castile Brine Pocket or Culebra Aquifer
$1,2$ = Time 1, time 2

Refer to Figure 1, assuming steady-state flow is positive between the Castile Brine Pocket and the Culebra Aquifer, the following Darcy Law equations are used to obtain the flowrates out of the brine pocket (Q_{bp}), through the borehole (Q_{bh}) and into the aquifer (Q_{cul}), based upon the pressures, rock and fluid properties and brine pocket/abandoned borehole/aquifer geometries:

$$Q_{cul} = \left\{ \frac{k_{cul} h_{cul}}{\mu \left[\ln\left(\frac{r_{e_{cul}}}{r_w} \right) - 0.5 \right]} \right\} \left(P_{wf_{cul}} - P_{cul} \right) \qquad \text{[Equation 3]}$$

$$Q_{bh} = \left[\frac{k_{bh} A_{bh} \left(P_{wf_{bh}} - P_{wf_{cul}} - \rho g L \right)}{\mu L} \right] \qquad \text{[Equation 4]}$$

$$Q_{bp} = \left\{ \frac{k_{bp} h_{bp}}{\mu \left[\ln\left(\frac{r_{e_{bp}}}{r_w} \right) - 0.5 \right]} \right\} \left(P_{bp} - P_{wf_{bp}} \right) \qquad \text{[Equation 5]}$$

The flowrates through each of these systems are assumed to be equal (i.e. no fluid leaves the system), therefore:

$$Q_{bp} = Q_{bh} = Q_{cul} \qquad \text{[Equation 6]}$$

This results in four equations (Equations 3-6) and two unknowns (P_{wbp} and P_{wbp}) which can be algebraically solved for Q_{bp} as follows:

$$Q_{bp} = \frac{\left\{ \frac{k_{bp} h_{bp}}{\mu \left[\ln\left(\frac{r_{e_{bp}}}{r_w} \right) - 0.5 \right]} \right\} \left(P_{bp} - \rho g L - P_{cul} \right)}{\left[1 + \left\{ \frac{k_{bp} h_{bp}}{\mu \left[\ln\left(\frac{r_{e_{bp}}}{r_w} \right) - 0.5 \right]} \right\} \right] \left\{ \frac{\mu \left[\ln\left(\frac{r_{e_{cul}}}{r_w} \right) - 0.5 \right]}{k_{cul} h_{cul}} + \frac{\mu L}{k_{bh} A_{bh}} \right\}} \qquad \text{[Equation 7]}$$

Equation 7 is the steady-state solution for flow through the brine pocket/abandoned borehole/aquifer system. To account for bounded brine pocket/aquifer sizes, pressure drawdown can be estimated by redefining the brine pocket and aquifer pressures over a series of discrete time intervals by the following:

The pore volume compressibility (c_f) as a function of rock bulk compressibility (c_b) may be defined by:

$$c_f = \frac{c_b}{\phi} \qquad \text{[Equation 8]}$$

The total compressibility (c_t) is the sum of the brine compressibility (c_{br}) and pore volume compressibility (c_f) as follows:

$$c_t = c_{br} + c_f \qquad \text{[Equation 9]}$$

The bulk volume of the bounded brine pocket is a function of the volume of brine removed, average pressure drop, compressibility and porosity as follows:

$$V_R = A_R h = \frac{\Delta N_{1,2}}{\left(\overline{P_1} - \overline{P_2}\right) c_t \phi} \qquad \text{[Equation 10]}$$

Equation 10 can be used to solve for the average pressure at the end of a given time interval by:

$$\overline{P_2} = \overline{P_1} - \frac{\Delta N_{1,2}}{V_R c_t \phi} \qquad \text{[Equation 11]}$$

METHODOLOGY AND RESULTS

Since the size of the brine pocket is unknown, comparisons were made for various areal size and thickness as shown in the following table (consistent with interpreted results from WIPP-12 data [Larson & Freeze, 1996]):

Table 1 - Constant Brine Volumes by Varying Thickness and Areal Extent

Thickness (m)	Areal Extent 1 (m^2)	Areal Extent 2 (m^2)	Areal Extent 3 (m^2)
133.6	6.0E+07	3.0E+06	3.0E+04
66.8	12.0E+07	6.0E+06	6.0E+04
24.0	33.4E+07	16.7E+06	16.7E+04

For the Culebra aquifer, the areal extent was assumed to be 100 times the LWB for all cases (4144 km^2). All other properties were median values obtained from the 1996

CCA database. The combination of three thicknesses and three areas for the Castile Brine Pocket resulted in 9 cases for comparison. Initial brine pocket pressure was assumed to be 12.7 E+07 Pa for all cases.

Table 2 shows an example spreadsheet calculation assuming an area of 6.0 E+07 m^2 and 133.6 m brine pocket thickness.

Table 2 - Example Spreadsheet Calculation

BP area	6.00E+07	m^2
Cul area	4.14E+09	m^2
Pcul (init)	850000	Pa
U	1.80E-03	Pa-s
hCul	7.7	m
L	641.5	m
total L	708.3	m
hBP	133.6	m
Pbp (init)	1.27E+07	Pa
kBH	3.16E-13	m^2
kCUL	2.10E-14	m^2
rw	0.1556	m
Area BH	0.0760622	m^2
kBP	1.58E-12	m^2
rho	1220	kg/m^3
g	9.8	
rho*g*l aban	8.5E+6	Pa
rho*g*l open	11.2E+6	Pa
s/year	3.16E+07	
poros BP	0.008	
poros Cul	0.151	
Cr BP	1.00E-10	1/Pa
Cr Cul	1.00E-10	1/Pa
Cf BP	1.28E-08	1/Pa
Cf Cul	6.623E-10	1/Pa
Cbrine	1.00E-09	1/Pa
Ctot BP	1.36E-08	1/Pa
Ctot Cul	1.66E-09	1/Pa
Brine Pocket bulk vol =	8.0E+9	m^3
Culebra bulk vol =	31.9E+9	m^3
Open BH Dt	2.59E+05	seconds
No. open BH/Dt	2.88E+01	
re BP	822.96809	
Patm	101320	Pa
drlg rate=	0.47	bh/km^2/100years

Time years	Num BH in BP	Number of sand BH	Number of creep BH	BP press Pa	Cul Pres Pa	BP radius per ab BH m	Cul radius per well m	Cengt	Qsp open BH per well m^3/s	delta flow open m^3
200.0	56.40	0.0	0.0	12.7E+6	850.0E+3	4.3702E+13	4.37E+13	3.58E-08	0.020465974	149.6E+3
400.0	112.80	28.2	0.0	12.5E+6	850.0E+3	822.965089	4.37E+13	1.48E-08	0.017988998	131.2E+3
600.0	169.20	84.6	0.0	12.4E+6	851.3E+3	475.132342	4.37E+13	1.59E-08	0.016578228	113.9E+3
800.0	225.60	141.0	0.0	12.2E+6	855.0E+3	368.036704	4.37E+13	1.61E-08	0.013188622	96.3E+3
1,000.0	282.00	197.4	0.0	12.0E+6	860.9E+3	311.047796	4.37E+13	1.65E-08	0.010769946	78.7E+3
1,200.0	338.40	253.8	0.0	11.9E+6	868.5E+3	274.318989	4.37E+13	1.68E-08	0.008417087	61.5E+3
1,400.0	394.80	310.2	0.0	11.7E+6	877.9E+3	248.130285	4.37E+13	1.71E-08	0.006146544	44.9E+3
1,600.0	451.20	366.6	84.6	11.6E+6	889.3E+3	228.240674	475.1338	1.73E-08	0.003978129	29.1E+3
1,800.0	507.60	366.6	84.6	11.4E+6	900.2E+3	228.240674	475.1338	1.73E-08	0.001891285	13.8E+3
2,000.0	564.00	366.6	141.0	11.3E+6	911.2E+3	228.240674	368.0367	1.73E-08	0.000179823	1.3E+3
2,200.0	620.40	366.6	197.4	11.2E+6	921.7E+3	228.240674	311.0478	1.73E-08	0	000.0E+0
2,400.0	676.80	366.6	253.8	11.1E+6	931.7E+3	228.240674	274.3184	1.73E-08	0	000.0E+0
2,600.0	733.20	366.6	310.2	11.0E+6	941.2E+3	228.240674	248.1303	1.73E-08	0	000.0E+0
2,800.0	789.60	366.6	366.6	10.9E+6	950.3E+3	228.240674	228.2407	1.73E-08	0	000.0E+0
3,000.0	846.00	366.6	423.0	10.9E+6	959.0E+3	228.240674	212.4861	1.73E-08	0	000.0E+0
3,200.0	902.40	366.6	479.4	10.8E+6	967.3E+3	228.240674	199.5869	1.73E-08	0	000.0E+0
3,400.0	958.80	366.6	535.8	10.7E+6	975.2E+3	228.240674	188.7988	1.73E-08	0	000.0E+0
3,600.0	1,015.20	366.6	592.2	10.6E+6	982.8E+3	228.240674	179.5836	1.73E-08	0	000.0E+0
3,800.0	1,071.60	366.6	648.6	10.6E+6	989.7E+3	228.240674	171.589	1.73E-08	0	000.0E+0
4,000.0	1,128.00	366.6	705.0	10.5E+6	996.4E+3	228.240674	164.591	1.73E-08	0	000.0E+0
4,200.0	1,184.40	366.6	761.4	10.5E+6	1.0E+6	228.240674	158.3778	1.73E-08	0	000.0E+0
4,400.0	1,240.80	366.6	817.8	10.4E+6	1.0E+6	228.240674	152.8189	1.73E-08	0	000.0E+0
4,600.0	1,297.20	366.6	874.2	10.3E+6	1.0E+6	228.240674	147.8071	1.73E-08	0	000.0E+0
4,800.0	1,353.60	366.6	930.6	10.3E+6	1.0E+6	228.240674	143.2581	1.73E-08	0	000.0E+0
5,000.0	1,410.00	366.6	987.0	10.3E+6	1.0E+6	228.240674	139.1046	1.73E-08	0	000.0E+0
5,200.0	1,466.40	366.6	1,043.4	10.2E+6	1.0E+6	228.240674	135.293	1.73E-08	0	000.0E+0
5,400.0	1,522.80	366.6	1,099.8	10.2E+6	1.0E+6	228.240674	131.7783	1.73E-08	0	000.0E+0
5,600.0	1,579.20	366.6	1,156.2	10.1E+6	1.0E+6	228.240674	128.524	1.73E-08	0	000.0E+0
5,800.0	1,635.60	366.6	1,212.6	10.1E+6	1.0E+6	228.240674	125.4996	1.73E-08	0	000.0E+0
6,000.0	1,692.00	366.6	1,269.0	10.1E+6	1.0E+6	228.240674	122.6789	1.73E-08	0	000.0E+0
6,200.0	1,748.40	366.6	1,325.4	10.0E+6	1.0E+6	228.240674	120.0403	1.73E-08	0	000.0E+0
6,400.0	1,804.80	366.6	1,381.8	10.0E+6	1.1E+6	228.240674	117.548	1.73E-08	0	000.0E+0
6,600.0	1,861.20	366.6	1,438.2	10.0E+6	1.1E+6	228.240674	115.2288	1.73E-08	0	000.0E+0
6,800.0	1,917.60	366.6	1,494.6	9.9E+6	1.1E+6	228.240674	113.0416	1.73E-08	0	000.0E+0
7,000.0	1,974.00	366.6	1,551.0	9.9E+6	1.1E+6	228.240674	110.9672	1.73E-08	0	000.0E+0
7,200.0	2,030.40	366.6	1,607.4	9.9E+6	1.1E+6	228.240674	109.0031	1.73E-08	0	000.0E+0
7,400.0	2,086.80	366.6	1,663.8	9.9E+6	1.1E+6	228.240674	107.1306	1.73E-08	0	000.0E+0
7,600.0	2,143.20	366.6	1,720.2	9.9E+6	1.1E+6	228.240674	105.3656	1.73E-08	0	000.0E+0
7,800.0	2,199.60	366.6	1,776.6	9.8E+6	1.1E+6	228.240674	103.6826	1.73E-08	0	000.0E+0
8,000.0	2,256.00	366.6	1,833.0	9.8E+6	1.1E+6	228.240674	102.075	1.73E-08	0	000.0E+0
8,200.0	2,312.40	366.6	1,889.4	9.8E+6	1.1E+6	228.240674	100.54	1.73E-08	0	000.0E+0
8,400.0	2,368.80	366.6	1,945.8	9.8E+6	1.1E+6	228.240674	99.07215	1.73E-08	0	000.0E+0
8,600.0	2,425.20	366.6	2,002.2	9.8E+6	1.1E+6	228.240674	97.6666	1.73E-08	0	000.0E+0
8,800.0	2,481.60	366.6	2,058.6	9.8E+6	1.1E+6	228.240674	96.31061	1.73E-08	0	000.0E+0
9,000.0	2,538.00	366.6	2,115.0	9.7E+6	1.1E+6	228.240674	95.02067	1.73E-08	0	000.0E+0
9,200.0	2,594.40	366.6	2,171.4	9.7E+6	1.1E+6	228.240674	93.78444	1.73E-08	0	000.0E+0
9,400.0	2,650.80	366.6	2,227.8	9.7E+6	1.1E+6	228.240674	92.59996	1.73E-08	0	000.0E+0
9,600.0	2,707.20	366.6	2,284.2	9.7E+6	1.1E+6	228.240674	91.43946	1.73E-08	0	000.0E+0
9,800.0	2,763.60	366.6	2,340.6	9.7E+6	1.1E+6	228.240674	90.33108	1.73E-08	0	000.0E+0
10,000.0	2,820.00	366.6	2,397.0	9.7E+6	1.1E+6	228.240674	89.25207	1.73E-08	0	000.0E+0

Figure 2 is a semilog plot comparing the number of borehole penetrations for different brine pocket areal sizes based upon the DOE criterion of 0.47/100 year/km^2 drilling rate. The same number of penetrations apply to each respective areal size regardless of thickness.

Figure 2

Comparison of Drilling Penetrations to Castile Brine Pocket for Different Areas

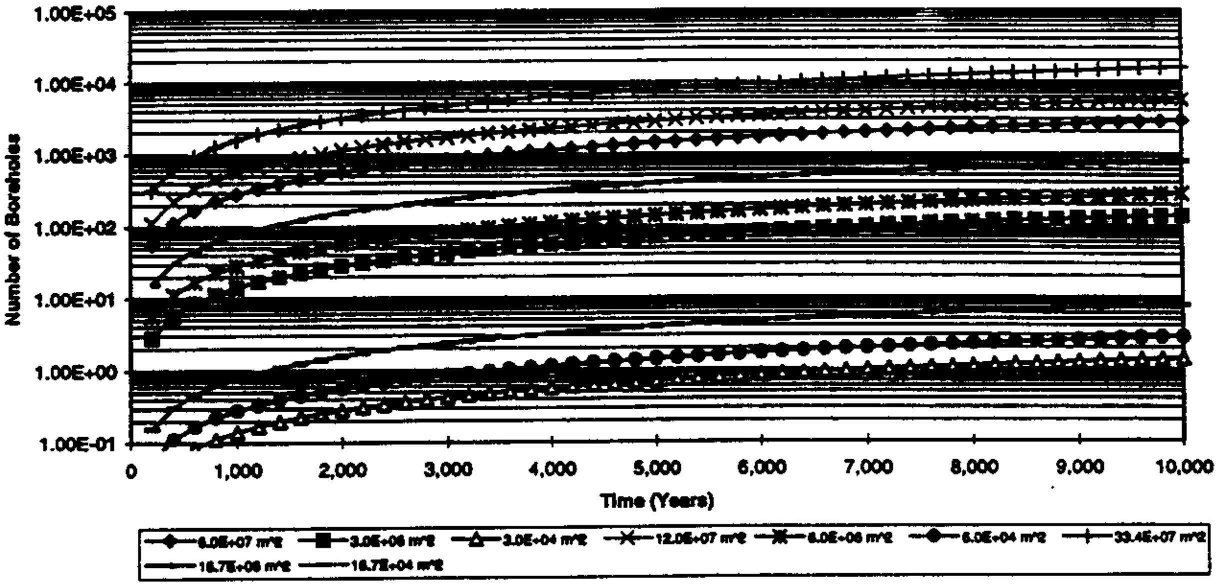
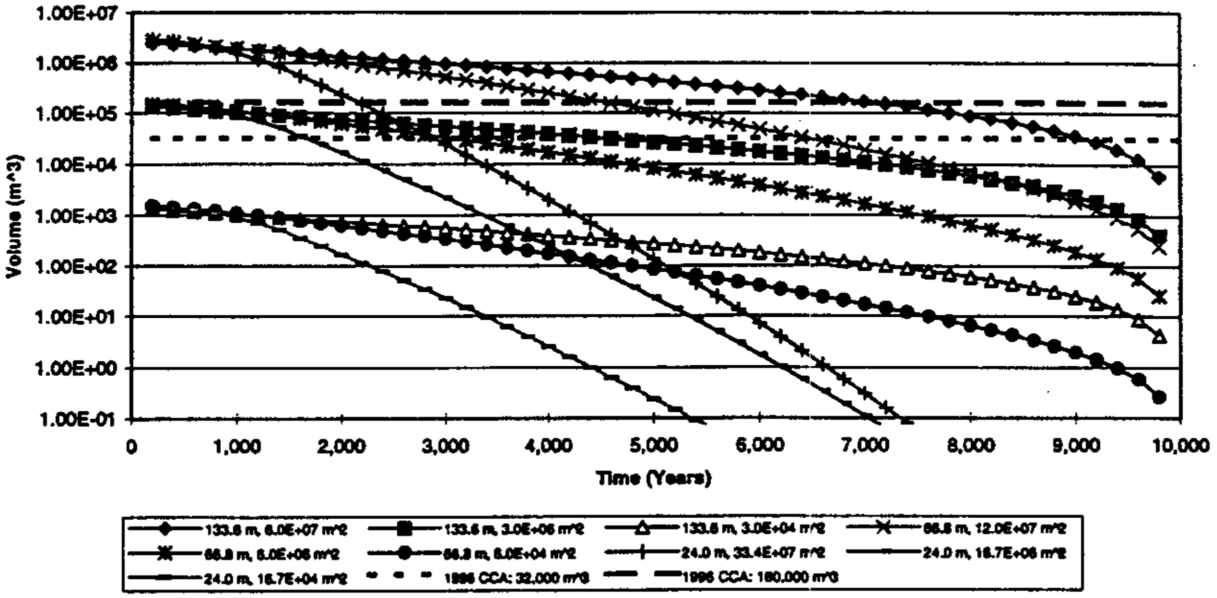


Figure 3 is a semilog plot comparing the amount of Castile brine volume which can be released. This was determined by subtracting the cumulative brine released at a given time from the total cumulative brine released at 10,000 years. The 24 m thickness cases again demonstrate faster depletion than the corresponding 133.6 m thickness cases of equivalent area. For a given thickness, the differences in remaining available flow is caused by differences in the number of depletion boreholes which is a function of the area.

Figure 3



Comparison of Remaining Castile Brine Available for Flow
(Initial Pbp = 12.7 MPa, 72 hour open flow period)

CONCLUSIONS

The 1996 CCA calculations varied the brine pocket volume from 32,000 m^3 to 160,000 m^3. From Figure 3, the only cases which show more brine available for flow for an extended period of time (~2000 to ~7000 years) are the maximum area cases. DOE does not consider the 19 km radius brine pocket to be a realistic estimate of the areal extent, rather an artifact of the unreasonably low rock compressibility ($5X10^{-12}$ pa^{-1}) used for that estimate. In addition, the DOE does not include the depressurization or volume reduction to the brine pocket that would result in numerous borehole penetrations that would statistically "miss" a WIPP panel but penetrate the brine pocket, prior to the first "E1" borehole through a panel. In the CCA calculations for E1 scenarios, the DOE assumes brine pockets of 32,000 m^3 to 160,000 m^3 pore volume at virgin (undepleted) pressures in determining potential releases to the accessible environment, which bounds the range of consequences associated with penetrating a larger but partially depleted brine pocket.

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