WSRC-TR-2003-00080
Rev. 0

Porous Medium Analysis of Tank 41 Drain Operations (U)

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This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-96SR18500 with the U. S. Department of Energy.

Executive Summary

Under the Low Curie Salt Program, interstitial liquid is being drained from saltcake in Tank 41 to remove most of the Cs-137 activity. After the liquid content in saltcake approaches the residual saturation level, the tank will be re-flooded to a level 2" above the saltcake level. Then at least 30" of saltcake will be dissolved off the top and disposed of as saltstone according to near-term plans. The program is contingent upon reducing residual liquid content, and thus residual Cs-137 content, to a sufficiently low level. High Level Waste requested assistance from the Savannah River Technology Center in analyzing drain operations from 9/8/02 through 12/9/02 to better understand the interstitial liquid level profile across the tank, and the liquid saturation profile from tank bottom to top.

A static gravity-equilibrium analysis of the well level before and after net removal of 113,000 gallons of liquid indicates the drainable water content of Tank 41 saltcake is in the range of 13-18 volume percent, with a best-estimate of 14%. Over a time scale of several days for drainage, the drainage porosity is close to 13%. For longer drain times and higher elevations above the interstitial liquid level and capillary fringe, the effective drainage porosity may be higher, possibly approaching 18%, due to additional drainage. Several non-unique combinations of assumed porosity and residual saturation can produce a drainage porosity of 14%. Therefore, the drainage data by itself are insufficient to define the residual liquid content. Additional information in the form of a total porosity estimate or a residual saturation estimate is needed to define the residual liquid content after drainage. Some example combinations of initial and residual water content that produce a drainage porosity of 14% are shown below:

Initial water content in submerged saltcake θ_{ws}	*Radiolytic gas lumped with salt - excluded from "voids"* Pseudo total porosity n'	Drainable liquid content $n'(1-S_{wr}')$	Residual liquid content $n'S_{wr}'$	Pseudo residual saturation S_{wr}'	Pseudo drainable saturation $1-S_{wr}'$
0.20	0.20	0.14	0.06	0.30	0.70
0.25	0.25	0.14	0.11	0.44	0.56
0.30	0.30	0.14	0.16	0.53	0.47
0.35	0.35	0.14	0.21	0.60	0.40
0.40	0.40	0.14	0.26	0.65	0.35

Initial water content in submerged saltcake θ_{ws}	*Radiolytic gas included in void space* Initial gas content θ_g	Total porosity n	Drainable liquid content $n(S_{ws}-S_{wr})$	Residual liquid content nS_{wr}	Initial saturation S_{ws}	Residual saturation S_{wr}	Drainable saturation $S_{ws}-S_{wr}$	Gas saturation S_g
0.20	0.105	0.31	0.14	0.06	0.66	0.20	0.46	0.34
0.25	0.105	0.36	0.14	0.11	0.70	0.31	0.39	0.30
0.30	0.105	0.41	0.14	0.16	0.74	0.40	0.35	0.26
0.35	0.105	0.46	0.14	0.21	0.77	0.46	0.31	0.23
0.40	0.105	0.51	0.14	0.26	0.79	0.51	0.28	0.21

A semi-empirical analysis of dynamic liquid levels during pumping suggests that mean tank level can be related to well level and pumping rate under pseudo-steady flow

conditions (slow transients). The correlation appears to be reasonably accurate at predicting the equilibrium liquid level after 2-3 weeks of downtime. The mean tank level is expected to be a reasonable surrogate for the peak tank level, given that the largest gradients are at the well. However, the flow model considers only the effect of leveling of the interstitial liquid level, and not continued drainage from unsaturated saltcake above the liquid level. Thus long-term recovery will be somewhat higher than predicted by the flow model. In addition, the time required for tank liquid level to reach equilibrium after transient pumping at a well can be roughly estimated from the flow model. This information can be used to estimate the time required to drain residual amounts of liquid from the tank bottom.

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Introduction

Under the Low Curie Salt Program, interstitial liquid is being drained from saltcake in Tank 41 to remove most of the Cs-137 activity. After the liquid content in saltcake approaches the residual saturation level, the tank will be re-flooded to a level 2" above the saltcake level. Then at least 30" of saltcake will be dissolved off the top and disposed of as saltstone according to near-term plans. The program is contingent upon reducing residual liquid content, and thus residual Cs-137 content (Romanowski, 2002), to a sufficiently low level. High Level Waste (HLW) requested assistance from the Savannah River Technology Center (SRTC) in analyzing drain operations from 9/8/02 through 11/11/02 to better understand the interstitial liquid level profile across the tank, and the liquid saturation profile from tank bottom to top (TTR No. HLE-TTR-2003-057, Rev. 1).

Tank 41 drawdown and well recovery data

A hole of approximately 3 ft in diameter was bored through Tank 41 saltcake by water jetting and dissolution to create a well. The well is centered approximately 6.5 ft from the tank wall. Prior to draining, the saltcake level was at approximately 350" and the liquid level at 357.17". A submersible pump was then used to draw supernate from the tank at a variable rate between 9/8/02 and 9/22/02, and then 10/11 through 11/11. The well drawdown curve, covering both phases of the overall drain operation, is shown in Figure 1. Net liquid removal volumes are compiled in Table 1.

For the purpose of performing mass balances, the average interstitial liquid level in Tank 41 is needed as opposed to the level at the well. Given sufficient time, the well level will recover to an equilibrium level equal to the average tank level during dynamic operations. Two recovery periods are sufficiently long to project equilibrium/average tank liquid level with reasonable accuracy. As indicated in Figure 1, the projected well recovery levels for these intervals are 260" and 160". The 260" equilibrium tank level was estimated from the well recovery curve plotted in semi-log form (Figure 2). Between 1 and 10 days the data exhibits a logarithmic trend (straight-line on semi-log plot). Supposing this trend continues out to 30 days based on engineering judgment, the well level is projected to reach approximately 260". Taking this as the equilibrium level after pumping ceased, the tank liquid drawdown becomes 357" - 260" = 97". The 160" level is based on inspection of Figure 1 and engineering judgment.

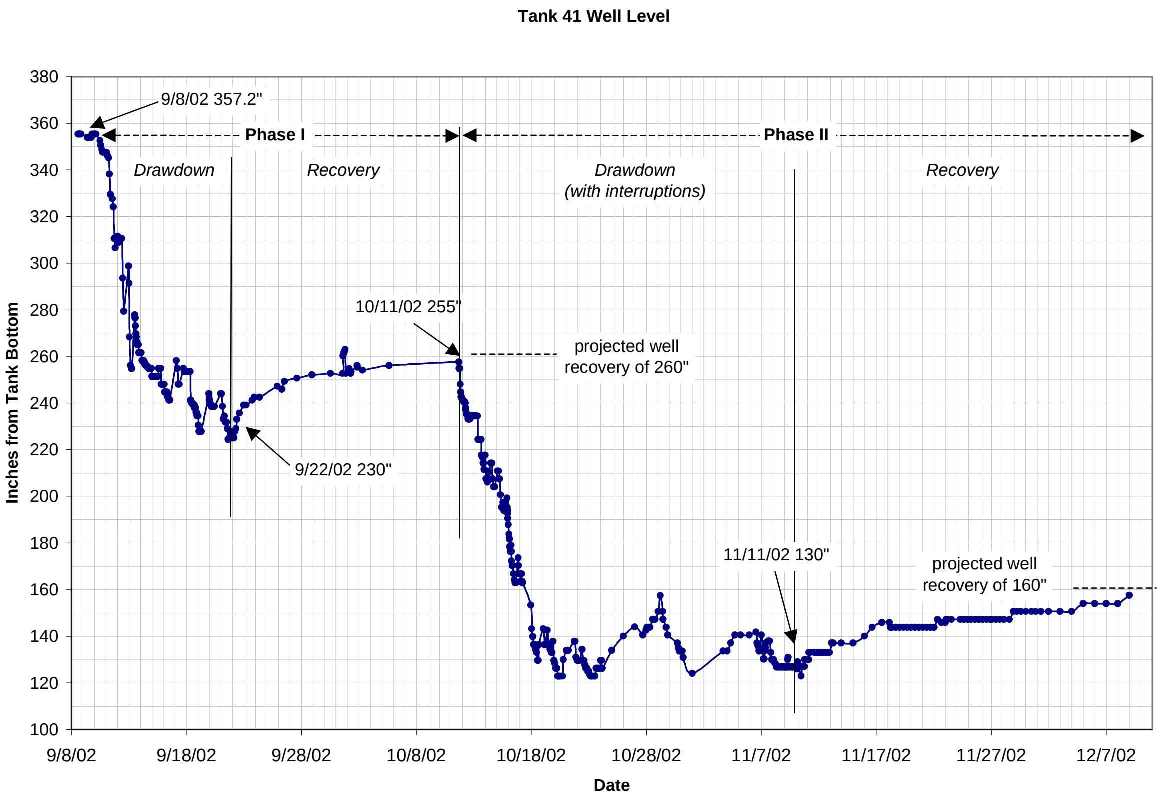

Figure 1. Well drawdown and recovery data for Tank 41 between 9/8/02 and 12/9/02.

Table 1. Net liquid removal during Tank 41 drain operations from 9/8/02 through 12/9/02.

Phase	*Date range*	*Range in average tank level*	*Liquid removed (gal)*	*Liquid added (gal)*	*Net removal (gal)*
I	9/8 - 10/11	357.2" - 260"	71,800	3,596	68,204
II	10/11 - 12/9	260" - 160"	59,400	14,630	44,770
I+II	9/8 - 12/9	357.2" - 160"	131,200	18,226	112,974

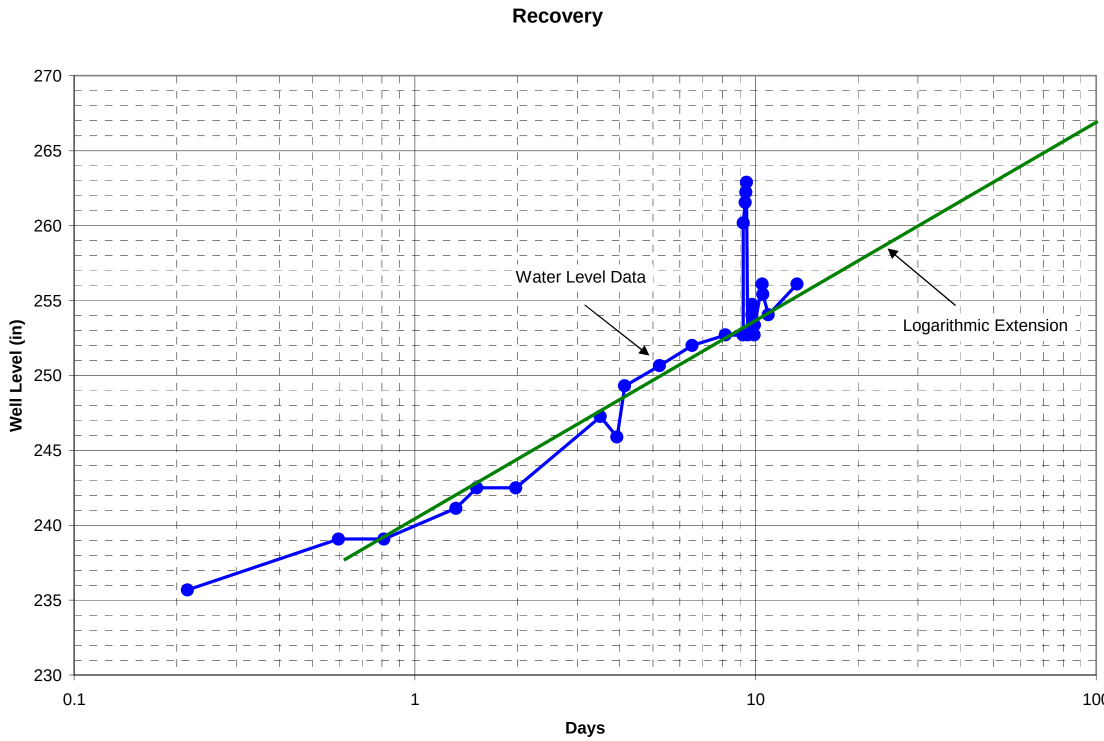

Figure 2. Well recovery curve with logarithmic forecast.

Static gravity-equilibrium analysis of pre- and post-drain tank level

Saltcake is comprised of salt crystals, and interstitial liquid and radiolytic gas. The gas content of submerged Tank 41 saltcake has been accurately estimated to be 10.5% as a fraction of total volume (Hester, 2001, p. 4). The liquid content of saltcake is less well known. Based on work by Fowler (1982) and Wiersma (1996), Hester (2002) roughly estimated total porosity at 42%, or equivalently a liquid content of 31.5% for submerged saltcake. However, the drainable liquid content was based on simulated saltcake that contains no appreciable gas. Therefore, the total porosity should exclude the gas contribution and be closer to 31.5%. Samples taken from Tank 41 have averaged about 42% porosity, and ranged from 30% to 49% (Pike et al., 2001; Pike, 2002). Hence the porosity of Tank 41 saltcake is uncertain. The liquid retention characteristics of saltcake under unsaturated conditions are equally uncertain.

Given uncertainties in total porosity and liquid retention characteristics of saltcake, many combinations of values could be assumed for these parameters. However, knowing pre- and post-drain tank levels and the volume of pumped liquid, a static mass balance can be used to constrain the combinations of total porosity and liquid retention values that saltcake could possibly take on. The method for doing so, and results for Tank 41 based on drain operations from 9/8/02 through 12/9/02, are presented below.

Method

The volume of interstitial supernate per unit thickness equals tank cross-sectional area times total porosity times liquid saturation:

$$\frac{\Delta V}{\Delta z} = A(z) \cdot n \cdot S_w(z) \tag{1}$$

Total porosity is the volume of saltcake voids divided by total volume ($n = V_{void} / V_{total}$). Saturation is the liquid volume divided by void volume ($S_w = V_{liquid} / V_{void}$). The product of total porosity and saturation is then the volume of liquid divided by total volume ($\theta_w = n \cdot S_w = V_{void} / V_{total} \cdot V_{liquid} / V_{void} = V_{liquid} / V_{total}$), commonly termed "water content" in hydrology.

Note that both cross-sectional area and liquid saturation are assumed to vary with elevation. The liquid inventory of the entire tank is the summation of equation (1) from tank bottom to top:

$$V = \sum_{bot}^{top} A(z) \cdot n \cdot S_w(z) \cdot \Delta z \tag{2}$$

For a tank drain operation, the change in inventory associated with the pre- and post-operation equilibrium or average tank liquid levels should equal the volume pumped.

$$V_{pumped} = \Delta V \tag{3}$$

The cross-sectional area of Tank 41 can be approximated as the area between the outer wall and center column ignoring cooling tubes and other hardware (Figure 3). Below the conical "funnel" portion of the center column, this area is about 3510 gal/in (Table 2). The total porosity and liquid retention properties of saltcake are not known with certainty. Lacking information to the contrary, total porosity averaged over a cross-section is assumed to be roughly constant with elevation. Under static conditions, saltcake liquid saturation as a function of elevation can be estimated directly from an appropriate liquid retention curve.

Liquid flow, whether under full or partial saturation conditions, is driven by hydraulic head variations. Hydraulic head is defined by

$$h = \frac{p}{\rho g} + z = \psi + z \tag{4}$$

where p is gage pressure, ρ is liquid density, g is gravitational acceleration, z is elevation, and ψ is pressure head. Under static conditions, i.e. after any flow transients have subsided, hydraulic head must be constant, and equal to the interstitial liquid level (the liquid level that would be measured in a well):

$$h = \text{constant} = z_{WL} \tag{5}$$

The latter is true because at the elevation of the liquid level in the well, the gage pressure is zero and the elevation is $z = z_{WL}$, thus $h = p/\rho g + z = 0 + z_{WL}$. While hydraulic head is constant under static conditions, the pressure head varies linearly with elevation as

$$\psi(z) = h - z = z_{WL} - z \tag{6}$$

Knowing the pressure head variation in the tank, the saturation profile can be determined from the liquid retention curve, a physical property of the porous medium:

$$S_w = fcn(-\psi) \tag{7}$$

The quantity $-\psi$ is sometimes referred to as "capillary suction head" and is positive-valued for saturations less than 100% in typical situations. Other terms used for the relationship indicated by equation (7) are "water retention curve", "capillary pressure curve", and "soil curve". Figure 4 illustrates some of the attributes and terminology associated with water retention curves. A very commonly used functional form for the liquid retention curve is (van Genuchten, 1980)

$$\frac{S_w - S_{wr}}{1 - S_{wr}} = \left[1 + \left(-\alpha\psi\right)^{\beta}\right]^{-(1-1/\beta)} \tag{8}$$

where S_{wr} (residual saturation), α and β are medium-specific empirical constants determined from laboratory measurements of saturation and capillary suction head. Generic parameters for six soils were chosen as potential surrogates for saltcake (Table 3). The parameter settings are from Schaap and Leij (1998). The corresponding water retention curves for Sand, Loamy Sand, Sandy Loam, Loam, Silt Loam and Clay are shown in Figure 5.

Equation (8) implicitly assumes that liquid saturation is 100% ($S_w = 1$) at (and below) the water table ($\psi = 0$). This is the normal situation for a porous media. Tank 41 saltcake is an exception because of radiolytic gas. Rather than voids being 100% liquid filled in submerged saltcake, gas bubbles occupy a significant fraction of total porosity. As stated previously, the gas content in Tank 41 saltcake is 10.5% on a bulk basis. If the total porosity were 42% following Hester (2002), the gas and liquid saturations would be 25% and 75% respectively, for example. Thus a modified version of equation (8) is required to deal with partial liquid saturation of submerged saltcake.

A simple and straight-forward modification to equation (8) is

$$\frac{S_w - S_{wr}}{S_{ws} - S_{wr}} = \frac{S_w / S_{ws} - S_{wr} / S_{ws}}{1 - S_{wr} / S_{ws}} = \frac{S_w' - S_{wr}'}{1 - S_{wr}'} = \left[1 + (-\alpha\psi)^{\beta}\right]^{-(1-1/\beta)} \tag{9}$$

where S_{ws} is the liquid saturation for submerged saltcake. This modification amounts to lumping radiolytic gas with salt crystals as "solids" and redefining "voids" to be only that volume occupied by liquid in submerged saltcake. Then a new "total" porosity can be defined as $n' = V_{ws} / V_{total}$ where V_{ws} is liquid volume for submerged saltcake, and liquid saturation can be re-interpreted as liquid volume divided by liquid volume under submerged conditions, i.e. $S_w' = V_w / V_{ws}$. In mass balance equation (2) and elsewhere, the product nS_w can be replaced with $n'S_w'$ ($nS_w = n'S_w'$). In Table 3 and Figure 5, values for the liquid saturation would be used for the new pseudo-liquid saturation S_w' for Tank 41 saltcake.

Another issue is that the density and surface tension of Tank 41 supernate differ from water. Therefore supernate can be expected to exhibit a different liquid retention curve than water in the same porous medium. The differences that might be observed can be qualitatively estimated by considering capillary rise in a tube (Figure 6). The capillary rise, h, is given by

$$h = \frac{2\sigma}{\rho g r} \tag{10}$$

where σ is surface tension, ρ is density, g is gravitational acceleration, and r is radius. For Tank 41 supernate compared to water

$$\frac{\rho_{Tk41}}{\rho_w} \approx 1.5 \qquad \frac{\sigma_{Tk41}}{\sigma_w} \approx 1.3 \tag{11}$$

(Sebastian Aleman, personal communication). Because these ratios are similar, the capillary rise for Tank 41 supernate would be similar to water. This suggests the curves shown in Figure 5 are reasonable candidates for supernate retention.

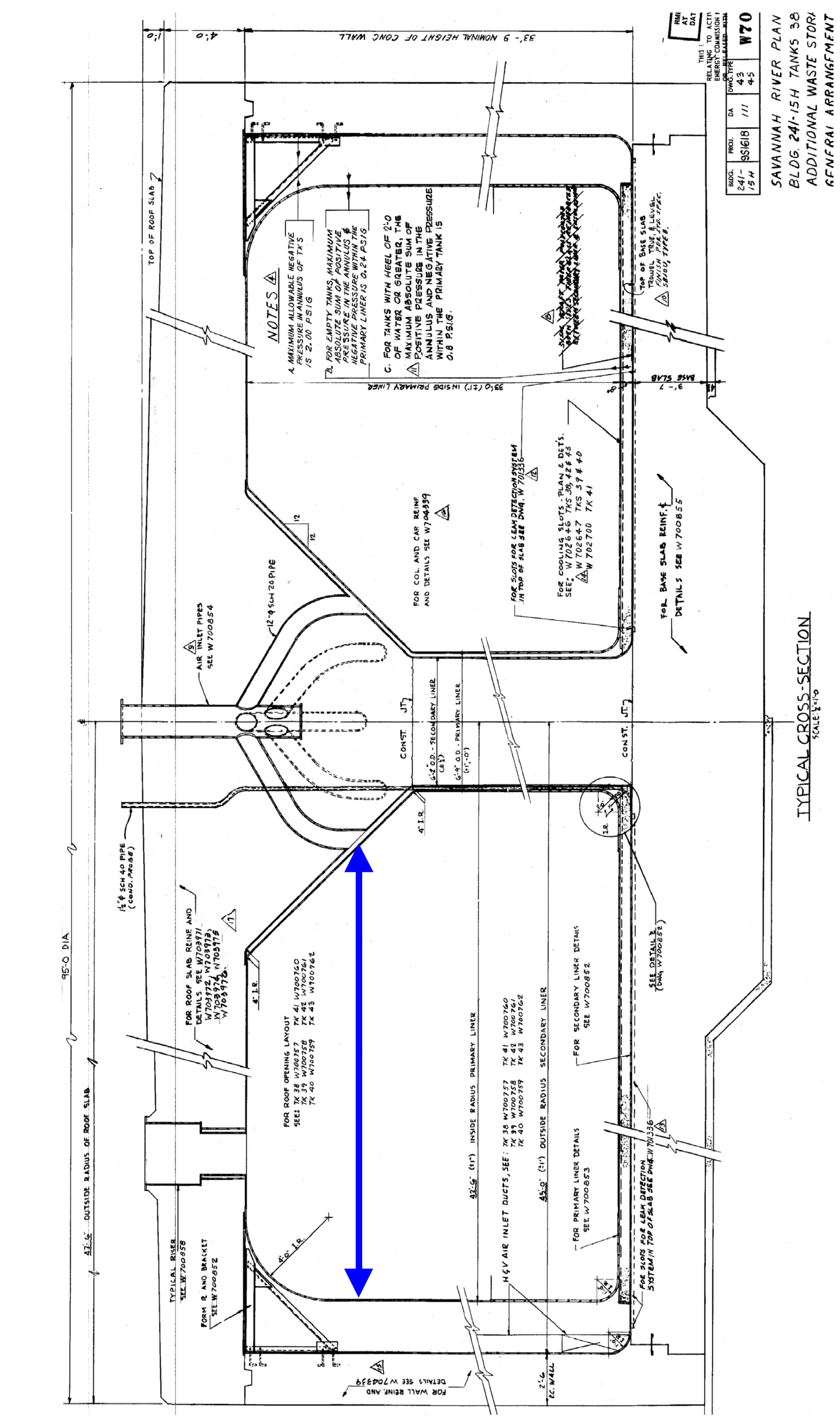

Figure 3 Cross-sectional area computation for Tank 41.

Table 2. Cross-sectional area of Tank 41 at various elevations.

Depth ft	*Elevation* ft	*Outer radius* ft	*Inner radius* ft	*Xsec area* ft^2	*Xsec area* gal/ft	*Xsec area* gal/in	*Elevation* in
0	34	42.5	11.7	5244	39231	3269	408
1	33	42.5	10.7	5315	39758	3313	396
2	32	42.5	9.7	5379	40237	3353	384
3	31	42.5	8.7	5437	40669	3389	372
4	30	42.5	7.7	5488	41055	3421	360
5	29	42.5	6.7	5533	41393	3449	348
6	28	42.5	5.7	5572	41685	3474	336
7	27	42.5	4.7	5605	41929	3494	324
8	26	42.5	3.7	5631	42126	3511	312
9	25	42.5	3.4	5638	42177	3515	300
10	24	42.5	3.4	5638	42177	3515	288
11	23	42.5	3.4	5638	42177	3515	276
12	22	42.5	3.4	5638	42177	3515	264
13	21	42.5	3.4	5638	42177	3515	252
14	20	42.5	3.4	5638	42177	3515	240
15	19	42.5	3.4	5638	42177	3515	228
16	18	42.5	3.4	5638	42177	3515	216
17	17	42.5	3.4	5638	42177	3515	204
18	16	42.5	3.4	5638	42177	3515	192
19	15	42.5	3.4	5638	42177	3515	180
20	14	42.5	3.4	5638	42177	3515	168
21	13	42.5	3.4	5638	42177	3515	156
22	12	42.5	3.4	5638	42177	3515	144
23	11	42.5	3.4	5638	42177	3515	132
24	10	42.5	3.4	5638	42177	3515	120
25	9	42.5	3.4	5638	42177	3515	108
26	8	42.5	3.4	5638	42177	3515	96
27	7	42.5	3.4	5638	42177	3515	84
28	6	42.5	3.4	5638	42177	3515	72
29	5	42.5	3.4	5638	42177	3515	60
30	4	42.5	3.4	5638	42177	3515	48
31	3	42.5	3.4	5638	42177	3515	36
32	2	42.5	3.4	5638	42177	3515	24
33	1	42.5	3.4	5638	42177	3515	12
34	0	42.5	3.4	5638	42177	3515	0

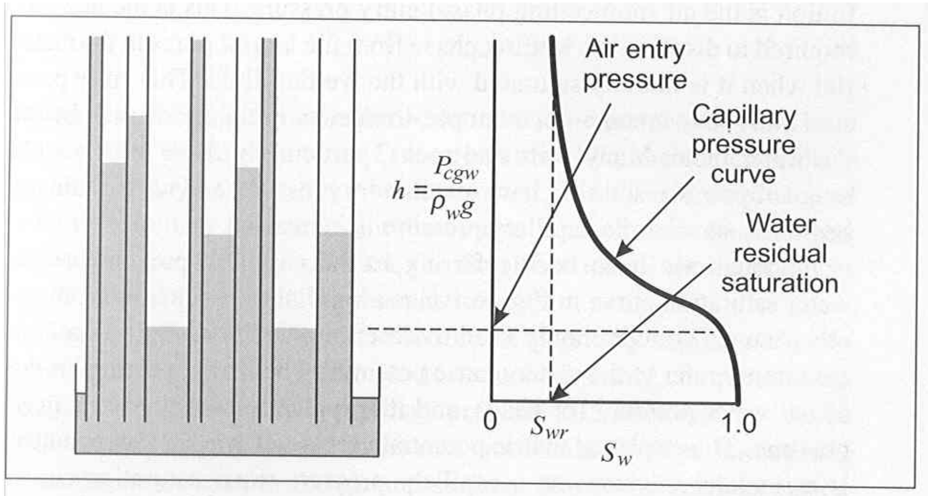

Figure 4 Water retention curve corresponding to varying capillary rise with varying pore sizes in a porous medium; reproduced from Looney and Falta (2000, Figure 1-6).

Table 3 van Genuchten (1980) parameters for various soils as defined by Schaap and Leij (1998).

van Genuchten (1980) parameter	*Sand*	*Loamy sand*	*Sandy Loam*	*Loam*	*Silt Loam*	*Clay*
S_{wr}	0.141	0.126	0.101	0.153	0.148	0.214
α, cm^{-1}	0.0355	0.0347	0.0269	0.0112	0.0050	0.0151
β	3.16	1.74	1.45	1.48	1.66	1.26

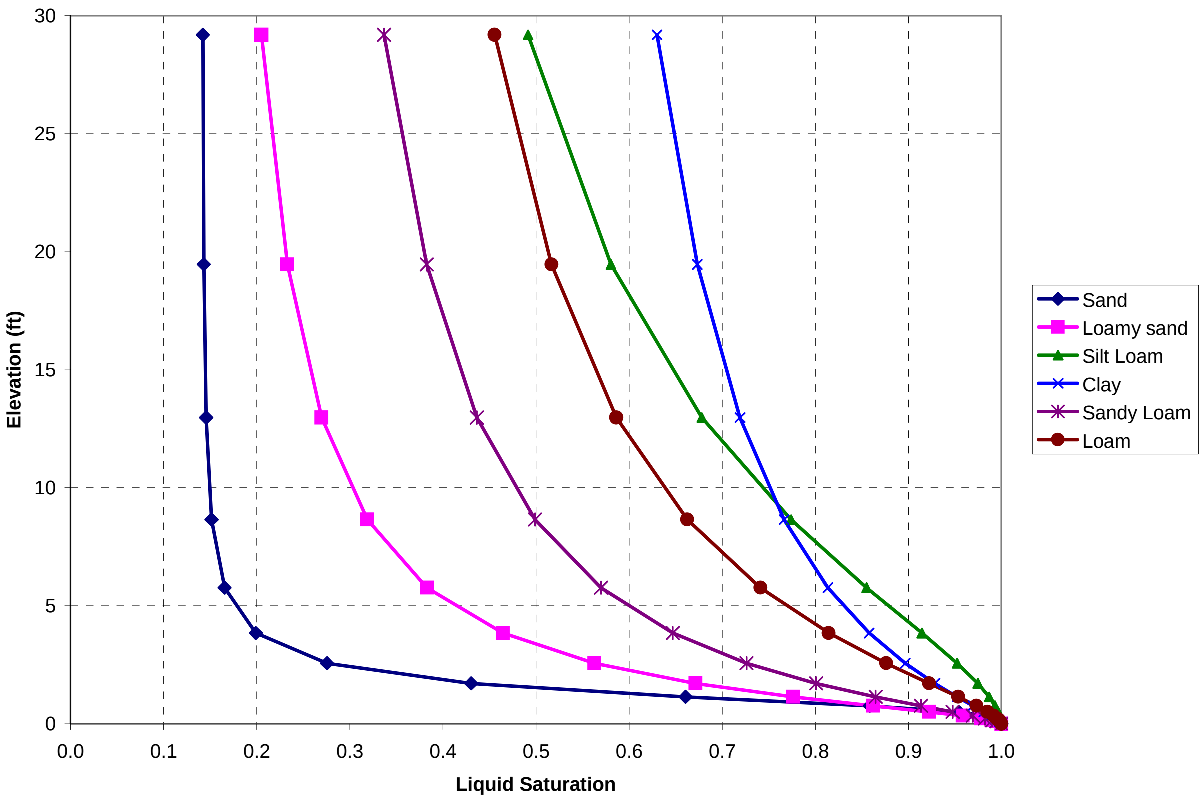

Figure 5 Water retention curves for various soils as defined by Schaap and Leij (1998).

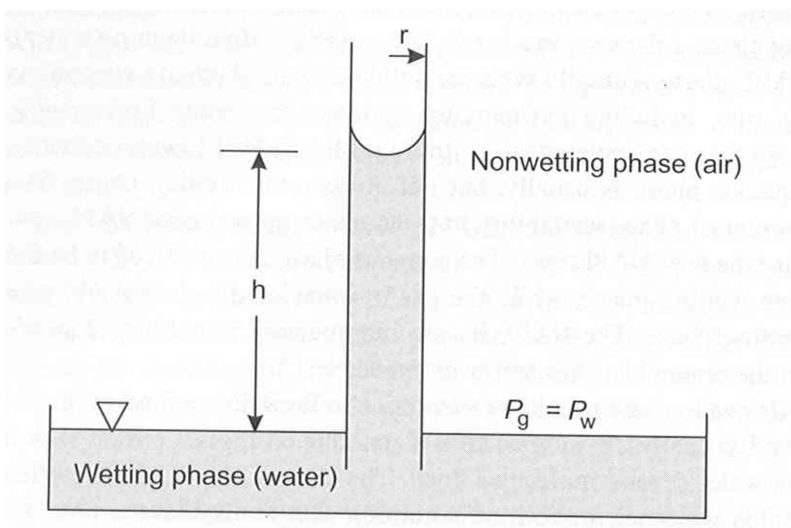

Figure 6. Capillary rise in a small diameter tube; reproduced from Looney and Falta (2000, Fig. 1-5).

Results of parametric study

Combinations of total porosity and liquid retention settings that are consistent with the saltcake dewatering operation in Tank 41 can be identified through a parametric study. In this section, the term "pseudo total porosity" refers to the fraction of total volume occupied by liquid in submerged saltcake, i.e. n', as opposed to the true porosity n. In other words, "pseudo total porosity" refers to the initial liquid content in Tank 41 saltcake. Likewise, "pseudo saturation" is the volume of liquid divided by the volume of liquid in submerged saltcake, i.e. S_{wr}'. These definitions are used to deal with the presence of radiolytic gas as discussed above.

Consistent combinations are those for which the computed inventory change matches the actual net liquid removal, i.e. satisfy equations (1) through (3). An example inventory change (mass balance) calculation for 10% initial water content ($n' = 0.1$), a "Sand" water retention curve, a 350" saltcake level, and a liquid level change from 357.2" to 260" is shown in Table 4. For this case the modeled inventory change is 34% lower than the actual volume of liquid removed. Assuming the gas content is 10.5%, the true void fraction in this example becomes 20.5%.

Table 5 shows the results for the reported saltcake level of 350", pseudo total porosity between 10 and 40%, and liquid retention characteristics ranging from "Sand" to "Clay" (Figure 5). Combinations of porosity and liquid retention curve that produce agreement between the modeled inventory change and net volume pumped are highlighted. Note that the optimal values differ between the Phases I and II of drain operations. A potential explanation is that saltcake properties differ between the upper and middle portions of Tank 41.

Alternatively, the drawdown data plotted in Figure 1 suggest the average saltcake level may be closer to 345", where the curve abruptly declines. This is inferred to be a result of the liquid level falling below the saltcake level. Table 6 shows results analogous to Table 3, but with the saltcake level set to 345". Also, the resolution of the porosity variations has been increased. The optimal parameter settings show closer overlap between the two drainage phases, suggesting more uniformity in the saltcake than implied by Table 5. Figure 7 shows three of the optimal parameter settings from Table 6. Note that the difference (area) between the pre- and post-drain curves, representing the reduction in liquid inventory, is the same. However, the residual liquid content varies significantly between cases.

The parameter values in Tables 5 and 6 are values of pseudo total porosity and residual liquid saturation, n' and S_{wr}'. Knowing the gas content of submerged saltcake $\theta_g = V_{gas}/V_{total}$, these can be converted into true porosity (void fraction) n and saturation $S_{wr}{}'$ as follows. True porosity is the sum of the water and gas contents for submerged saltcake:

$$n = \frac{V_{void}}{V_{total}} = \frac{V_{ws}}{V_{total}} + \frac{V_{gas}}{V_{total}} = \theta_{ws} + \theta_g = n' + \theta_g \tag{12}$$

Noting that water content can be expressed as

$$n'S_w{}' = \frac{V_{ws}}{V_{total}} \frac{V_{liquid}}{V_{ws}} = \theta_w = \frac{V_{void}}{V_{total}} \frac{V_{liquid}}{V_{void}} = nS_w \tag{13}$$

true liquid saturation can be then be computed from

$$S_w = \frac{n'}{n} S_w{}' \tag{14}$$

As an example from Table 6, 30% pseudo total porosity and 46% pseudo residual saturation correspond to a true porosity of

$$n = n' + \theta_g = 0.3 + 0.105 = 0.405 = 40\% \tag{15}$$

and a true liquid saturation of

$$S_{wr} = \frac{n'}{n} S_{wr}{}' = \frac{0.3}{0.405} 0.46 = 0.34 = 34\% \tag{16}$$

for a gas content of 10.5%. Both sets of numbers correspond to the residual water content of nearly 14% ($0.3 \times 0.46 = 0.405 \times 0.34 = 0.138$) for this example.

Simplified analysis of Phase II drainage

For the second phase of drainage operations (Figure 1), both the pre- and post-liquid levels have a capillary fringe and the cross-sectional area is constant. Under these conditions, the mass balance can essentially be simplified to

$$\Delta V = A \cdot n' \cdot \left(1 - S_{wr}{}'\right) \cdot \left(z_{initial} - z_{final}\right) \tag{17}$$

Defining a drainage porosity (drainable water content) as

$$\theta_d = n' \cdot \left(1 - S_{wr}{}'\right) = n - \theta_g - \theta_{wr} \tag{18}$$

produces

$$\Delta V = A \cdot \theta_d \cdot (z_{initial} - z_{final}) \tag{19}$$

or conversely

$$\theta_d = \frac{\Delta V}{A \cdot (z_{initial} - z_{final})} \tag{20}$$

Of interest to the Low Curie Salt Program is residual water content

$$\theta_r = n' \cdot S_{wr}' = n \cdot S_{wr} \tag{21}$$

Note that the sum of drainage and residual water content is pseudo total porosity:

$$n' = \theta_r + \theta_d \tag{22}$$

or equivalently true porosity is

$$n = \theta_g + \theta_r + \theta_d \tag{23}$$

As shown in Table 7, drainage porosity is estimated to be approximately 13% for the second phase of Tank 41 operations. Because Phase II affected the middle portion of the tank, this estimates applies to that region of the tank.

Also shown in Table 7 are the residual water contents corresponding to a range of pseudo total porosity values. Knowledge of the porosity of saltcake, expressed as n or n', would be needed to determine which residual liquid content value is appropriate. If θ_d and n' are known then

$$S_{wr}' = 1 - \frac{\theta_d}{n'} \tag{24}$$

and residual liquid content can be directly computed as $n' \cdot S_{wr}'$. Alternatively, if θ_d and S_{wr}' are known then

$$n' = \frac{\theta_d}{(1 - S_{wr}')} \tag{25}$$

and residual liquid content can again be directly computed as $n' \cdot S_{wr}'$.

Drainage porosity can also be estimated directly from Tables 5 and 6 for both Phase I and II operations. Shown in Table 8 are optimal combinations of porosity and residual saturation values from Tables 5 and 6. In some cases, interpolated values are used. For

Phase II and the middle portion of the tank (260" to 160"), the drainage porosity averages 17.5%. This result is somewhat larger than the 13% estimated from the simplified analysis above. This is probably because the calculation in Table 8 assumes the dewatered saltcake has reached residual saturation. Most likely the saltcake had not completely drained when the level was at 160" and/or residual conditions had not been reached at the top of the saltcake when the level was at 260". Either situation would bias the simplified analysis towards a lower estimate, e.g. 13% versus 17.5%. Hence, 13% would likely be a lower bound on drainage porosity, while 18% would likely be an optimistic or upper bound. A sensitivity analysis involving Table 7 suggests a best-estimate slightly higher than 13%. For example, if the well level is assumed to eventually recovery to 168" in Phase II due to slow additional drainage, the drainage porosity estimate becomes 14%.

The drainage porosity estimates for Phase I and the upper portion of the tank vary strongly with assumed saltcake level (22% for 350" saltcake versus 16% for 345" saltcake level). The uncertainty in these estimates precludes any conclusion on whether the saltcake physical composition varies between the upper and middle portions of the tank. If the saltcake is believed to be relatively uniform between the upper and middle portions of the tank, then the Phase II estimates are preferred because they are more certain.

Table 9 shows various non-unique combinations of initial and residual water content that produce a drainage porosity of 14%. Additional information is needed to narrow the possibilities. As stated previously, data from Fowler (1982), Wiersma (1996), Pike et al., (2001) and Pike (2002) suggest a total porosity of 42% and an initial liquid content of 31.5%. If this estimate is accepted, then the highlighted rows in Table 9 define the characteristics of Tank 41 saltcake. Note that the residual liquid content is 16%.

Table 4 Mass balance results for 10% initial water content, "Sand" water retention, and a 350" saltcake level.

Summary

case 1	
357.17	z (in)
147109	Tank inventory (gal)
260	z (in)
102057	Tank inventory (gal)
45052	Inventory change (gal)
68204	Target (gal)
-23152	Difference (gal)
-34%	Difference (%)

Detail for 357" level

Depth ft	Elevation ft	Outer radius ft	Inner radius ft	Xsec area ft^2	Xsec area gal/ft	Xsec area gal/in	Porosity	Water saturation	Water content	Water volume per unit z gal/ft	Water volume per increment gal	Cumulative volume gal	Elevation in	Water volume per unit z gal/in	x for plotting
0	34.00	42.5	11.70	5244	39231	3269	1	0.000	0.000	0	0	147109	408	0	0
0.08	33.92	42.5	11.62	5251	39277	3273	1	0.000	0.000	0	0	147109	407	0	20000
0.17	33.83	42.5	11.53	5257	39322	3277	1	0.000	0.000	0	0	147109	406	0	
⋮															
4.00	30.00	42.5	7.70	5488	41055	3421	1	0.000	0.000	0	0	147109	360	0	
4.08	29.92	42.5	7.62	5492	41085	3424	1	0.000	0.000	0	0	147109	359	0	
4.17	29.83	42.5	7.53	5496	41115	3426	1	0.000	0.000	0	1714	147109	358	0	
4.25	29.75	42.5	7.45	5500	41144	3429	1	1.000	1.000	41144	3430	145395	357	3429	
4.33	29.67	42.5	7.37	5504	41173	3431	1	1.000	1.000	41173	3432	141965	356	3431	
4.42	29.58	42.5	7.28	5508	41202	3433	1	1.000	1.000	41202	3435	138532	355	3433	
⋮															
4.58	29.42	42.5	7.12	5515	41258	3438	1	1.000	1.000	41258	3439	131661	353	3438	
4.67	29.33	42.5	7.03	5519	41286	3440	1	1.000	1.000	41286	3442	128221	352	3440	
4.75	29.25	42.5	6.95	5523	41313	3443	1	1.000	1.000	41313	1894	124780	351	3443	
4.83	29.17	42.5	6.87	5526	41340	3445	0.1	1.000	0.100	4134	345	122886	350	345	
4.92	29.08	42.5	6.78	5530	41367	3447	0.1	1.000	0.100	4137	345	122542	349	345	
5.00	29.00	42.5	6.70	5533	41393	3449	0.1	1.000	0.100	4139	345	122197	348	345	
⋮															
33.83	0.17	42.5	3.40	5638	42177	3515	0.1	1.000	0.100	4218	351	703	2	351	
33.92	0.08	42.5	3.40	5638	42177	3515	0.1	1.000	0.100	4218	351	351	1	351	
34.00	0.00	42.5	3.40	5638	42177	3515	0.1	1.000	0.100	4218	0	0	0	351	

Detail for 260" level

Depth ft	Elevation ft	Outer radius ft	Inner radius ft	Xsec area ft^2	Xsec area gal/ft	Xsec area gal/in	Porosity	Water saturation	Water content	Water volume per unit z gal/ft	Water volume per increment gal	Cumulative volume gal	Elevation in	Water volume per unit z gal/in	x for plotting
0	34.00	42.5	11.70	5244	39231	3269	1	0.000	0.000	0	0	102057	408	0	0
0.08	33.92	42.5	11.62	5251	39277	3273	1	0.000	0.000	0	0	102057	407	0	20000
0.17	33.83	42.5	11.53	5257	39322	3277	1	0.000	0.000	0	0	102057	406	0	
⋮															
4.58	29.42	42.5	7.12	5515	41258	3438	1	0.000	0.000	0	0	102057	353	0	
4.67	29.33	42.5	7.03	5519	41286	3440	1	0.000	0.000	0	0	102057	352	0	
4.75	29.25	42.5	6.95	5523	41313	3443	1	0.000	0.000	0	27	102057	351	0	
4.83	29.17	42.5	6.87	5526	41340	3445	0.1	0.155	0.016	641	54	102030	350	53	
4.92	29.08	42.5	6.78	5530	41367	3447	0.1	0.155	0.016	643	54	101977	349	54	
5.00	29.00	42.5	6.70	5533	41393	3449	0.1	0.156	0.016	645	54	101923	348	54	
⋮															
11.92	22.08	42.5	3.40	5638	42177	3515	0.1	0.974	0.097	4110	345	93128	265	342	
12.00	22.00	42.5	3.40	5638	42177	3515	0.1	0.987	0.099	4163	348	92784	264	347	
12.08	21.92	42.5	3.40	5638	42177	3515	0.1	0.995	0.099	4196	350	92435	263	350	
12.17	21.83	42.5	3.40	5638	42177	3515	0.1	0.999	0.100	4211	351	92085	262	351	
12.25	21.75	42.5	3.40	5638	42177	3515	0.1	1.000	0.100	4217	351	91734	261	351	
12.33	21.67	42.5	3.40	5638	42177	3515	0.1	1.000	0.100	4218	351	91383	260	351	
⋮															
33.83	0.17	42.5	3.40	5638	42177	3515	0.1	1.000	0.100	4218	351	703	2	351	
33.92	0.08	42.5	3.40	5638	42177	3515	0.1	1.000	0.100	4218	351	351	1	351	
34.00	0.00	42.5	3.40	5638	42177	3515	0.1	1.000	0.100	4218	0	0	0	351	

Table 5 Results of total porosity/water retention parameter study for 350" saltcake level; table shows the percentage deviation between the modeled liquid inventory change and the actual net volume of liquid removed from Tank 41.

saltcake = 350"

initial level = 357.2"
final level = 260"

Soil curve	Total porosity 0.1	0.2	0.3	0.4	Residual saturation
Sand	-34%	-3%	28%	58%	14%
Loamy sand	-43%	-22%	0%	21%	21%
Sandy Loam	-50%	-36%	-22%	-7%	34%
Loam	-57%	-49%	-41%	-33%	46%
Silt Loam	-61%	-57%	-53%	-49%	49%
Clay	-59%	-53%	-47%	-41%	63%

initial level = 260"
final level = 160"

Soil curve	Total porosity 0.1	0.2	0.3	0.4	Residual saturation
Sand	-34%	33%	99%	165%	14%
Loamy sand	-45%	10%	64%	119%	21%
Sandy Loam	-59%	-19%	22%	63%	34%
Loam	-72%	-44%	-16%	12%	46%
Silt Loam	-80%	-60%	-41%	-21%	49%
Clay	-82%	-64%	-46%	-29%	63%

Table 6 Results of total porosity/water retention parameter study for a 345" saltcake level; table shows the percentage deviation between the modeled liquid inventory change and the actual net volume of liquid removed from Tank 41.

saltcake = 345"

initial level = 357.2"
final level = 260"

Soil curve	*Total porosity* 0.15	0.20	0.25	0.30	0.35	0.40	*Residual saturation*
Sand	4%	18%	32%	47%	61%	75%	14%
Loamy sand	-10%	0%	10%	20%	30%	40%	21%
Sandy Loam	-20%	-13%	-6%	0%	7%	13%	34%
Loam	-29%	-25%	-22%	-18%	-15%	-11%	46%
Silt Loam	-34%	-32%	-31%	-29%	-27%	-25%	49%
Clay	-31%	-29%	-26%	-23%	-20%	-18%	63%

initial level = 260"
final level = 160"

Soil curve	*Total porosity* 0.15	0.20	0.25	0.30	0.35	0.40	*Residual saturation*
Sand	0%	34%	67%	101%	134%	168%	14%
Loamy sand	-16%	11%	39%	67%	95%	123%	21%
Sandy Loam	-37%	-16%	6%	27%	48%	69%	34%
Loam	-55%	-40%	-25%	-10%	5%	20%	46%
Silt Loam	-67%	-56%	-44%	-33%	-22%	-11%	49%
Clay	-71%	-61%	-52%	-42%	-32%	-22%	63%

Table 7 Drainage porosity estimate based in Phase II of Tank 41 drain operations.

44770	ΔQ (gal)
260	z before (in)
160	z after (in)
100	Δz (in)
3510	A (gal/in)
12.8%	$\theta(1-S_r)$

drainable liquid fraction of total volume $\theta(1-S_r)$	void fraction/ total porosity θ	drainable saturation $1-S_r$	residual saturation S_r	residual liquid fraction of total volume θS_r
0.128	0.16	0.80	0.20	0.032
0.128	0.18	0.71	0.29	0.052
0.128	0.20	0.64	0.36	0.072
0.128	0.22	0.58	0.42	0.092
0.128	0.24	0.53	0.47	0.112
0.128	0.26	0.49	0.51	0.132
0.128	0.28	0.46	0.54	0.152
0.128	0.30	0.43	0.57	0.172
0.128	0.32	0.40	0.60	0.192
0.128	0.34	0.38	0.62	0.212
0.128	0.36	0.35	0.65	0.232
0.128	0.38	0.34	0.66	0.252
0.128	0.40	0.32	0.68	0.272
0.128	0.42	0.30	0.70	0.292
0.128	0.44	0.29	0.71	0.312
0.128	0.46	0.28	0.72	0.332

Table 8 Drainage porosity estimates based on optimal results from parametric study summarized by Tables 5 and 6.

Level change from 357.2" to 260"

Saltcake level (in)	void fraction/ total porosity θ	residual saturation S_r	drainable saturation $1-S_r$	drainable liquid fraction of total volume $\theta(1-S_r)$	residual liquid fraction of total volume θS_r	Comments
350	0.20	0.14	0.86	0.17	0.03	Table 5
350	0.30	0.21	0.79	0.24	0.06	Table 5
350	0.40	0.34	0.66	0.26	0.14	Table 5
350				**0.22**		**average**
345	0.15	0.14	0.86	0.13	0.02	Table 6
345	0.20	0.21	0.79	0.16	0.04	Table 6
345	0.25	0.34	0.66	0.17	0.09	Table 6
345	0.30	0.34	0.66	0.20	0.10	Table 6
345	0.35	0.34	0.66	0.23	0.12	Table 6
345	0.40	0.46	0.54	0.22	0.18	Table 6
345				**0.18**		**average**

Level change from 260" to 160"

Saltcake level (in)	void fraction/ total porosity θ	residual saturation S_r	drainable saturation $1-S_r$	drainable liquid fraction of total volume $\theta(1-S_r)$	residual liquid fraction of total volume θS_r	Comments
350	0.15	0.14	0.86	0.13	0.02	Table 5
350	0.25	0.34	0.66	0.17	0.09	Table 5
350	0.35	0.46	0.54	0.19	0.16	Table 5
350				**0.16**		**average**
345	0.15	0.14	0.86	0.13	0.02	Table 6
345	0.20	0.21	0.79	0.16	0.04	Table 6
345	0.25	0.34	0.66	0.17	0.09	Table 6
345	0.30	0.46	0.54	0.16	0.14	Table 6
345	0.35	0.46	0.54	0.19	0.16	Table 6
345	0.40	0.49	0.51	0.20	0.20	Table 6
345				**0.17**		**average**

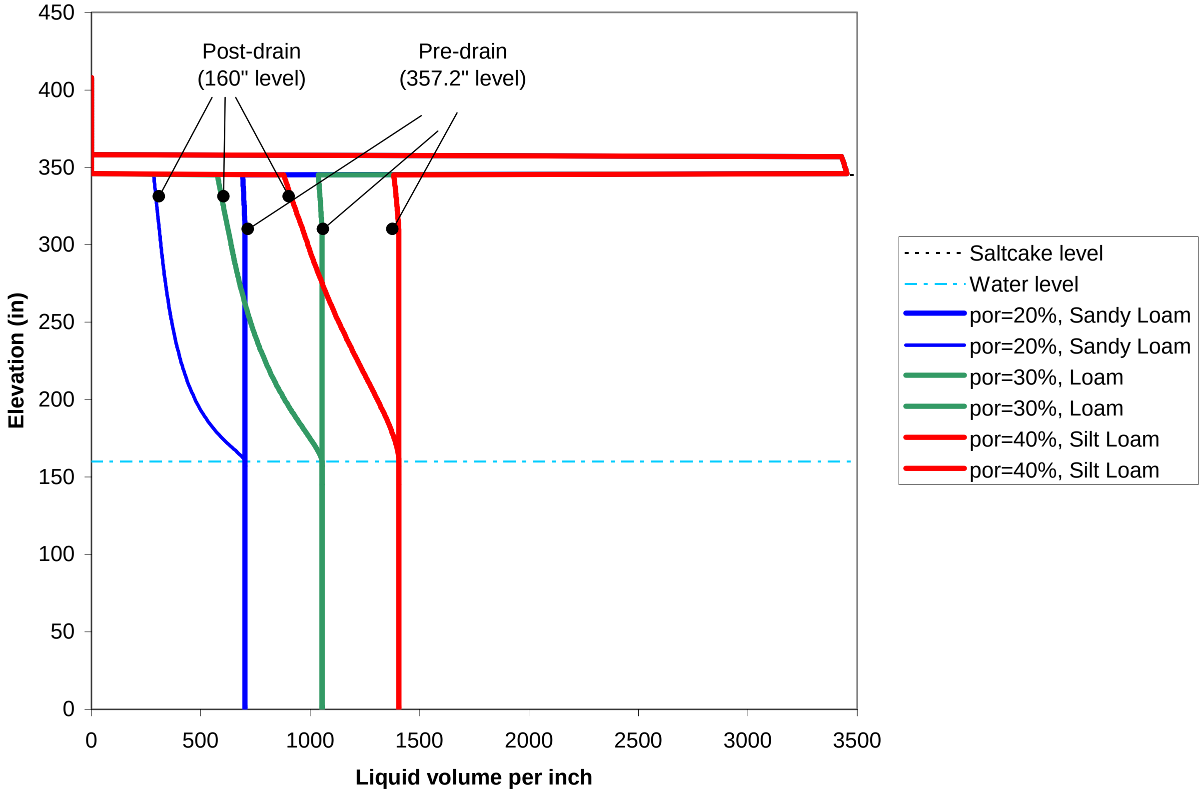

Figure 7 Liquid inventories in Tank 41 before and after pumping for three optimal parameter settings (345" saltcake level).

Table 9 Example combinations of initial and residual liquid content that are consistent with a 14% drainable liquid content; equivalent calculations shown for radiolytic gas excluded from and included in voids.

Initial water content in submerged saltcake θ_{ws}	*Radiolytic gas lumped with salt - excluded from "voids"* Pseudo total porosity n'	Drainable liquid content n'(1-S_{wr}')	Residual liquid content n'S_{wr}'	Pseudo residual saturation S_{wr}'	Pseudo drainable saturation 1-S_{wr}'
0.20	0.20	0.14	0.06	0.30	0.70
0.25	0.25	0.14	0.11	0.44	0.56
0.30	0.30	0.14	0.16	0.53	0.47
0.35	0.35	0.14	0.21	0.60	0.40
0.40	0.40	0.14	0.26	0.65	0.35

Initial water content in submerged saltcake θ_{ws}	*Radiolytic gas included in void space* Initial gas content θ_g	Total porosity n	Drainable liquid content n(S_{ws}-S_{wr})	Residual liquid content nS_{wr}	Initial saturation S_{ws}	Residual saturation S_{wr}	Drainable saturation S_{ws}-S_{wr}	Gas saturation S_g
0.20	0.105	0.31	0.14	0.06	0.66	0.20	0.46	0.34
0.25	0.105	0.36	0.14	0.11	0.70	0.31	0.39	0.30
0.30	0.105	0.41	0.14	0.16	0.74	0.40	0.35	0.26
0.35	0.105	0.46	0.14	0.21	0.77	0.46	0.31	0.23
0.40	0.105	0.51	0.14	0.26	0.79	0.51	0.28	0.21

Analysis of dynamic tank liquid levels during drain operations

The above static analysis was possible because an equilibrium tank level could be estimated from recovery data acquired during unplanned downtime due to an equipment problem. In general, the tank may not be at equilibrium and the liquid level will differ across Tank 41. In Tank 41 the well is located near the tank wall, so during drainage the liquid level will be lowest at the well and highest at the far wall. A rigorous estimate of the interstitial liquid level across the tank requires numerical simulation. However, the mean liquid level can be approximately estimated from the pumping rate and well level under pseudo-steady conditions using a simple analytical approach, as shown below. The motivation for estimating the mean tank level is two-fold. First, the mean tank level should be a reasonable surrogate for the maximum level, as shown schematically in Figure 8. The difference between the well water level and the maximum water level is an indication of the overall gradient across the tank. Second, the mean tank level would also be the equilibrium tank level after transients subside. A projection of the equilibrium water level could be useful for performing liquid inventory calculations, such as performed in the preceding section. The semi-empirical relationship of mean tank level to well level and pumping rate developed herein can also be used to estimate drainage times when the well level is held at a long-term low (e.g. minimum) level, as shown below.

Average tank level estimation

Analytical solutions of steady-state, unconfined, porous media flow in a variety of radial and rectangular geometries have the form

$$h(\vec{x})^2 - h_{ref}^2 = \frac{\mu}{k\rho g} Q \cdot C_{geom}(\vec{x}) \tag{26}$$

where $h(\vec{x})$ is water level at location $\vec{x}$, h_{ref} is a reference water level, $C_{geom}(\vec{x})$ is a geometric function, k is intrinsic permeability, μ is viscosity, ρ is density, g is gravitational acceleration, and Q is a constant pumping or flow rate. A well-known example is the Dupuit-Forchheimer formula for well discharge (cf. de Marsily, 1986, p. 150)

$$h^2 - h_{ref}^2 = \frac{\mu}{k\rho g} Q \cdot \frac{1}{\pi} \ln \frac{r}{r_{ref}} \tag{27}$$

where r is the radial distance from the well, and r_{ref} is the radius of the boundary where $h = h_{ref}$. The average of water level squared can be readily computed from equation (26) as

$$\overline{h^2} = h_{ref}^2 + \frac{\mu}{k\rho g} Q \cdot \overline{C_{geom}} \tag{28}$$

and then

$$h(\vec{x})^2 - \overline{h^2} = \frac{\mu}{k\rho g} Q \cdot \left[C_{geom}(\vec{x}) - \overline{C_{geom}} \right] \tag{29}$$

For a given well location, porous medium, and fluid properties, equation (29) can be simplified as

$$h_w^2 - \overline{h^2} = \frac{Q}{C} \tag{30}$$

where the constant C can be treated as an empirical constant to be estimated from data. Assuming the head gradient at the well under the conditions of interest is not too large

$$\overline{h^2} \cong \bar{h}^2 \tag{31}$$

and then equation (30) can be replaced by the approximation

$$h_w^2 - \bar{h}^2 = \frac{Q}{C} \tag{32}$$

Equation (32) is assumed to be approximately valid for the tank and well configuration of Tank 41. With some approximation, the expression should also be valid under pseudo-steady conditions, i.e. slow transients. Thus, the latter portion of the drawdown transient from 9/8/02 through 9/22/02 can be used to determine C. During this period, the pumping rate averaged 3.19 gpm, while the well and mean (equilibrium) tank levels were inferred above to be approximately 227.6" and 260", respectively. As shown in Table 10, these inputs produce an estimate of $C = Q/\Delta h^2 = 2.02 \times 10^{-4}\,\text{gpm/in}^2$.

Example solutions of equation (32) are shown in Figure 9 to illustrate the behavior of the flow model with respect to different pumping rates. For example, at a pumping rate of 5 gpm and a well level of 200", the average or equilibrium tank level is estimated from equation (32) to be 254". At the pumping rate of 1 gpm and a well level of 200", the mean tank level is predicted to be 212".

Recovery data from Phase II (Figure 1) provide an opportunity to validate expression (32). Over the three days prior to the second major well recovery, 11/8 through 11/10 inclusive, a net volume of 3725 gallons was removed from Tank 41. The average removal rate was thus 0.86 gpm. Going into recovery, the well level was 130". Equation (32) predicts an equilibrium well level of 145". Two weeks later, the well level had recovered to 147" and appeared to be leveling off. By three weeks, the level was at 150". Since then however, the well level has risen at roughly a constant, rather than, declining rate. At the end of the data record, the well level was 157"on 12/9.

The shape of the recovery curve suggests two phenomena are having an impact. The first is a leveling of the interstitial liquid level across the tank. The second is continued drainage of liquid from unsaturated saltcake above the interstitial liquid level. Equation (32) considers only the first phenomenon, which probably dominates in the early stage of well recovery. In this respect, equation (32) appears to have predicted the short-term recovery level with reasonable accuracy. Over longer time scales, equation (32) appears to under-predict well recovery, due to small amounts of additional drainage from saltcake above the interstitial level. A more sophisticated (i.e. numerical) modeling approach would be needed to more accurately predict well recovery.

Another contributing factor to discrepancy between the model and recovery data could be changes in the well diameter. The analysis assumes a constant diameter well. If the well diameter is smaller in the lower portion of the well where the second recovery occurred, the rebound would have been greater because the gradients in the radially converging flow would have been steeper.

Drain time estimation

When the well liquid level is lowered to some minimum elevation near the tank bottom, and maintained through continued pumping, drainage to the well will occur at a continually slower rate as the head gradient across the tank declines. The time required to further lower the current mean level to a particular desired level can be roughly estimated by combining equation (32) with the mass balance

$$Q(t) = \frac{d\bar{h}}{dt} An - \frac{d\bar{h}}{dt} AnS_{wr} = \frac{d\bar{h}}{dt} An(1 - S_{wr}) \tag{33}$$

which equates the pumping rate from the well to the rate of change in liquid inventory. The right-hand side of the expression is rate of decrease of saturated saltcake minus the rate of gain of saltcake at residual saturation. Although, equation (32) was developed assuming a constant pumping rate, as stated earlier, it should also be approximately valid under pseudo-steady conditions (slow transients). If equations (32) and (33) are combined by eliminating Q under this assumption, the result is an ordinary differential equation in terms of mean tank level, given a fixed well level and porous medium properties:

$$h_w^2 - \bar{h}^2 = \frac{An(1 - S_{wr})}{C} \frac{d\bar{h}}{dt} \tag{34}$$

Defining

$$C' = \frac{An(1 - S_{wr})}{C} \tag{35}$$

results in the simplified expression

$$h_w^2 - \bar{h}^2 = C' \frac{d\bar{h}}{dt} \tag{36}$$

The solution can be derived by separating variables

$$dt = \frac{C'}{h_w^2 - \bar{h}^2} d\bar{h} \tag{37}$$

Equation (37) can then be integrated as

$$\int_{t_0}^{t} dt = \int_{\bar{h}_0}^{\bar{h}} \frac{C'}{h_w^2 - \bar{h}^2} d\bar{h}$$
$$t - t_0 = C' \int_{\bar{h}_0}^{\bar{h}} \frac{d\bar{h}}{h_w^2 - \bar{h}^2} \quad (38)$$
$$t - t_0 = -C' \int_{\bar{h}_0}^{\bar{h}} \frac{d\bar{h}}{\bar{h}^2 - h_w^2}$$

Using integral formula #18 in the 27th edition of the CRC Standard Mathematical Tables,

$$t - t_0 = -C' \frac{1}{2h_w} \log \frac{\bar{h} - h_w}{\bar{h} + h_w} \Bigg|_{\bar{h}_0}^{\bar{h}}$$
$$\Delta t = \frac{C'}{2h_w} \left[\log \frac{\bar{h}_0 - h_w}{\bar{h}_0 + h_w} - \log \frac{\bar{h} - h_w}{\bar{h} + h_w} \right] \quad (39)$$

where $h_w > 0$. If the well level is zero, the result is

$$\Delta t = -C' \int_{\bar{h}_0}^{\bar{h}} \frac{d\bar{h}}{\bar{h}^2} = -C' \frac{\bar{h}^{-1}}{-1} \Bigg|_{\bar{h}_0}^{\bar{h}} = C' \frac{1}{\bar{h}} \Bigg|_{\bar{h}_0}^{\bar{h}} = C' \left[\frac{1}{\bar{h}} - \frac{1}{\bar{h}_0} \right] \quad (40)$$

Equation (39) or (40) provides a crude estimate of the time required to drain Tank 41 when the well water level is maintained at some constant, minimum feasible, height. The drainage time is seen to depend on the well level, initial mean tank level, the desired final mean tank level.

An example set of solutions for an <u>initial mean tank level of 48"</u> is shown in Figure 10 for illustrative purposes. In this example, if the well level is maintained at 10" and the desired final average tank level is 36", then the drainage time is projected to be on the order of 15 days. If the desired final average tank height is 24", the drain time becomes 50 days. Because a number of assumptions and approximations are built into equations (39) and (40), the accuracy of estimates such as those depicted in Figure 11 is not known. Lacking quantitative validation of these expressions through numerical modeling and/or field experience, drain times from these expressions should be viewed as order-of-magnitude estimates.

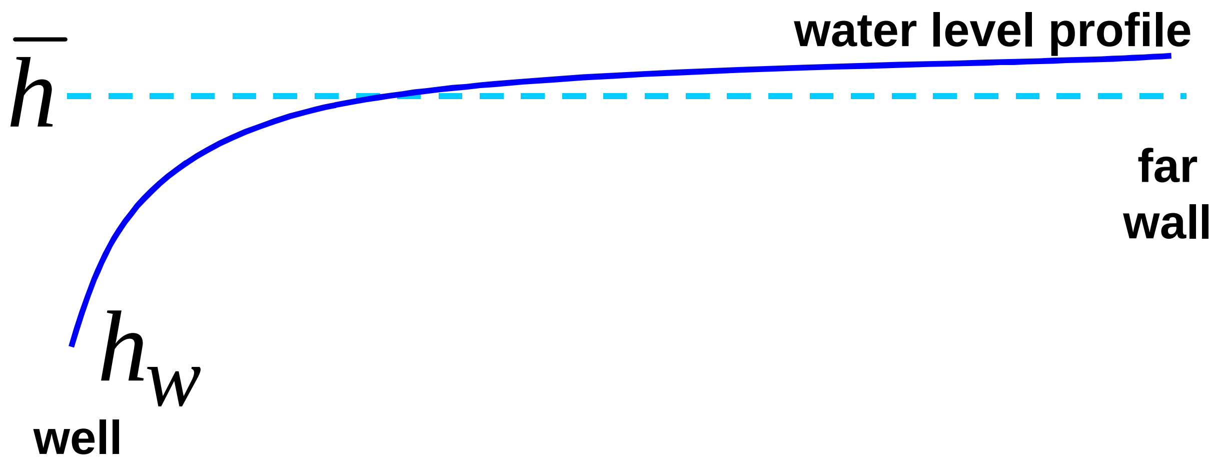

Figure 8 Schematic representation of interstitial liquid level across Tank 41.

Table 10. Calibration of pseudo-steady flow solution to Tank 41 data.

	Metric		*English*		*Preferred*	
T	~35	deg C	~95	deg F		
sp. gr. IL	1.478	unitless	1.478	unitless		
ρ_{ref}	1000	kg/m^3	62.4	lbm/ft^3		
ρ_{IL}	1478	kg/m^3	92.3	lbm/ft^3		
μ	0.003	N-s/m^2	0.002016	lbm/ft-s	3	cP
g	9.81	m/s^2	32.2	ft/s^2		
h_w	5.78	m	18.97	ft	227.6	in
h_{avg}	6.60	m	21.67	ft	260	in
Q	-0.000201538	m^3/s	-0.007117	ft^3/s	-3.19	gpm
$C_{geom}/k=(h_w^2-h_{avg}^2)\rho g/\mu Q$	2.45E+11	1/m^2	2.27E+10	1/ft^2	0.241	1/Darcy
$(C_{geom}/k)(\mu/\rho g)=\Delta h^2/Q$	50592	s/m	15421	s/ft		
$C=Q/\Delta h^2$	1.98E-05	m/s	6.48E-05	ft/s	2.02E-04	gpm/in^2

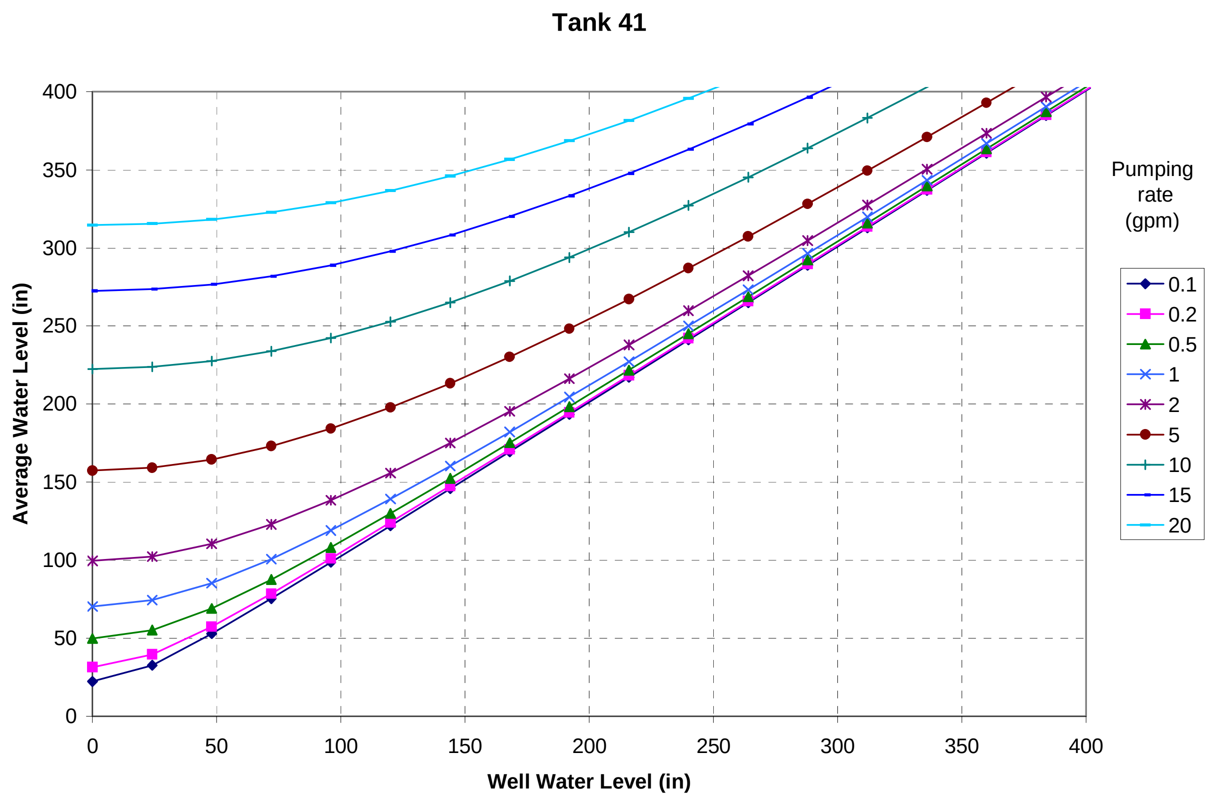

Figure 9 Pseudo-steady flow solutions for Tank 41.

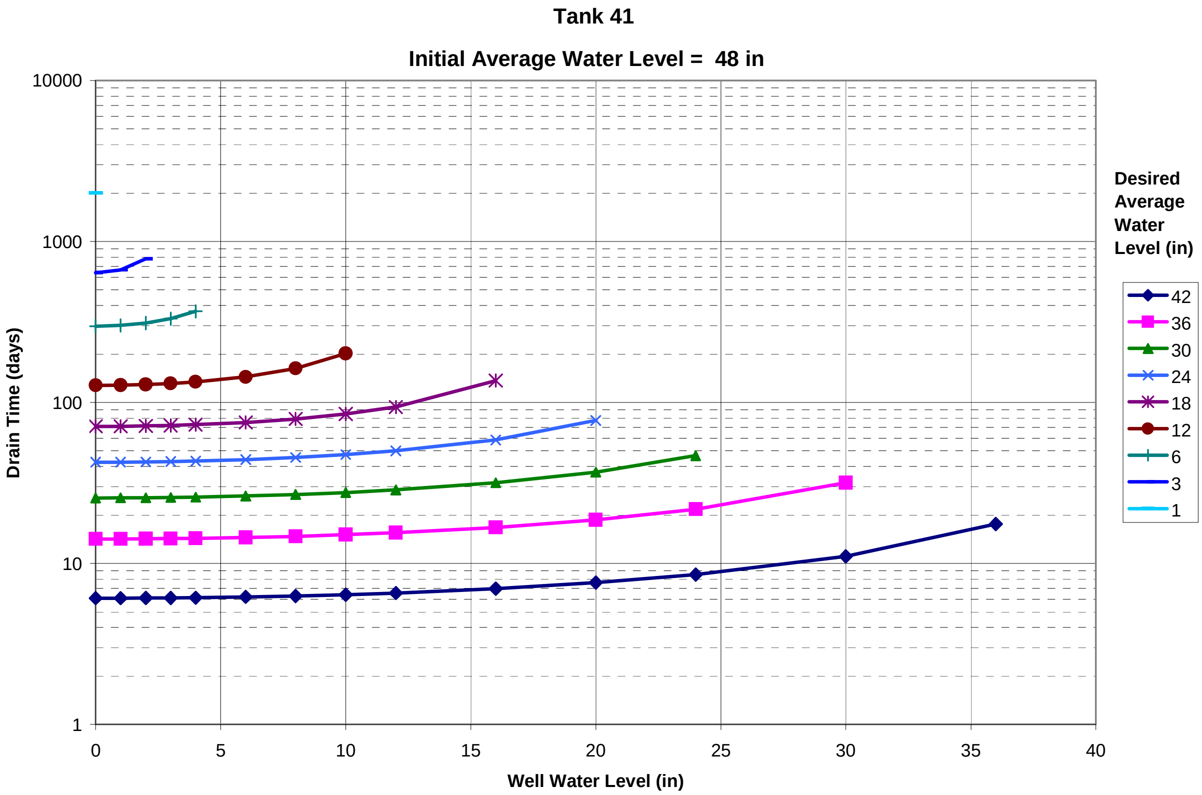

Figure 10 Estimated drainage time starting from a mean tank level of 48".

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