

Letter Report for Westinghouse Hanford Company

A Simplified Model of Saltcake Moisture Distribution

C. S. Simmons

September 1995

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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PNL-10803

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Executive Summary

This letter report describes the formulation of a simplified model for finding the moisture distribution in a saltcake waste profile that has been stabilized by pumping out the drainable interstitial liquid. The model is based on assuming that capillarity mainly governs the distribution of moisture in the porous saltcake waste. A steady upward flow of moisture driven by evaporation from the waste surface is conceptualized to occur for isothermal conditions. To obtain hydraulic parameters for unsaturated conditions, the model is calibrated or matched to the relative saturation distribution as measured by neutron probe scans. The model is demonstrated on Tanks 104-BY and 105-TX as examples. A value of the model is that it identifies the key physical parameters that control the surface moisture content in a waste profile. Moreover, the model can be used to estimate the brine application rate at the waste surface that would raise the moisture content there to a safe level. Thus, the model can be applied to help design a strategy for correcting the moisture conditions in a saltcake waste tank.

Background

The moisture distribution that prevails in a stabilized waste tank is critical information for resolving safety concerns that are being addressed by both the Organic Safety and Ferrocyanide Safety Programs managed by Westinghouse Hanford Company. The presence of moisture at sufficient levels keeps organic or ferrocyanide wastes combined with nitrate salts from being a combustion hazard, if those chemicals are present in quantities that might sustain ignition. Moisture in saltcake waste is emphasized because it appears that sludge-type wastes will generally retain enough moisture to be considered safe from potential ignition. A liquid-saturated saltcake is likely to be safe also, but a drained saltcake has an unknown moisture state. Therefore, the mathematical model presented here focuses on a drained saltcake waste profile.

A simplified physical model of the moisture distribution in a saltcake waste tank profile is discussed in this report. The mathematical model presented is called simplified because it emphasizes the physical influences of capillary phenomena and neglects thermal effects that induce moisture vapor flow. The model describes the likely moisture distribution that occurs in a saltcake waste profile that has been stabilized and drained by pumping. When the drainable interstitial liquid in a saltcake profile has been pumped out, then the final distribution of liquid is determined mainly by capillarity. Once stabilized, a tank's waste moisture distribution does not appear to change much over the years as is indicated by past neutron probe scanning. Thus, the assumption is made that a post-stabilized moisture distribution is static or in a steady-state condition. A steady long-term evaporation of moisture at the waste surface may also determine the moisture distribution in conjunction with a saltcake's hydraulic properties. Also, the horizontal variability of waste properties is unknown, so a one-dimensional vertical perspective is taken in the model.

This chapter discusses the following: saltcake characteristics, modeling emphasis, hydraulic property model, evaporation estimation, relative saturation, modeling applications, determining the pore-size index from pumping, surface dryness sensitivity, remediation of surface moisture, and modeling limitations.

Saltcake Waste Characteristics

The hydraulic characteristics of actual saltcake in waste tanks are not available. The radioactivity of saltcake core samples has precluded any direct measurement of properties by standard laboratory methods. Usual mechanical measurements of hydraulic properties that require manipulation of core samples have not been obtained because of the involved radioactivity hazard. As an alternative approach, simulants of a particular waste have been characterized instead. Still, replicating an unknown saltcake waste to determine its related in-tank hydraulic properties has been difficult.

Handy (1975) and Strachan (1975) performed some of the earliest measurements of hydraulic properties for simulant saltcake. However, no proof exists that their simulants were comparable to

actual saltcake in Hanford tanks. The contrasting physical aspects of tank waste types were reviewed in a Westinghouse Hanford Company quarterly report (Cash et al. 1995).

In contrast, simulant sludges (Jeppson and Wong 1993) have made it possible to demonstrate the consolidation behavior of this form of tank waste. Sludges generally retain moisture at a high level of about 40 wt%, even when fully consolidated under tank conditions. Sludges do not drain by gravity in a tank. However, saltcake, which usually has much larger interstices (pores) in comparison to sludge and has a more rigid matrix, is subject to gravitational drainage when the brine is pumped out or when it leaks from a waste tank.

The dryness of a drained saltcake profile depends on the specific hydraulic properties of this waste form and the profile height. A higher saltcake profile will generally drain at the surface to a lower moisture content than found in a smaller profile. The principles of unsaturated flow in a porous matrix determine the final liquid distribution in a drained saltcake waste profile. Modeling incorporates these principles in terms of hydraulic properties to estimate the moisture distribution in saltcake.

Because manufacturing simulant saltcake that is physically representative of actual tank waste is difficult, modeling is especially helpful in estimating saltcake's hydraulic properties. Modeling can be used to infer what hydraulic property values are consistent with the observed moisture distributions in stabilized tanks. A relative measure of the moisture distribution in tank waste is obtained from neutron probe scans taken in an liquid observation well (LOW). This information when combined with the principles of unsaturated liquid retention and flow in a porous medium can be used to infer what the parameter values are for a saltcake's hydraulic properties.

Simulant saltcakes have been developed (Wanner 1993), but these samples were produced mainly to measure the mechanical properties such as bulk density and shear strength. Thermal conductivity measurements were also attempted with varying success. Hydraulic properties for the simulated saltcake, however, were not measured. The characterization of Tank 104-BY simulant reported by Wanner (1993) provided qualitative information that saltcake is indeed a porous matrix with a complicated structure. The porous structure is a result of the specific waste processing history. No effort, however, was made to evaluate the distribution of interstices or pore sizes. The simulant was primarily designed to determine mechanical properties to test core sample drill bits. Wanner (1993) reported a bulk density of about 1.41 g/cc for the Tank 104-BY simulated saltcake dried to 5 wt% moisture. This remaining moisture probably constitutes hydrated water. In contrast, hydraulic analysis is concerned with the free liquid - not the chemically bound water - held in the interstices.

Modeling Emphasis

A simplified model for the steady evaporation of moisture from a saltcake waste surface was devised based on the principles of unsaturated liquid flow in a rigid porous matrix. The mathematical development is based on a presumed constant upward liquid flux.

Even in a closed tank, moisture is continually evaporating from the waste surface because of the heat load and then recondensing on the cooler tank-wall surfaces. The water that condenses on the tank cover and sides returns to the waste in a continuous cycle, while heat is transferred to outside the tank. The greatest possible waste surface drying would be expected if the entire surface heat transfer occurred via evaporation, instead of partly by convection and radiation as it actually does. Thus, by assuming that all heat transfer through the waste surface takes place by evaporation, the greatest drying condition that is possible is conceived. On the other hand, evaporation cannot occur at a rate that exceeds how rapidly liquid (brine) can flow upward to maintain the surface moisture. When moisture is evaporated at the surface of an unsaturated porous medium, capillary forces draw liquid upward against gravity to maintain the volumetric liquid content (VLC) there.

A simplified model for steady, upward unsaturated flow driven by an evaporative liquid flux based on the heat transfer rate was formulated and programmed following the concepts just described. This mathematical model is simplified because it does not yet account for the diffusion of water vapor through the liquid-drained interstices or air-filled voids of the saltcake, as driven by the thermal gradients that are present. It is also only a vertical, one-dimensional evaluation of moisture flow. Future modeling analysis will consider the importance of equilibrium vapor pressure gradients for causing water vapor flow.

A solution to this simplified model follows the approach first given by Gardner (1958) for describing evaporation from a soil. Marshal and Holmes (1979) in their soil physics text further describe the flow equation's solution for a layered profile of porous media.

Another simplification is the neglect of dissolved salt transport caused by upward liquid flow. When the water component of the interstitial liquid is evaporated at the surface, the salt that exceeds local solubility with the saltcake would be precipitated. This surface accumulation of dissolved salts with evaporation is well known (Marshal and Holmes 1979). A continuous buildup of salt mass would gradually alter the local hydraulic properties over time, because the distribution in the porous structure would change. This transport of salt is neglected also in the present modeling approximation. However, because the model is matched to the existing moisture conditions in a tank's saltcake profile, the hydraulic properties are determined in a way that is consistent with the present state. Future modeling analysis must consider the long-term influence of saltcake dissolution and salt transport.

An isothermal waste profile is assumed, so that changes in liquid surface tension and viscosity are neglected. Liquid surface tension is not expected to vary substantially for the usual range of temperature observed in tank waste (Grigsby et al. 1992). Changes of viscosity with temperature and with dissolved salt concentration would affect the local variation of liquid conductivity. However, such variation in liquid conductivity can be introduced into the modeling solution when it is known for the steady flow conditions. Furthermore, spatial variations in the viscosity are considered a minor influence when compared with the more considerable uncertainty of the intrinsic permeability, which determines the liquid's hydraulic conductivity. In any event, a fixed spatial pattern for the interstitial liquid's properties, such as density, surface tension, and viscosity, could be introduced into the model when such information is available from tank sampling.

Hydraulic Property Model

The well-known and accepted empirical formulas for hydraulic properties, called the Brooks-Corey model, are employed in this solution for the steady upward unsaturated flow (see Campbell 1985). These formulas are assumed to describe a wide range of granular porous media types (soils) and also apply to saltcake. A laboratory study would be necessary to confirm this assumption. But past studies of simulant saltcake have confirmed that it is a porous medium and retains brine by capillarity, similar to sands (Handy 1975).

The Brooks-Corey model for the liquid capillary retention relation is the following equation:

$$h/h_o = [(VLC_s - VLC_r)/(VLC - VLC_r)]^b \quad (1)$$

where h = suction head
 h_o = holdup height
 VLC_s = volumetric liquid content, saturated
 VLC_r = volumetric liquid content, residual
 VLC = volumetric liquid content
 b = pore-size index for the porous medium.

Note that the saturated value usually equals the porosity. The height of interstitial liquid rise, h , is that achieved in a static equilibrium condition without any liquid movement; h is the matric suction head in units of liquid column height for its own density (i.e., as depends on the liquid's specific gravity). Matric suction head is the negative of the matric potential energy per unit weight of the particular liquid. (Note that h is a measure of the capillary pressure that holds the liquid up above the interstitial liquid level [ILL] in a drained saltcake.) If h is less than holdup height, the saltcake is entirely liquid saturated. Here the holdup height equals the difference between the ILL and the standing liquid level as seen in a salt well.

The pore-size index can be estimated from the pumping response of tanks having a certain drainable porosity (DeWeese 1988). The concept of drainable porosity was discussed by DeWeese to explain why different waste profiles contained relatively different amounts of liquid. Drainable porosity reflects the amount of liquid that can be gravity drained or pumped out to achieve a profile equilibrium distribution of liquid. The important result is that the profile-averaged pore-size index for a saltcake profile can be determined from the pumping response of a tank that has been stabilized, by assuming that equation (1) applies. The change in total liquid storage from a saturated profile leading to a final drained equilibrium distribution, as a result of pumping out a known quantity of liquid, is relatable to the pore-size index. This was found to apply to a group of tanks in the TX Tank Farm containing entirely saltcake waste.

However, the estimation approach, apparently, was not accurate when applied to tanks in the BY Tank Farm having a saltcake layer over sludge. The saltcake profiles in the BY tanks underwent considerable consolidation when pumped. This yields a much greater drainage quantity than could have been extracted from the final reduced saltcake profile. That is, the drainable porosity for BY tanks did not reflect the porous properties of the post-stabilized saltcake. This resulted in a pore-

size index that is much smaller (an average of 0.5) than that found for a group of TX saltcake tanks, having pore-size index values ranging from 1.2 to 4.5 with an average of 2.1. A pore-size index of 0.5 to 0.7 would be typical of coarse sands. Granular media with a pore-size index of about 2.1 retain more liquid when the same residual and saturated liquid contents apply.

The original plan to characterize tank waste was to estimate liquid retention parameters directly from particle size distributions for saltcake samples by using certain theoretical formulas. The plan's method was discussed in a quarterly report (Cash et al. 1995). The accuracy of that method, however, was questionable because the true crystal grain size distribution for actual tank saltcake is not available. An alternative approach is to infer the hydraulic parameters, such as pore-size index, by matching the modeling predictions to either pumping response information or to neutron probe scan data for selected tanks.

Presuming that the Brooks-Corey model equation is relevant, the unsaturated liquid conductivity is given by the following equation:

$$K/K_s = [(VLC - VLC_r)/(VLC_s - VLC_r)]^{(2b+3)} \quad (2)$$

where K_s is the liquid saturated conductivity for saltcake. Derivation of this model uses a distribution of capillary pore sizes based on the retention equation (1). Combined with the retention equation (1), these hydraulic functions are sufficient to model the unsaturated liquid movement in saltcake having a rigid porous matrix.

The unknown hydraulic parameter, i.e., the liquid saturated conductivity, can be found from laboratory column tests like that performed early by Handy (1975) or by a pumping drawdown test like that discussed by Metz (1976). Kirk (1980) reviewed the extent of what is known for the hydraulic properties of tank waste.

The liquid saturated conductivity (units of length per time) is determined from the permeability (in darcy units) of the porous medium and the liquid's viscosity, cp. Handy (1975) found a permeability of 22.2 darcy for a synthetic saltcake with a liquid density of 1.43 g/cc and viscosity of 12.5 cp. This was equivalent to a liquid saturated conductivity of 0.0025 cm/s, for this supernate. Using this value as a reference conductivity, K_{ref} , the liquid saturated conductivity for different liquid properties and permeability could be estimated by property scaling:

$$K_s = (\text{darcies}/22.2)(12.5/\text{viscosity})(\text{liquid density}/1.43) K_{ref}$$

Darcy's law is combined with this estimated hydraulic conductivity to calculate the liquid's flow rate. The Darcy liquid flow velocity, q , is given by

$$q = -K(h) \cdot (dh/dz + 1) \quad (3)$$

where $K(h)$ = hydraulic conductivity as function of suction head
 dh/dz = matric suction head gradient
 z = depth, measured positive downward from the surface.

Darcy flow velocity has units of volume per area per time or length per time and is a volumetric flux with the same units as the liquid saturated conductivity. In Darcy's law, equation (3), the flow is driven by the sum of the matric suction head gradient, dh/dz , and the gravitational potential gradient, which is unity here. Here h must be expressed in units of the rise height for the particular liquid's density. Note that the static equilibrium condition for which there is no flow, $q = 0$, is determined by $dh/dz + 1 = 0$. This defines the static distribution of VLC in the profile. An upward net flow is associated with a positive Darcy liquid flow velocity. If $dh/dz < -1$, then the liquid moves upward.

In equation (3), K is expressed as a function of h by using equations (1) and (2) to eliminate VLC. For steady flow conditions, the Darcy liquid flow velocity must be constant over the profile, and equation (3) can be solved for the value of h at each depth. Then using equation (1) gives the distribution of the VLC with z . The solution applies to each layer with different parameter values to describe a heterogeneously layered profile. A Mathcad program called LAYERS was written to solve this problem and to perform the calculations.

In this model, the Darcy liquid flow velocity is determined by the rate of water evaporation at the surface. However, only a fraction of the liquid that moves toward the surface can evaporate because the rest of the mass is salt. Letting E be the evaporation rate (units $g/s/cm^2$ of water), q and E are related by

$$E = (P_w/100)(\text{liquid density}) q$$

where P_w is weight percent water of the liquid. The heat flux, J , in units W/m^2 transferred by evaporation is

$$J = (\text{water latent heat of vaporization})(10,000) E$$

Latent heat of water vaporization is about 2,450 J/g at standard temperature.

The liquid flow model makes it clear what hydraulic parameters are needed to examine the possible dryout of saltcake. The required parameters are the following:

- Holdup height for capillary rise, h_o
- Pore-size index, b
- Permeability, or saturated conductivity, K_s
- Liquid surface tension
- Viscosity
- Depth to the stabilized ILL.

Then the Darcy liquid flow velocity must be established based on the fraction of surface heat flux that is partitioned into moisture evaporation with the latent heat transfer. The approach for estimating this evaporation flux, E , is discussed in the section on evaporation estimation.

By formulating this model, the most important physical parameters that control moisture distribution are identified. This provides direction on what properties of saltcake waste samples should be measured to adequately assess safety with regards to the driest conditions possible.

To determine the conversion from VLC to weight percent water in the saltcake, for any depth, the following quantities must also be known:

- Salt grain particle density
- Interstitial liquid density
- Actual interstitial porosity
- Percent water of salt-saturated liquid.

The VLC predicted by the model for any depth can then be used to estimate weight percent water. The conversion formula is discussed in a quarterly report (Cash et al. 1995).

Evaporation Estimation

Dickinson (letter to R. J. Cash and D. A. Turner, December 14, 1994) computed the water vapor flux based on diffusion and the water vapor concentration gradient associated with the temperature gradient in a waste profile. This calculation is common in soil physics and is called the thermal water vapor flux. The thermal vapor diffusivity is the product of the water vapor diffusion coefficient in air, tortuosity factor, vapor-filled porosity, RH, temperature slope of the saturation water vapor concentration, and an enhancement factor. Vapor flux is then the product of this vapor diffusivity and the local temperature gradient, dT/dz . Dickinson did not include the enhancement factor that accounts for increased vapor flux caused by microscopic temperature gradients acting across air-filled pores between liquid-filled pores. The enhancement factor could be 5 to 10 times as noted by Campbell (1985), but it approaches unity as the liquid content vanishes or as the porous medium becomes dried.

Dickinson calculated that the total surface heat flux is between 3 to 5 W/m^2 for typical tanks (3.4 W/m^2 for a tank with a 2 kW heat load, like 104-BY). He found about 0.033 g/s water vapor flow by thermal diffusion from an entire surface, which is equivalent to about 0.2 W/m^2 . He used a measured temperature gradient of about 15°C/m to obtain this evaporation rate; he noted that this evaporation rate is about two times greater than the amount that could be lost by a tank breathing or by exchange with the outside atmosphere. If enhanced, this thermal vapor flux might be 1 to 2 W/m^2 , which is a substantial fraction of the total surface heat transfer in a tank. Clearly this quantity of water vapor is not lost through breathing, so the water must be condensed on cooler tank wall to be returned into the waste.

An approach for estimating the required temperature gradient to calculate the thermal vapor flux is suggested here, for when it is not directly measured. The total surface heat flux should equal the waste thermal conductivity multiplied by the required derivative, dT/dz , near the surface. This total heat flux is a percentage, about 50% to 70%, of the entire tank heat load distributed over the waste surface area (facing a tank's headspace). Thus, the calculation of water vapor flux calls for the additional parameters:

- Saltcake thermal conductivity
- Tank waste heat load, watts output.

Relative Saturation

The ratio of VLCs appearing as the argument in the Brooks-Corey model for the hydraulic properties in equations (1) and (2) is called the relative saturation:

$$S = (VLC - VLC_r)/(VLC_s - VLC_r)$$

The value of the relative saturation remains in the range of zero to unity. To calibrate the model for actual tank moisture conditions, this variable is related to the neutron probe counts rate taken in LOWs. If the neutron counts rate data taken over past years in many tanks could be calibrated to determine the actual VLC at each profile location, then the relative saturation could be calculated directly and used in adjusting the flow model to fit actual measurements. Because the range of counts rate tends to drift from session to session for each profile scan when taken at different times, normalizing the scans for a common relative range is necessary.

Letting C_{min} and C_{max} be the minimum and maximum counts rate, C , for a particular measurement session, and letting C_{min} be selected for a certain depth associated with where the VLC takes its residual value approximately, then the ratio $(C - C_{min})/(C_{max} - C_{min})$ can be viewed as a measurement of the relative saturation at each depth where the counts rate is measured. Also, the maximum counts rate is assumed to be associated with the saturated liquid content. This equality of saturation estimates is based on the assumption that unknown linear calibration factors defined for each profile location would factor out of the calculation of the relative saturation, as based on counts rate. Given that the unknown calibration is not always actually linear, this assumption, of course, produces an unknown error in estimating the relative saturation. However, the estimated relative saturation derived from neutron probe counts is still useful for an approximate model calibration.

Figures 1a and 1b demonstrate the conversion of counts rate data to relative saturations over the waste profile of Tank 118-TX. A percent relative saturation is defined by multiplication by 100. Curves that are different in Figure 1a are brought together in a common range in terms of relative saturation in Figure 1b. Because counts rate values near the waste surface are less than the selected reference, C_{min} , the relative saturation drops below zero or is negative, for a height above the reference. Only the range of positive relative saturation values, however, would be relevant to movement of liquid with a VLC greater than the residual value. The relative saturation can be used to evaluate the "true" relative changes that occur in the moisture distribution over time. It turns out that the average relative saturation over the Tank 118-TX profile has been increasing from 1986 to 1994, from 74% to 84%. Such an increase, however, does not necessarily suggest that the volume of liquid is increasing over time. Without knowing the change in saturated liquid content at each profile location, the relative saturation cannot be converted to the actual VLC needed to calculate the actual liquid storage in the profile. The trend in relative saturation gives only a measure of the relative moisture changes - not the actual.

Location of the reference height for the minimum counts rate was arbitrarily chosen as about 8 ft. The record based on total waste volume indicates a surface height of 11.1 ft, but Figure 1a suggests a height of about 9 ft where the counts rate begins to vanish. Also, the record (Grigsby et al. 1992) indicates an ILL of 4.4 ft, while the salt well liquid level is 3.3 ft. This suggests that either the

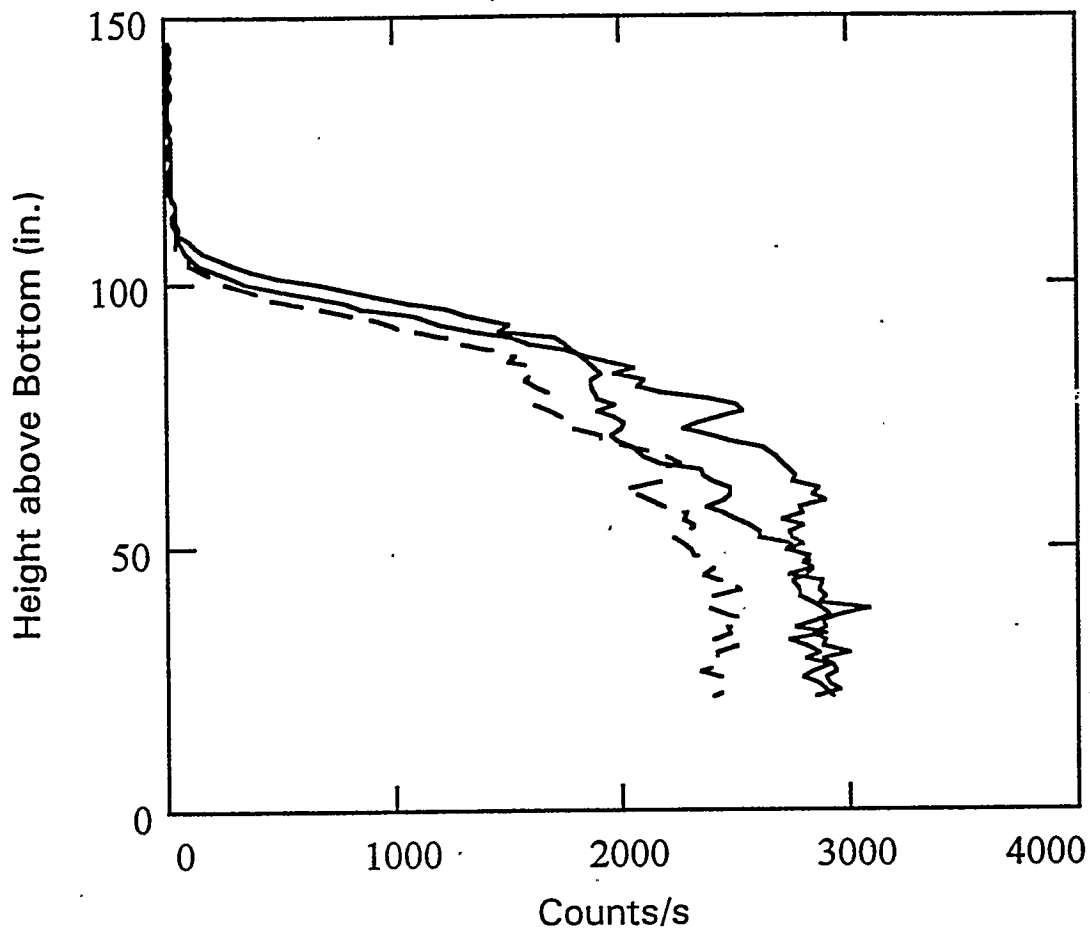


Figure 1a. Neutron Probe Scans for the Waste Profile of Tank 118-TX. Dates (middle curve) 3-18-86; (left dash curve) 10-23-92; (right most curve) 4-18-94.

holdup height is about 1.1 ft above a saturated saltcake zone, or there is a sludge-like waste on the bottom going up to about 4 ft high in this tank (assuming a 6-in. holdup instead), where the relative saturation has remained about the same over the years. This tank, however, is supposed to contain entirely saltcake waste by inventory records.

Modeling Applications

The model for steady upward unsaturated flow has been applied to Tanks 105-TX and 104-BY to test it. These tanks have a waste moisture profile that is more complicated than that of Tank 118-TX. They appear to display layers or possibly moisture variations associated with anomalies around the

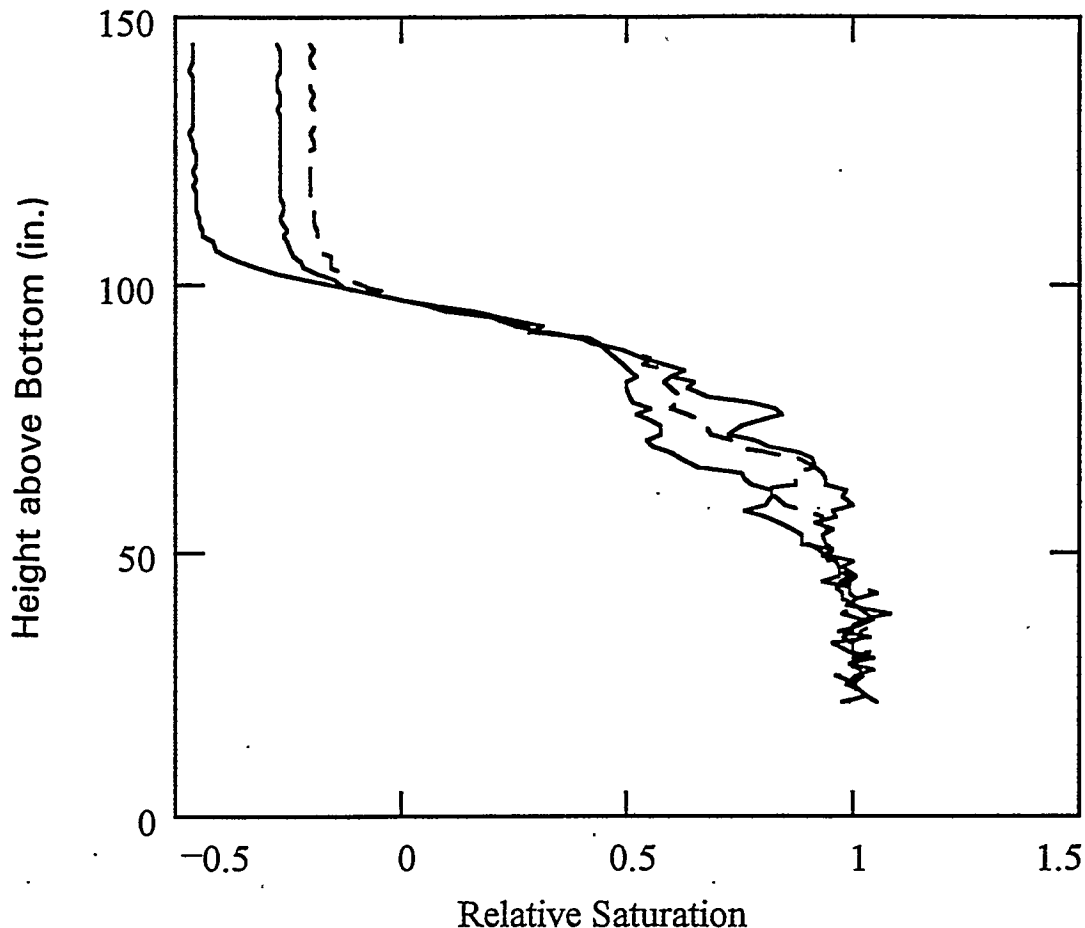


Figure 1b. Profile Neutron Probe Scans in Terms of Relative Saturation for Tank 118-TX. Original data is shown in Figure 1a. Dash curve for 10-23-92 is now between. An upward redistribution of water over time is indicated by the relative saturation increase (assuming no external sources of water).

LOW. The Tank 105-TX and 104-BY examples are reviewed here briefly. A challenge in applying the model was to find effective parameters that represent the possible layer patterns of moisture as viewed, or measured, by the neutron probe scan.

Figure 2 shows the Brooks-Corey retention curve for $b = 2.2$ and $h_0 = 6$ in. compared to a recent moisture profile, expressed in terms of relative saturation. A height for relative saturation equal to zero was selected arbitrarily below the surface to indicate where the minimum residual moisture of 5 wt% is supposed to occur. The sludge is indicated by a nearly vertical fluctuating trace with a relative saturation of about unity. In the sludge, near the bottom, the relative saturation decreases below one, possibly because the sludge is more compressed or consolidated there than near the interface with the assumed water-saturated saltcake. A pore-size index of 0.77 for an absolute porosity of 50 vol% was determined initially from the pumping response. Such a pore-size index

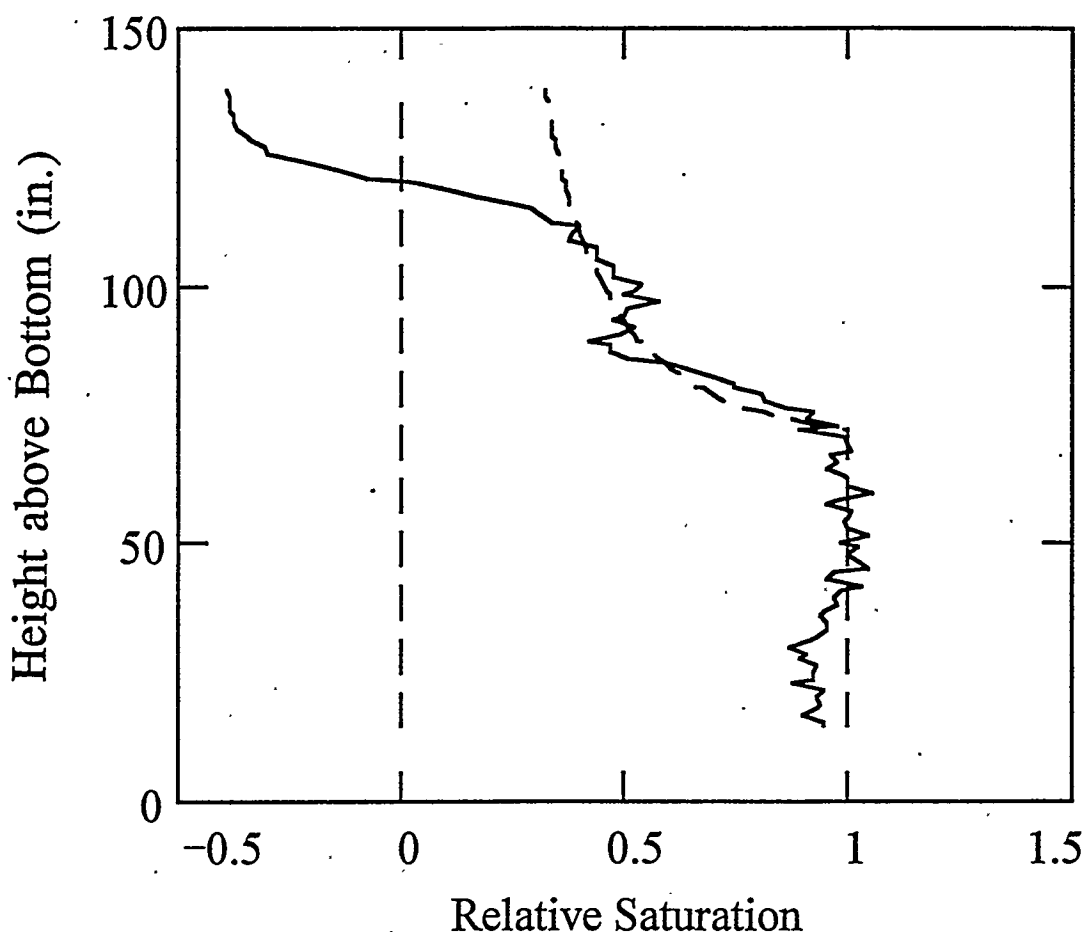


Figure 2. Relative Saturation Profile for Tank 104-BY (Neutron Scanned 3-30-94) Compared with Brooks-Corey Retention Curve. The curve is given by $\log(H/h) = b \log(S)$, where $H = 6$ in. is the holdup height, $b = 2.2$ is the pore-size index, S is relative saturation, and h is the capillary rise height. The ILL is set 72 in. from the bottom.

would, however, define a retention curve that falls far below the relative saturation obtained from the neutron scan. Thus, the pore-size index determined from pumping for this saltcake-over-sludge profile would not be representative.

In Figure 3, four material layers were introduced into the model, and parameter values were selected to give a reasonable match with the estimated relative saturation profile. The result was then converted back to weight percent water, as plotted in the figure. A substantial heat flux of 3.6 W/m^2 was associated with the evaporative moisture flux. That value is slightly greater than the expected total heat load passing out of the waste surface. A minimal permeability within the range of the known values for simulant saltcake was assumed (2.2 darcy). Still, the surface is only slightly dried from the condition where no evaporative flux is present: 12.9 wt% water for no flux to 12.4 wt% water for 3.6 W/m^2 . Beck et al. (1992), using auger samples taken 6 in. below the surface, reported

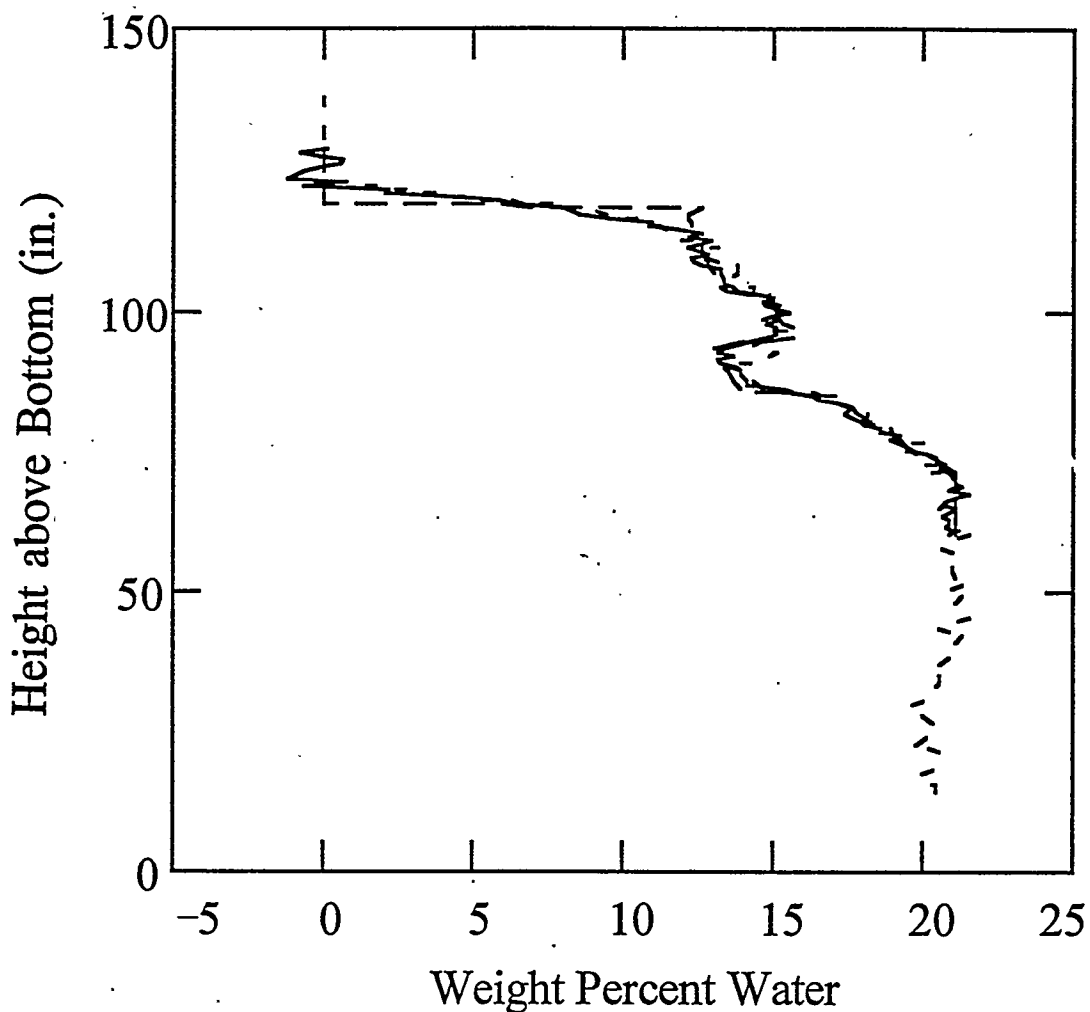


Figure 3. Moisture Content Profile in Tank 104-BY Estimated by Steady State Model. Four saltcake layers are present with a pore-size index of 1.8, 2.2, 1.8 and holdup height of 12, 8, 10, 12 in. ordered from the waste bottom to the top. Absolute porosity is 50 vol%, 46 vol%, 50 vol%, and 47 vol% in the layers from the bottom up. Dash curve is the analytical model prediction, and the fluctuating solid curve represents the measurement as viewed by a simulated neutron scan. Actual scan measurements converted to weight percent water are indicated by a black dot line. Absolute porosity as given and a residual 8 vol% liquid content are used to convert the relative saturation to volumetric liquid content, which is converted to weight percent water by assuming particle density of 2.1 g/cc and liquid density of 1.43 g/cc, with 52 wt% water in the interstitial liquid. A steady upward liquid flux equivalent to 3.6 W/m² of heat transfer via evaporation is maintained for permeability of 2.2 darcy (hydraulic conductivity is 2.5×10^{-4} cm/s and liquid velocity is 2×10^{-7} cm/s for brine viscosity of 12.5 cP.

about 15 wt% to 17 wt% water in the Tank 104-BY waste. Not until the drying flux is 14.6 W/m^2 does surface moisture reduce to 11 wt%. The surface dries to the residual level when the evaporative flux is greater than about 17.9 W/m^2 . This is the critical value for which complete surface dryout would occur. It is a value that is far in excess of the entire heat load, but still only about five times greater. Handy's (1975) value of 22 darcy for permeability would allow a much greater surface flux, about 10 times greater, before dryout occurs.

Figure 4 shows how the ideal moisture retention distribution, assuming uniform hydraulic properties, compares with the actual neutron probe scan for Tank 105-TX. The pore-size index of 1.82 obtained from the pumping response analysis, which used the reported drainable porosity, was found

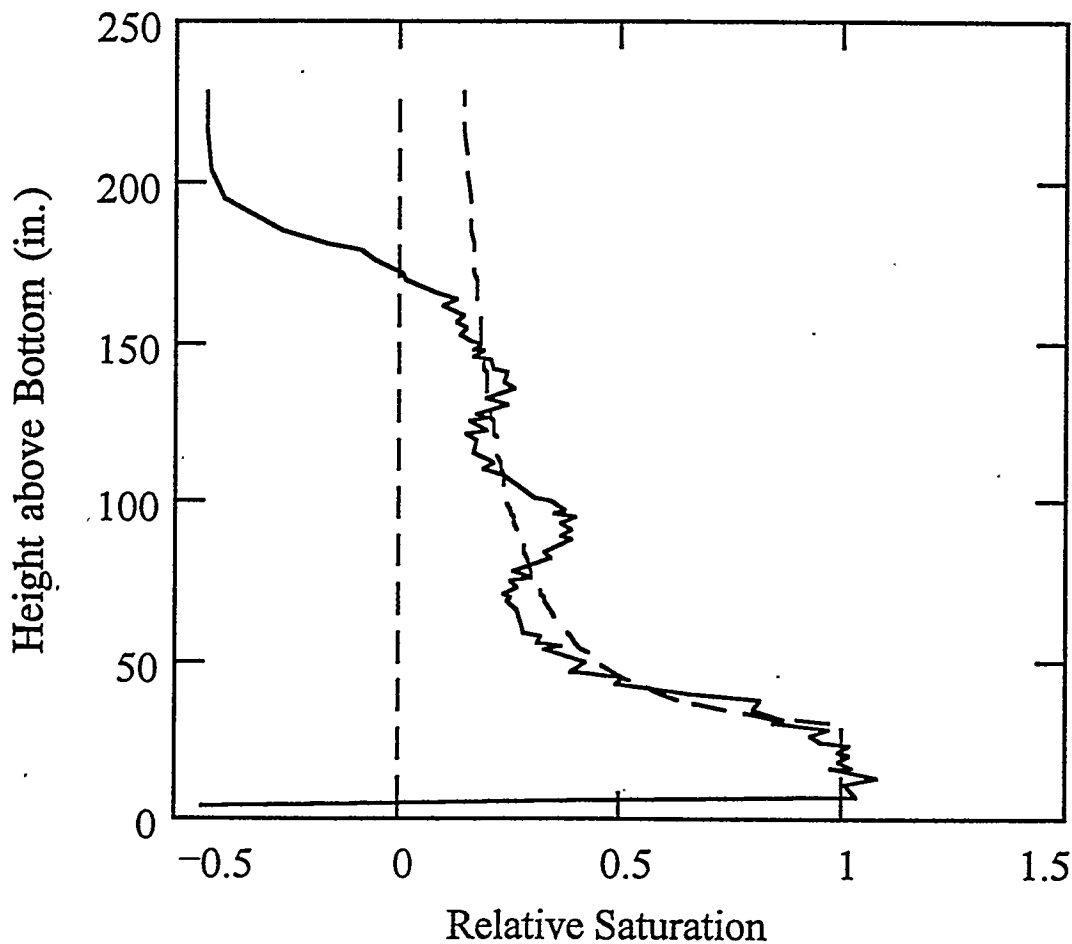


Figure 4. Moisture Profile in Tank 105-TX in Terms of Relative Saturation. Solid line curve is based on neutron counts rate using 800 count/s to correspond to 8 vol% liquid (5 wt% water), while maximum counts per second corresponds to 50 vol% porosity (20 wt% water). The dash line was determined from the pumping response using the Brooks-Corey retention model with pore-size index of 1.82. The ILL is 30 in. from the bottom and the holdup height is 6 in.

to describe the average distribution fairly well. The physical surface is about 200 in. above the tank bottom, and the neutron scan indicates that the surface is dried out to about 40 in. below the surface. However, the theoretical average retention curve indicates that moisture content remains greater than the residual value up to the surface. An interpretation of this disparity is that there may be a salt dissolution cavity (cone shaped) around the LOW near the surface.

In Figure 5, six layers with slightly different hydraulic properties were assumed to comprise the profile. The moisture content is converted to weight percent water using the same physical properties

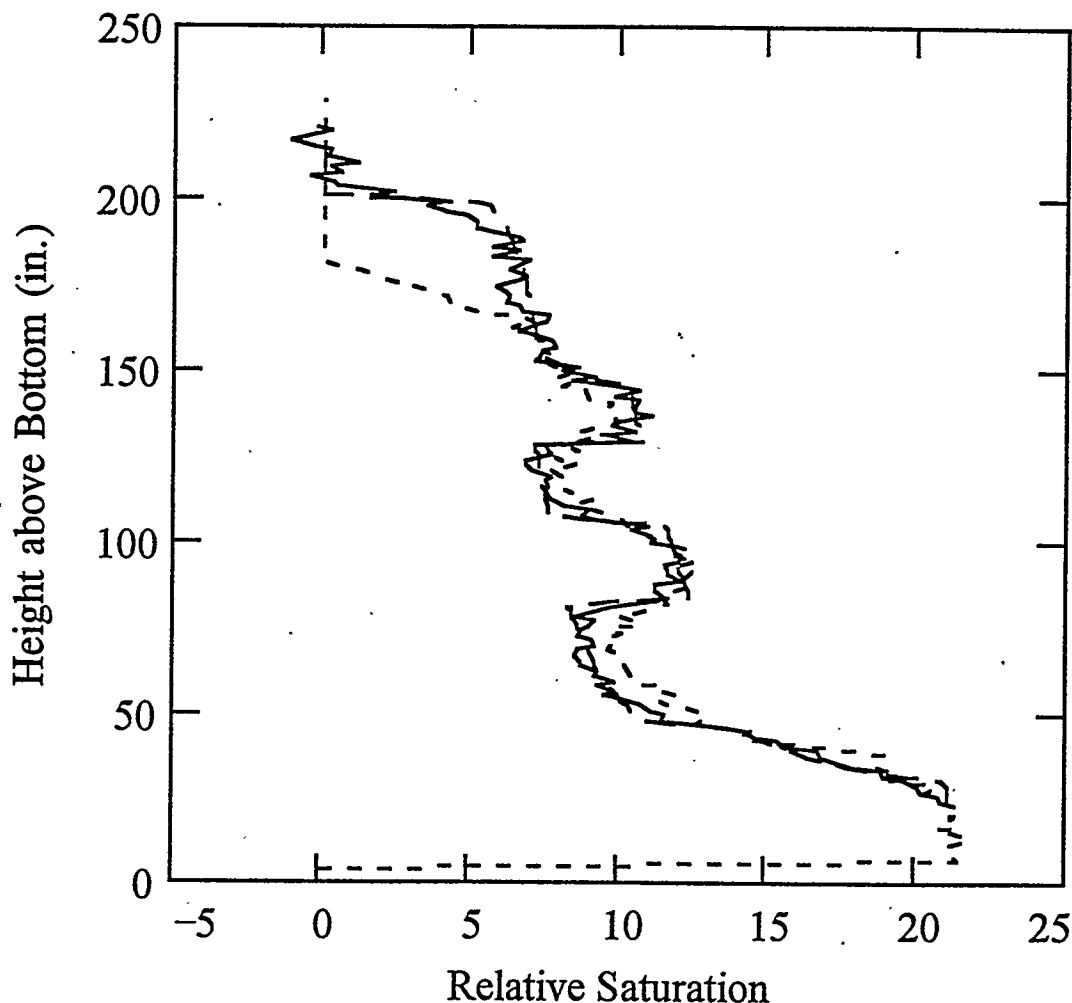


Figure 5. Moisture Profile in Tank 105-TX Based on Modeling and Neutron Counting Scan. Scan data converted to moisture weight percent is shown by dotted line. Fluctuating solid curve is the modeling result as viewed by a simulated neutron scan. The theoretical prediction of the model is the dashed curve, as determined for six different layers of saltcake. An evaporative flux equivalent to 0.17 W/m^2 of heat transfer is sustained at the surface by the steady upward flow model. Note that the actual neutron scan indicates complete drying to about 40 in. below the surface.

assumed for Tank 104-BY saltcake and liquid, as given in Figure 3. Notice that the residual moisture content is approached near the surface in this case, in contrast to the case for Tank 104-BY, which was wetter at the surface. The pattern of moisture variation that is seen over the profile, however, could also be attributed to contact anomalies between the LOW and saltcake profile, but this possibility is not known. Nevertheless, the example is a test of the model's capability for simulating a variable moisture profile.

Determining the Pore-Size Index from Pumping

This section describes how the pore-size index of the Brooks-Corey liquid retention model can be estimated from the pumping response of waste tanks. The data provided by DeWeese (1988) is used to estimate the pumping response, which is the amount of liquid withdrawn from a tank when the drop in ILL is measured. Pumping response is usually quantified as the decrease in ILL as measured in a salt well, when the waste profile is initially saturated with liquid. DeWeese (1988) used the concept of "drainable porosity" to express how much liquid by volume could be extracted from an initially saturated volume of waste.

After being pumped down to an equilibrium condition or drained, the distribution of liquid in a waste profile is determined by the capillary rise as described by a retention relation. The liquid retention relation is assumed to be given by the Brooks-Corey equation in terms of the pore-size index.

At equilibrium (static conditions), for a known height to the waste surface, as measured from the standing liquid level at $h = 0$, the integral of VLC over height, h , gives the total liquid storage, when that integral is multiplied by the tank's base area. The change in liquid storage, when an initially saturated saltcake profile is pumped down, equals the pumped liquid volume. By equating the known pumped volume to the calculated storage change given by the Brooks-Corey equation, the unknown value of the pore-size index can be estimated, provided the other retention parameters, holdup height, porosity, and residual VLC, are known.

Drainable Porosity

Tank farm waste management engineers have used the term "drainable porosity" as a relative measure of how much liquid can be removed from a waste profile when pumped. DeWeese (1988) reported on the pumpability of 26 tanks, mainly from the BY and TX Tank Farms. He used the reevaluation of drainable porosity to estimate the pumpable liquid volume expected in all tanks, as based on the known volume of waste.

In this document, drainable porosity is defined as the ratio of pumped liquid volume to the volume of waste drained. The volume of waste drained is indicated by the drop in height of the ILL, multiplied by the tank base area. Apparently, a controversy has existed for some time about what the average or representative drainable porosity is for all tanks, taken collectively. Because drainable

porosity is not the absolute porosity and depends on capillary retention, DeWeese reported a distribution of values, ranging from 12% to 52% by volume. The distribution found by DeWeese peaks at around 32% to 36%. DeWeese suggested the value of 35% as the best value to use to predict pumpable interstitial liquid volume. A value of 45%, however, has been used to administratively stabilize tanks.

Because the drainable porosity varies from tank to tank or can be assigned a range of values, this may have contributed to some confusion about what the value of absolute porosity is for typical saltcake waste. The absolute porosity determines the volume of liquid that can be held in the interstices when the porous matrix is saturated, and it is greater than the drainable porosity. Variation in the drainable porosity seen in Figure 6 reflects the fact that saltcake profiles of different tanks have different capillary retention, or different relative storage of liquid.

The original data of DeWeese included greater porosity values for Tanks 110-BY, 111-BY, and 112-BY equal to 43 vol%, 52 vol%, and 42 vol%, respectively. These values were recalculated based on subtracting the waste volume decrease with stabilization from the measured total pumped liquid amount. This was done to better estimate the pumped interstitial liquid amount for the final profile's size. The calculation removes the supernatant volume from the total pumped volume to give

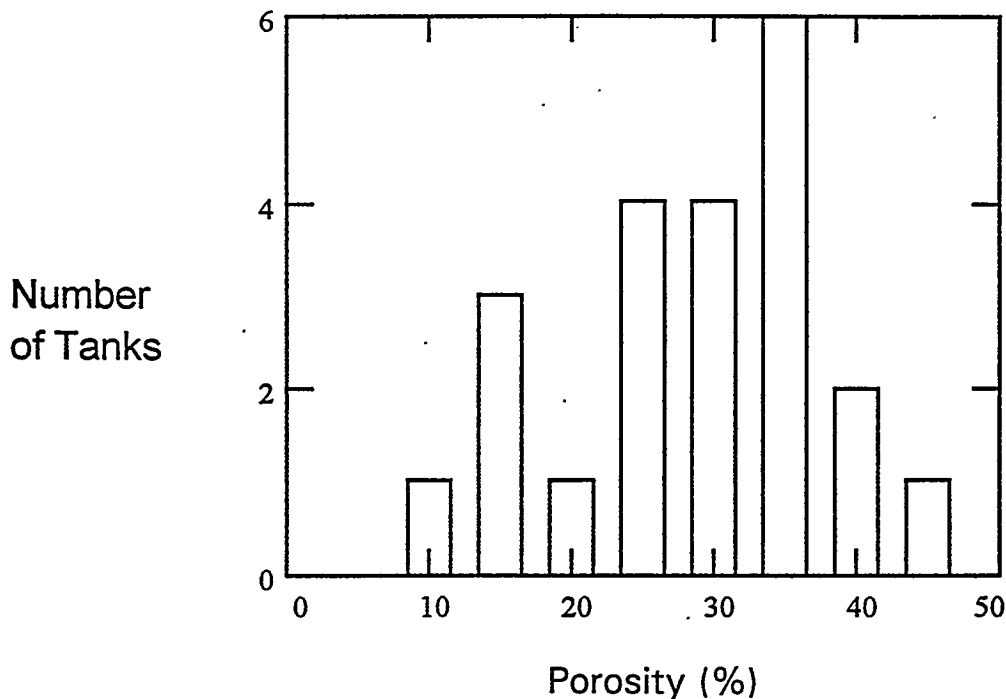


Figure 6. Drainable Porosity for Pumped Saltcake Tanks Reported by DeWeese (1988). Porosity is the ratio of the pumped interstitial liquid volume to the saltcake volume drained. The drained saltcake volume equals 2.75 kgal/in. multiplied by the decline in the interstitial liquid level (in.) as measured in a salt well.

only the interstitial contribution. The level decline was also recalculated by subtracting the actual reported liquid level from the final profile height, which is based on the summary volume of waste consistent with Hanlon (1993). This procedure decreased the estimated porosities to 42 vol%, 37 vol%, and 38 vol% for the three tanks. The estimated pumped interstitial liquid also decreased, especially for Tank 111-BY. The same calculation applied to Tanks 101-BY and 104-BY did not substantially alter the estimates, so the original values were kept.

When pumped down, the liquid level decline from a saturated condition to a stabilized equilibrium moisture distribution was correlated with the waste profile depth, as shown in Figure 7. The profile depth should usually be greater than the liquid level decline, as seen in the figure.

As seen in Figure 8, the saltcake tanks separate into two groups for the pumping response. The regression estimates of drainable porosity for each group, 43 vol% and 45.5 vol%, based on slope, are about the same, however. These values probably reflect the absolute porosity, however, rather than the variable values suggested in Figure 1. The line intercept for liquid level decline for zero amounts of pumped liquid are different for each group, as seen in Figure 8. Note that these lines should not be extrapolated to a zero liquid level decline, below the range of measurements.

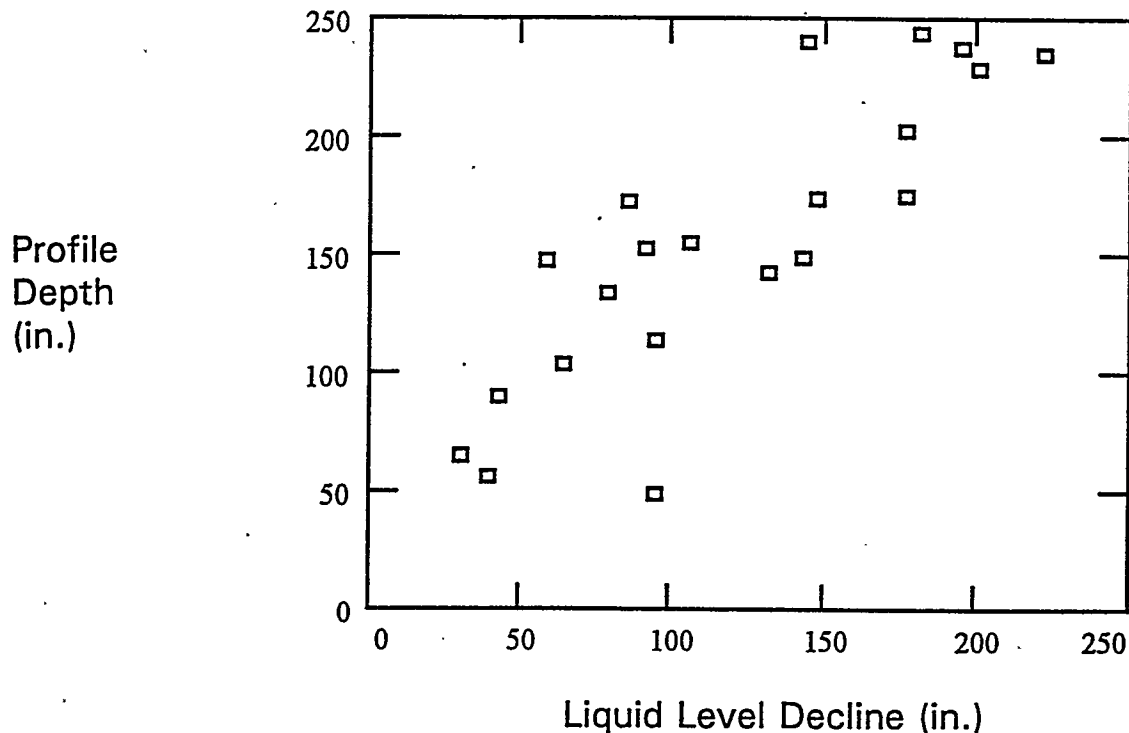


Figure 7. Correlation Between Saltcake Profile Depth and Liquid Level Decline after Pumping of Interstitial Liquid from a Tank. Profile depth is determined from sludge and saltcake summary waste volumes reported by DeWeese (1988). Correlation coefficient is 0.857.

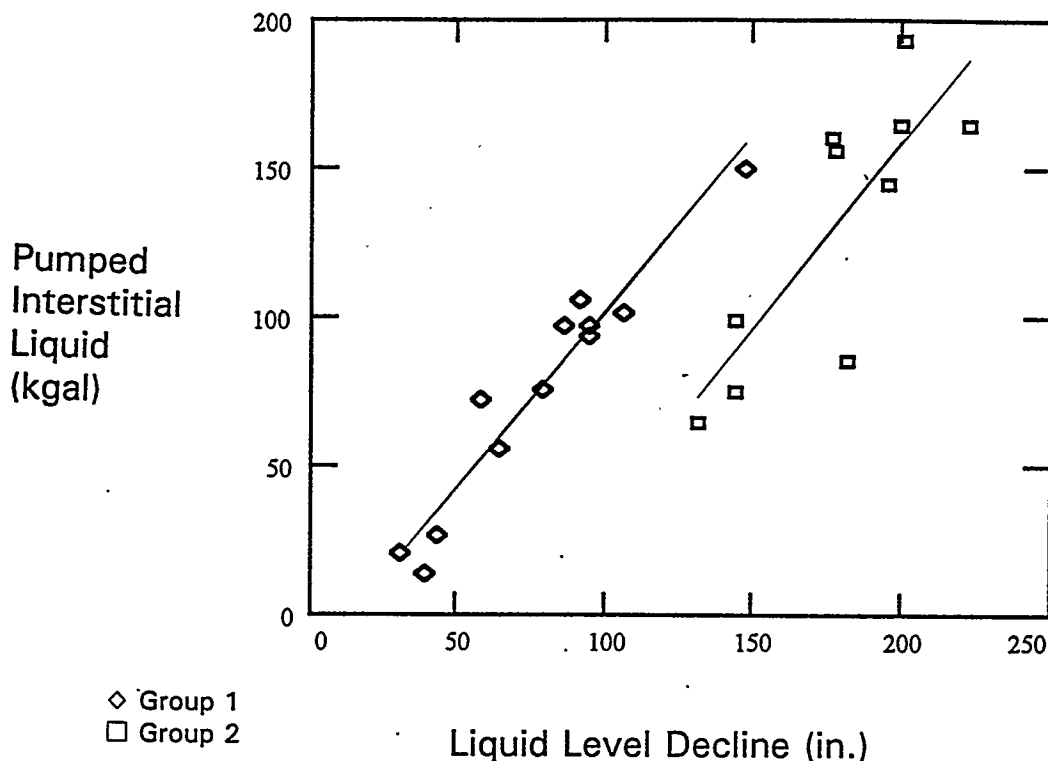


Figure 8. Pumped Interstitial Liquid for Two Tank Groups. Estimated drainable porosity is the slope of each line divided by 2.75 kgal/in. Values for porosity are 43 vol% (group 1) and 45.5 vol% (group 2). Group 2 is associated with greater interstitial liquid declines between 130 and 220 in. These are tanks with greater profile depth, see Figure 7. Correlation coefficients are 0.968 and 0.813.

Using a common set of parameters within each group, Figure 9 demonstrates the correlation of the model-estimated pumped interstitial liquid with the actual amount. For a distinct set of parameters for each saltcake profile, the match can be made exact. But then the absolute porosity and pore-size index must change for each tank. In actuality, the absolute porosity and residual liquid content for each tank are not known and they vary.

Figure 10 provides the final water retention curves for the two groups. Interpretation of these curves is further explained in the following text. Surface moisture is given in Figure 11, based on Figure 10.

Surface Moisture Content

Typical estimates of weight percent water in saltcake waste profiles are provided in Figure 10. There are two curves shown corresponding to two distinct tank groups that appear to exhibit different retention behavior when stabilized by pumping down the ILL. The curves give the weight percent

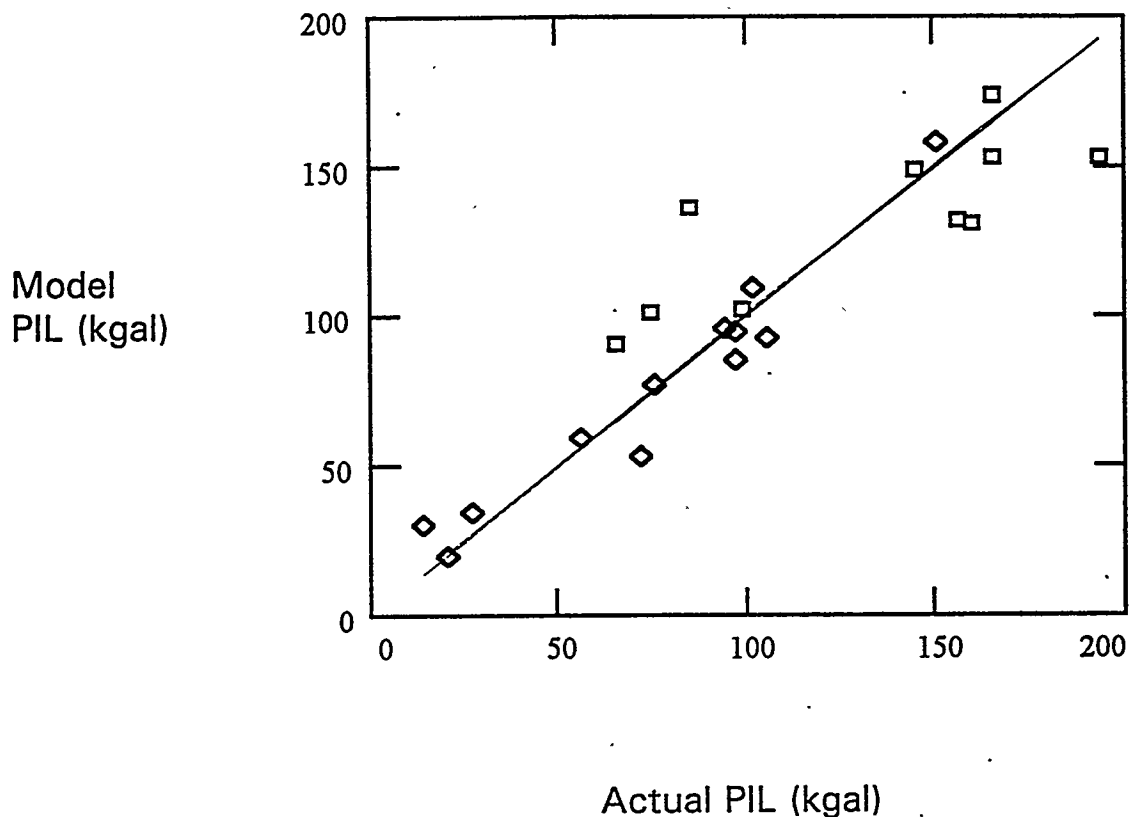


Figure 9. Model Estimated Pumped Interstitial Liquid (PIL) Compared with the Actual. Model pumped interstitial liquid is based on the Brooks-Corey retention curve for capillary holdup in the waste profile. Change in the interstitial liquid storage from the saturated profile condition to the equilibrium drained condition after pumping determines the pumped interstitial liquid amount. Correlation coefficients are 0.967 and 0.812 for groups 1 and 2.

water associated with a specific height above the standing liquid level in a salt well. Stabilized tanks have been pumped down to the maximum amount possible. Less completely pumped tanks would have smaller liquid level declines from the surface, thereby leaving the surface at a greater weight percent water content corresponding to smaller height above a tank's ILL. Figure 11 shows that surface moisture decreases with higher profiles (greater depth to liquid level).

In the first group of waste profiles in Figure 11, which mainly correspond to a smaller liquid level decline, the moisture content reaches a residual value above about 20 in. or 25 in. (A neutron scanner would detect this transition in moisture content with height.) The second tank group does not display an abrupt transition and remains much wetter near the surface. These later tanks when drained, however, have much deeper profiles. More interstitial liquid is pumped from this second group; the liquid level decline is no less than about 120 in. (see Figure 8). The first group has no more than about a 150-in. liquid level decline. Liquid level decline is correlated with profile depth as shown in Figure 7. In fact, the profile depth must be greater than level decline.

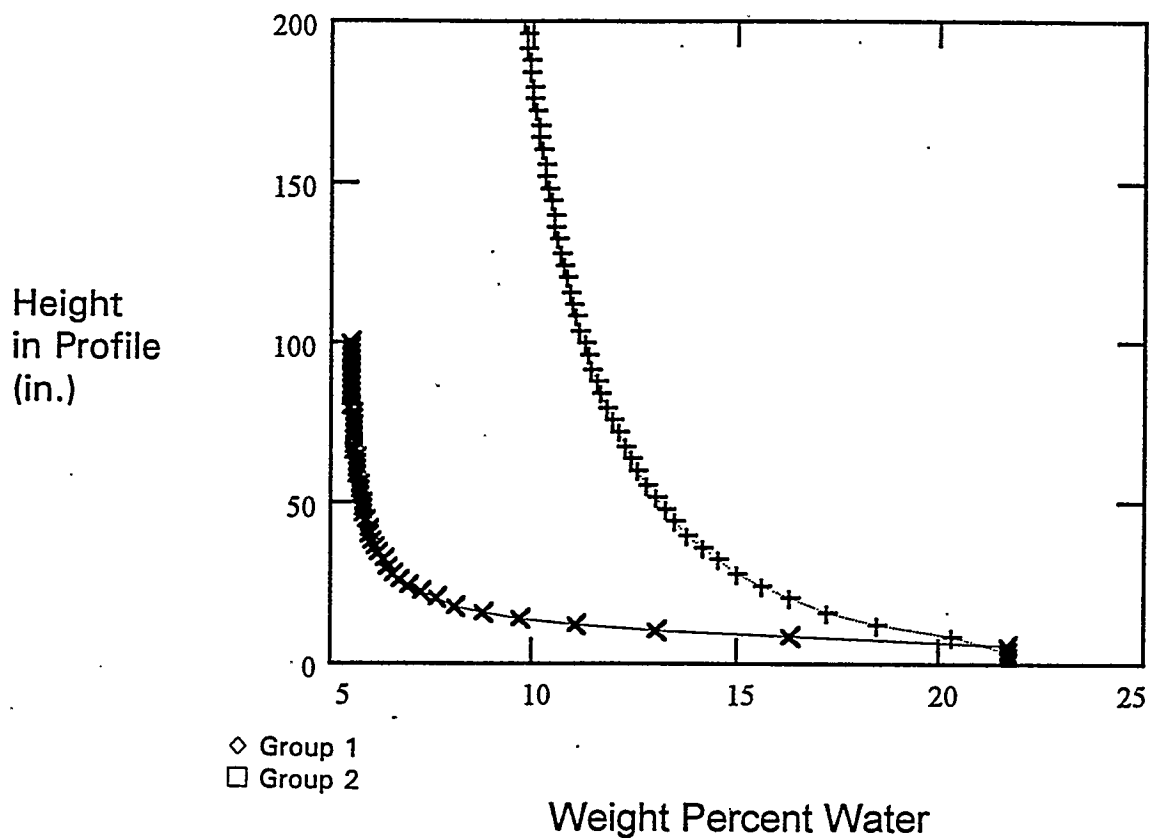


Figure 10. Moisture Retention in the Profiles of Drained Saltcake Waste Tanks. Height in profile is measured above the standing liquid level in a salt well. Pore-size index for the Brooks-Corey curve equals 0.5 (group 1) and 2.14 (group 2). An absolute porosity of 50 vol% and a residual weight percent moisture of 5 wt% (8 vol%) are used. The capillary holdup is 6 in. (Handy 1975) for both tank groups. To convert volumetric liquid content to weight percent water, salt grain density of 2.1 g/cc and liquid density of 1.5 g/cc with 52 wt% water in supernatant are used.

How well the capillary retention model in Figure 10 fits the pumped interstitial liquid amounts compared with actual measurements is shown in Figure 9. The model is based on using a best-fit set of parameters for each of the two tank groups. In actuality, each tank's saltcake profile would have its own set of retention parameters, and each tank would potentially have a distinct curve similar to that shown in Figure 10.

The capillary holdup of 6 in. was used to obtain Figure 10. Values of 12 in. of holdup in the capillary fringe could be applied to some tank profiles, however, depending on the assumed absolute porosity. Absolute porosity of 40 vol% to 60 vol% could be accepted for various saltcake profiles. The implication of this is unknown, but it may reflect considerable interstitial structural differences about the average between saltcake profiles.

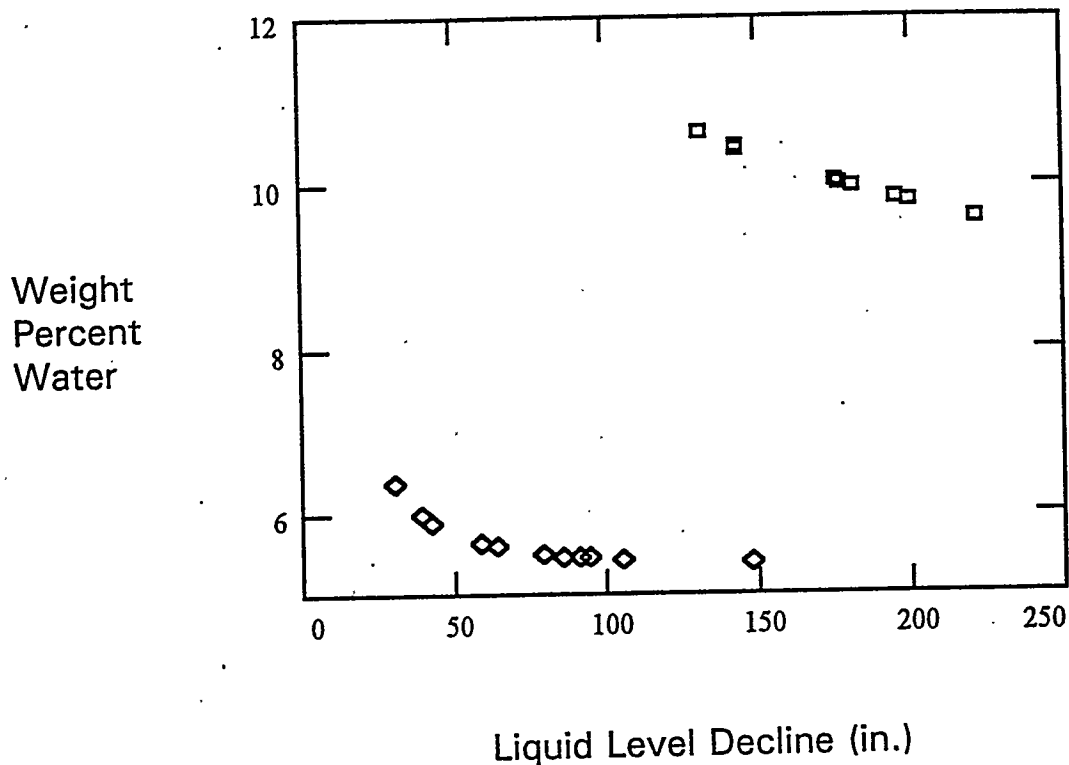


Figure 11. Weight Percent Moisture at the Surface of Each Stabilized Tank with the Retention Parameters of the Two Groups

The conversion of VLC to actual water content held in the interstices would be accomplished with specific information about salt grain crystal density and liquid density, when used along with the weight percent water in the salt-saturated brine. The correct absolute porosity is also needed to make an accurate conversion from volume percent liquid to weight percent water for specific saltcake waste.

Estimation Procedure Limitations

This model has three main limitations. First, this estimation procedure should be used with caution when used to find the pore-size index. The model is simplified and does not address vertical layered heterogeneity, although in principle it could. Each saltcake layer would have a different set of retention parameters. This produces a fluctuation in the retention curve with height above the ILL. Second, moisture associated with water chemically bound to the salt matrix is not taken into account. This water must be included also. Third, the model is entirely based on capillarity, although matched effectively to actual measurements. Nonisothermal evaporation and adsorption of moisture on hygroscopic salts could make the estimates inaccurate.

Two Tank Groups

Table 1 gives the exact pore-size index that produces the estimated pumped interstitial liquid amount for each tank. An absolute porosity of 50 vol% and holdup height of 6 in. were assumed. Recall that drainable porosity is the pumped interstitial liquid divided by the level decline multiplied by 2.75 kgal/in. In a few cases, the absolute porosity must be increased to yield a solution for the pore-size index. Then, the different absolute porosity used is indicated in parentheses. The model gives the pumped interstitial liquid as the difference between the initial liquid storage in the saturated profile and the final storage, as given by the Brooks-Corey capillary retention curve.

Generally, an increase in the holdup height would decrease the pore-size index, corresponding to a steeper decline in moisture retention with height. Increasing the value of absolute porosity would generally increase the pore-size index, for a fixed holdup.

The value of the pore-size index for group 1 is 0.51 and 2.14 for group 2. These values define the retention curves in Figure 5 and the surface moisture content in Figure 6. Forcing common values of the pore-size index in each group gives the deviation shown in Figure 9. Values in Table 1, however, give an exact match to actual pumped interstitial liquid for each tank. Note that the pore-size index generally increases as drainable porosity decreases.

Conclusions about Estimation Accuracy

The consequence for the two groups is that nearly residual moisture at the surface is attained following stabilization for the first group, whereas the second retains about 10 wt% on the average. However, the fact that most tanks in group 1 have a large layer of saltcake over sludge (BY tanks) suggests that substantial pumped interstitial liquid may come from the consolidated sludge when the saltcake overburden increases, as a result of decreased buoyancy of the salt matrix. In other words, the pumped interstitial liquid derived from the saltcake profile may be over estimated, so that a greater liquid storage decrease in the saltcake is required to account for the pumped liquid.

This possibility is supported by Tank 101-BY, which falls in group 2. In the original data given by DeWeese, the amount of sludge did not decrease with pumping in Tank 101-BY, whereas it did for the other BY tanks. In this case, apparently, all pumped liquid was derived from the saltcake; the retention curve appeared to be like that obtained for the purely saltcake profiles of TX tanks.

Possibly, the model must be made more complex to account for the liquid expelled below from the sludge into the saltcake through consolidation caused by pumping. An inferred retention curve for the entirely saltcake containing TX tanks is probably a more accurate description of saltcake retention behavior.

Thus, it should not be concluded that BY tanks are actually drier at the surface than TX tanks. More likely, the result that tanks fall into two groups of retention behavior suggests that sludge or saltcake consolidation plays an important part. In particular, if the larger pore-size index value of group 2 were applied to the BY tanks, thus giving a smaller predicted storage change or pumped interstitial liquid, then the additional liquid storage change following stabilization would have to come

Table 1. Pore-Size Index for an Exact Match of the Pumped Interstitial Liquid Amount

Tank	Drainable Porosity (%)	Level Decline (in.)	Pore-Size Index
Group 1			
104-BY	34	106	0.774
107-BY	32	64	0.713
108-BY	23	43	1.14
110-BY	42	92	0.389 (55%)
111-BY	37	147	0.741
112-BY	38	94	0.409
102-TX	36	95	0.60
103-TX	25	31	0.637
106-TX	41	86	0.466 (55%)
108-TX	13	39	2.561
109-TX	45	58	0.234 (60%)
118-TX	35	79	0.588
Note: Usually, tanks with a pore-size index less than 1 are in the first group. The tanks listed in group 1 with indexes greater than 1 likely should belong to group 2 or could be included in the group 2 regressions.			
Group 2			
101-BY	19	144	3.49
105-TX	30	200	1.82
110-TX	32	177	1.46
111-TX	18	131	3.62
112-TX	17	182	4.53
113-TX	35	201	1.17
114-TX	33	176	1.33
115-TX	25	144	2.25
116-TX	27	195	2.24
117-TX	27	222	2.37

from the sludge profile to account for the actual total pumped interstitial liquid. At this time, however, the data are not sufficient to confirm the hypothesis that consolidation of sludge or saltcake is causing the group distinction in the retention curves.

DeWeese and originally Kirk (1980) attributed 12.5 vol% drainable porosity to sludge. This value is used to estimate in Kirk's empirical model the expected pumpable liquid from the initial histogram volumes of tank waste types. That model also assumes a 2-ft capillary holdup for 66 kgal of undrainable liquid held in a sludge profile, provided the sludge profile height is larger than the holdup. The capillary holdup in sludge is generally known to be an order of magnitude greater than this holdup value. Therefore, if sludge contributes to the pumped interstitial liquid, it is likely via the mechanism of consolidation caused by either a saltcake overburden or the sludge's self-weight. The 12.5 vol% used in Kirk's model likely constitutes an average fraction of liquid loss from sludge when undergoing consolidation in typical tanks. Drainable porosities obtained for entirely sludge profiles show much smaller values, supporting the fact that sludge does not readily drain by gravity alone. Thus, incorporating the process of consolidation is necessary to estimate the pumpability of waste profiles having a saltcake layered over sludge.

Surface Dryness Sensitivity

This section examines how sensitive the model's predictions of surface moisture content are to hydraulic properties and evaporative flux. Figure 12a shows the surface moisture content as weight percent water depending on the evaporative flux and the height of the saltcake waste profile. The surface moisture content is predicted by the steady upward flow model, while assuming a waste profile with uniform hydraulic properties. The graphical floor shown in Figure 12a is the domain of flux and depth (or profile height) values for which the waste's top dries out to the minimum residual level of 5 wt%. Figure 12a shows that dryout occurs when the evaporative flux and the depth are together sufficiently large. Typical hydraulic parameters of 22 darcy for permeability and pore-size index of 2.1 are assumed to describe the waste profile.

Figure 12b provides a more quantitative description of when surface dryout will occur. The curves shown in Figure 12b are slices of the graphical surface shown in Figure 12a for particular values of evaporative flux. Evaporative fluxes of 0.1 W/m², 0.3 W/m², and 2 W/m² were selected. The middle value is about in the range expected to apply for water evaporation driven by the thermal gradient near the surface of typical tank waste. According to the curves, which begin to diverge when the depth becomes greater than 100 in., the surface does not dry out for only 0.1 W/m² of evaporative flux but certainly does for 2 W/m², a value having the magnitude of a tank's entire surface heat load.

When the saltcake permeability is reduced to 2 darcy, with the same pore-size index, the domain of dryout (floor region) is greater, as seen in Figure 13a. Figure 13b shows that the surface would dry out for a profile depth approaching 150 in. for an evaporative flux of only 0.1 W/m². Recall that a permeability of 2 darcy is the minimum value estimated for a laboratory simulant of saltcake.

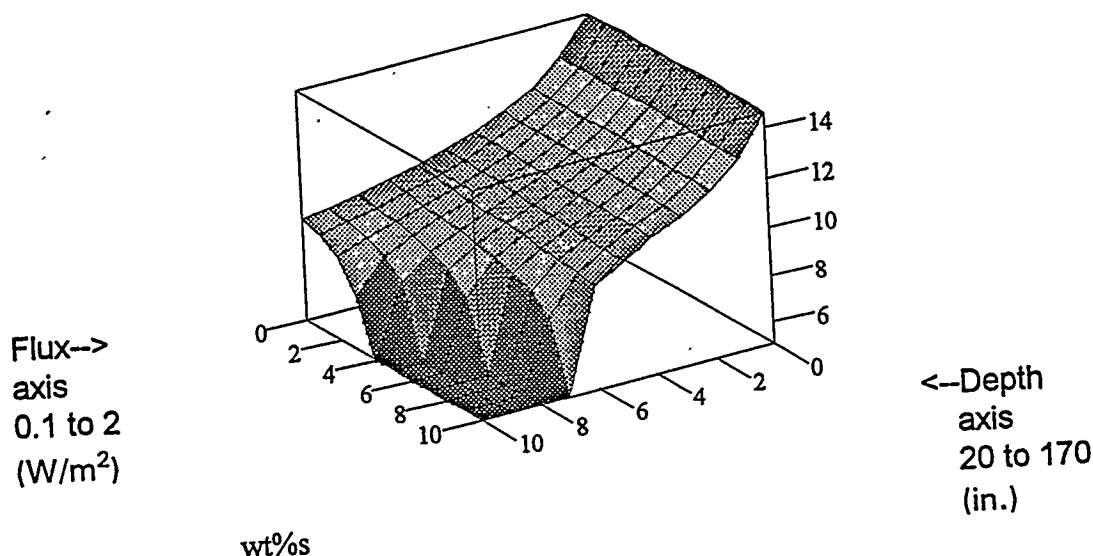


Figure 12a. Surface Moisture Content for Permeability of 22 darcy and Pore-Size Index of 2.1

Figures 14 and 15 demonstrate that dryout of surface moisture is very sensitive to the pore-size index, which describes how well moisture is retained by capillarity in a saltcake waste profile. These figures are based on the 22 darcy permeability value. For a smaller pore-size index of 1.5, a waste surface of sufficient height will dry out for the entire range of evaporative flux. On the other hand, Figure 14 shows that the surface will resist drying out if the profile depth to the ILL is less than 50 in. In contrast, Figure 1b shows that the waste surface would not dry out for depths less than 100 in. when the pore-size index is 2.1. For a larger pore-size index of 3, as found for some of the pumping responses of TX tanks, Figure 15 shows that profiles as high as 170 in. would not be dried out for the full range of evaporative fluxes.

These sensitivity results show that the surface moisture content is very dependent on the specific values of permeability and pore-size index that characterize the saltcake waste. However, as could be expected based on intuition, the surface can remain moist if the profile depth is sufficiently small, regardless of large evaporative flux. Clearly, to make better estimates of waste surface moisture, a better estimate of the unknown evaporative flux is required. More advanced modeling of water vapor flow under nonisothermal conditions will be required to pin down the relevant evaporative flux.

Remediation of Surface Moisture

By using modeling of moisture in saltcake, the effect of adding interstitial liquid to the surface of the waste can be estimated. By application of a sufficient brine flow rate to the surface, countering the drying influence of gravitational drainage and evaporation should be possible.

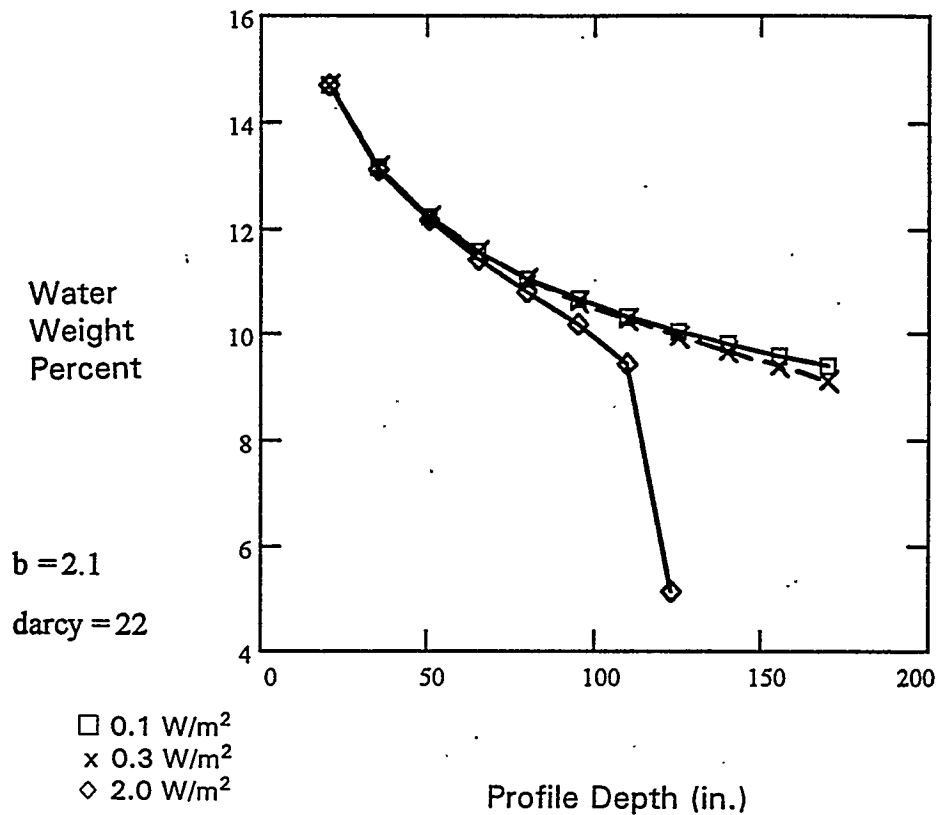


Figure 12b. Surface Moisture Content as Weight Percent Water Depending on Evaporative Flux. Pore-size index is 2.1 and permeability is 22 darcy.

Figure 16 demonstrates the result of applying a steady brine flow rate to the surface of waste in Tank 104-BY, as an example. The input flux was taken as one-tenth of the saturated liquid conductivity of the saltcake. The model shows an increased moisture content in the different layers of salt that compose the waste profile. Near the surface, weight percent water is increased from 10 wt% to more than 15 wt%, relative to the present moisture estimates (dot curve) based on a neutron scan. Note that the flow is equivalent to about 460 W/m² of water vapor condensation (applied). In contrast, the greatest evaporation possible based on the entire tank heat load is about 3.6 W/m² (removed). Thus, a substantially greater input of liquid flow is required to rewet the surface and counter the moisture profile caused by drainage.

How the surface moisture content generally responds to steady input of the brine liquid, which is 52 wt% water, is shown in Figure 17. A homogeneous saltcake profile is assumed in this calculation of the response surface as shown. Note that a 22 darcy permeability is assumed, so that the surface does not rewet as much as for the 2.2 darcy permeability used in Figure 16. For a shallower interstitial liquid level, less liquid needs to be input to increase the surface water weight percent, when compared with Figure 12a, in which evaporation reduces the surface moisture content.

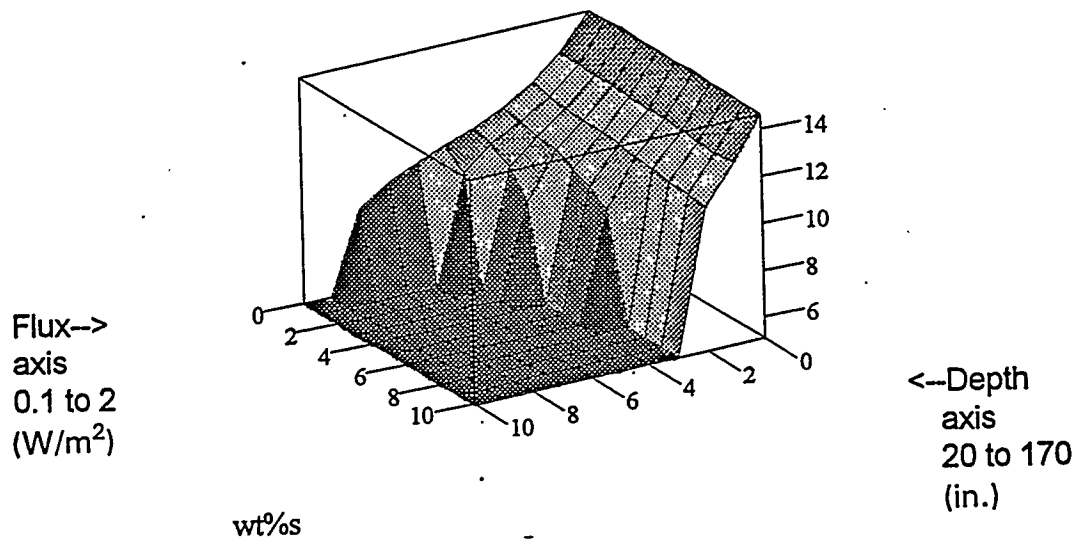


Figure 13a. Surface Moisture Content for Permeability of 2 darcy and Pore-Size Index of 2.1

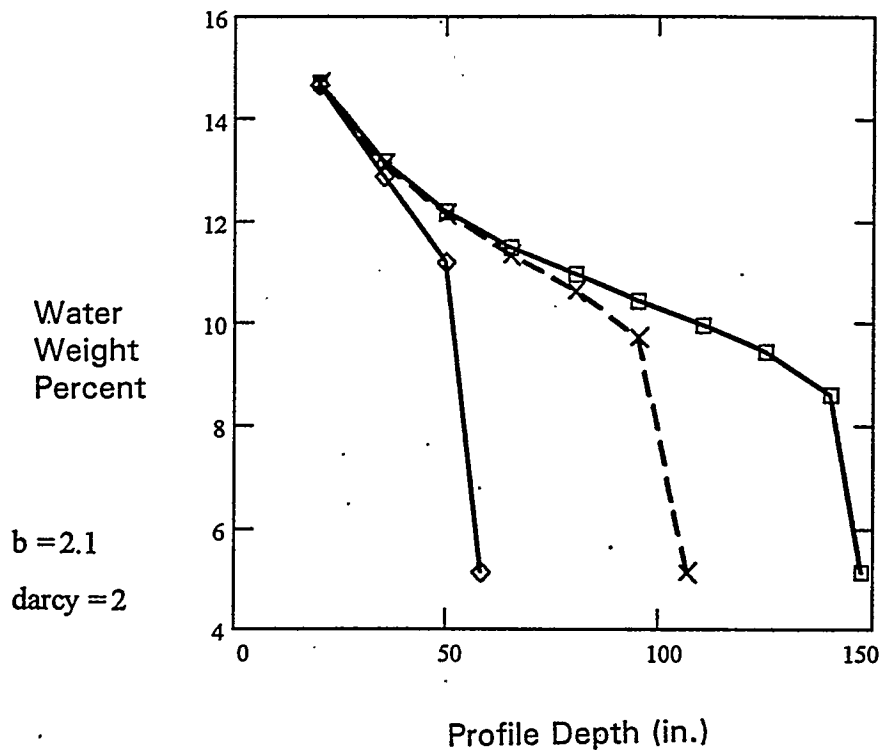


Figure 13b. Surface Moisture Content as Weight Percent Water for Permeability of 2 darcy and Pore-Size Index of 2.1

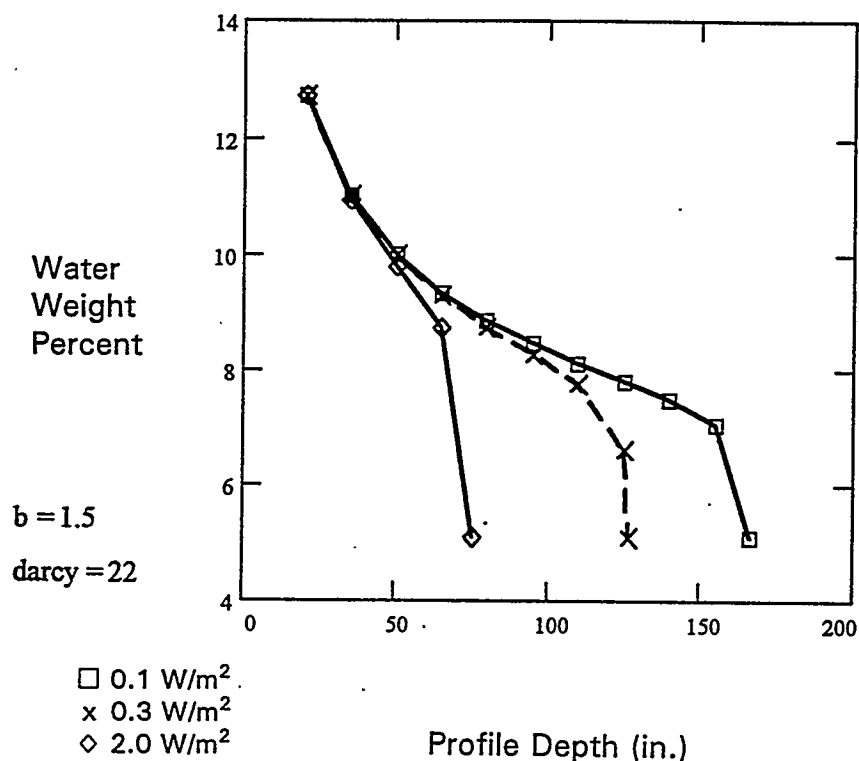


Figure 14. Surface Moisture Content for Evaporative Flux with Pore-Size Index Reduced to 1.5

Figure 18 shows that a sufficient brine liquid application rate will raise the surface moisture content even in a high drained profile. For application of 20 W/m² of condensation, the moisture content remains above 12 wt% for profiles up to 170 in. high.

These results represent steady-state flow through an entire waste profile. A more efficient way to rewet the surface while using less liquid would be to apply flux intermittently. Only after the preceding liquid pulse had drained and redistributed downward, then another pulse would be applied. However, modeling this moisture control tactic would require simulation of dynamic infiltration fronts. The present simplified steady-state model cannot describe the resulting complex pattern of downward liquid movement. A more general simulation model would be needed to engineer a more efficient water application sequence.

Modeling Limitations

The model represents only a first step in connecting evaporation with interstitial liquid flow controlled by capillarity. Liquid flow and water vapor movement in the unsaturated zone under nonisothermal conditions in the waste profile still need to be fully coupled to accurately assess the potential for dryout. The possibility of deliquescence near the cooler surface is not taken into account. This hygroscopic phenomenon depends on the extent of lowering the saturation vapor pressure by the particular salt composition near the surface.

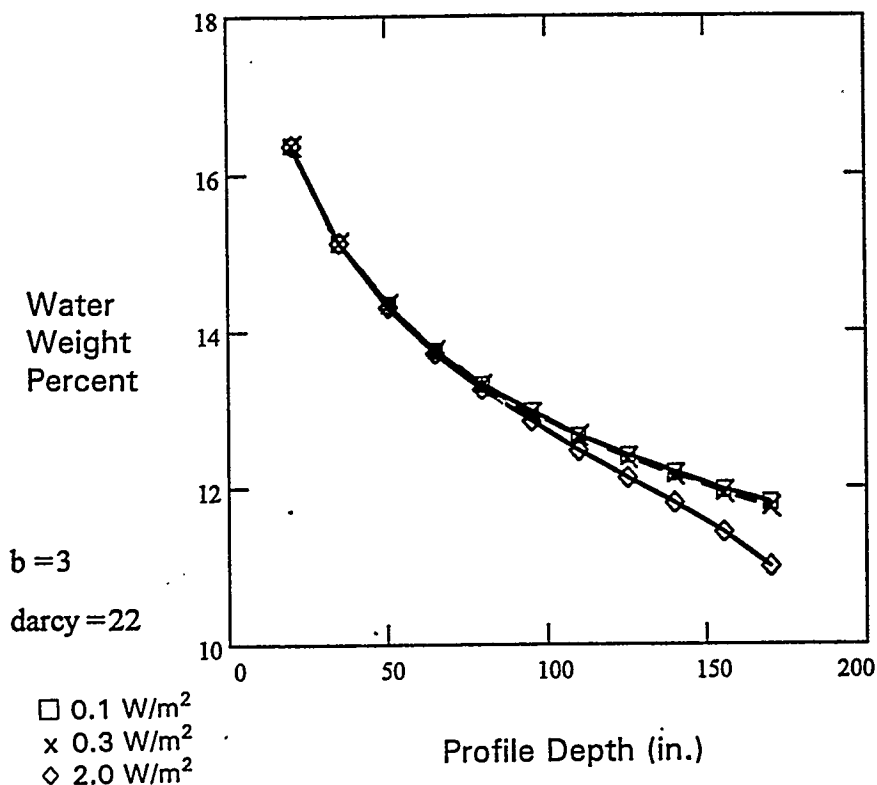


Figure 15. Surface Moisture Content for Evaporative Flux with Pore-Size Index Increased to 3

Depending on the thermal gradient in the profile, upward vapor flow may nearly balance a downward flow of liquid driven by gravity. Thus, the excess liquid condensed near the surface may produce a net downward liquid flow. This behavior would tend to increase moisture content near the surface over that of the static equilibrium condition. The present model cannot examine that possibility until more complete and correct physics is incorporated as described by Nassar and Horton (1989). Also better estimates of the hydraulic parameters and the water vapor pressure's dependence on the salt composition of the waste would be required.

Also, as the liquid flows either up or down, depending on the hydraulic and thermal gradients acting, dissolved salts will be transported. This salt migration if substantial would affect the porous matrix structure over time. A relatively small change in pore-size distribution can drastically influence the hydraulic properties and the moisture retention behavior. This aspect of the problem deserves consideration too. An experimental study under controlled laboratory conditions may be necessary to accurately determine the magnitude of these mechanisms that would move both water and dissolved salt when subjected to a thermal gradient.

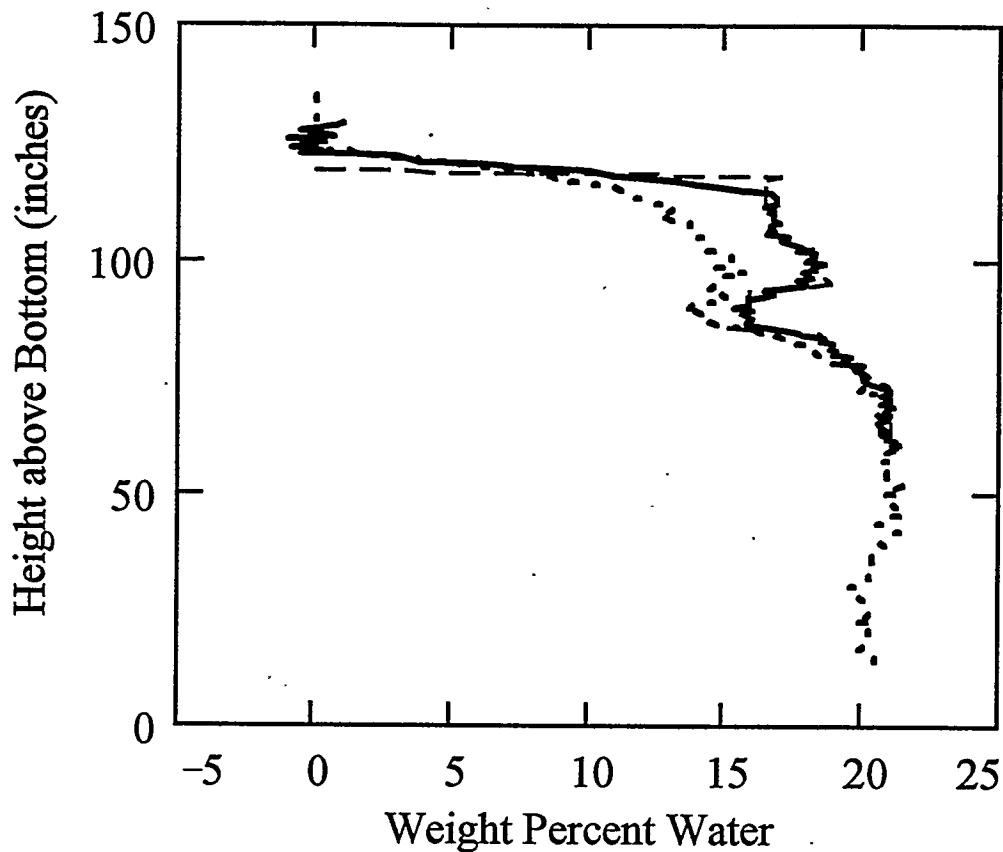


Figure 16. Moisture Content Profile in Tank BY-104 Under Steady Input of Brine Liquid. Input flux is one tenth of the saturated liquid conductivity, which is 2.5 E-4 cm/s for permeability of 2.2 darcy. Liquid flow is equivalent to 3.1 g/day/cm^2 , or $12,700 \text{ kg/day}$ over the waste surface area. Hydraulic properties for the saltcake profile given in Figure 3 are used in the simulation.

Conclusions

A simplified model was developed for calculating the moisture distribution in a saltcake waste profile that has been stabilized by removing all drainable liquid. The model is simplified because it neglects nonisothermal vapor flow, neglects the possible movement of dissolved saltcake, and is one dimensional. The basic physical properties and hydraulic parameters required to estimate the moisture content in a saltcake waste profile are identified for waste characterization purposes. Model parameters can be found by matching its prediction of the moisture distribution to the relative saturation determined from neutron probe scanning measurements.

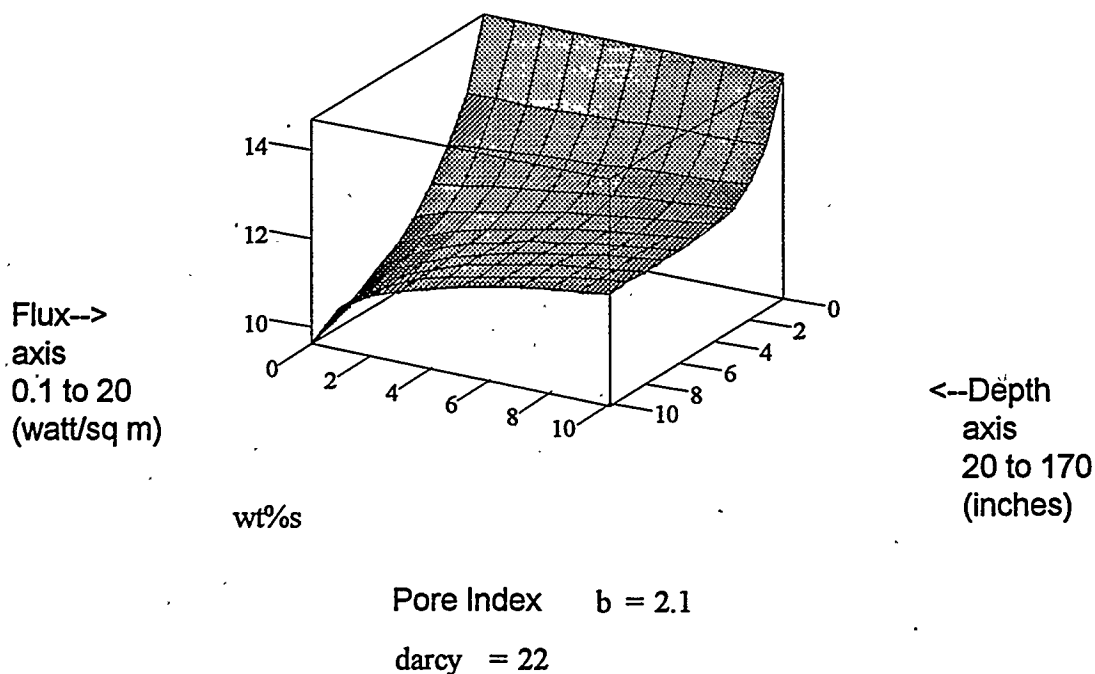


Figure 17. Weight Percent Moisture Content at the Waste Surface Under Steady Brine Liquid Input Conditions. Liquid flux is given in terms of equivalent water vapor latent heat transfer. Flux of 20 W/m^2 of heat transfer is equivalent to a brine liquid flow of about 550 kg/day passing into the entire waste surface area. Assumed brine liquid density is 1.43 g/cc with 52 wt\% water.

The model can be used best to determine how great an evaporative flux can be maintained at the waste surface without causing dryout to occur. Precise values for the surface moisture content, however, cannot be determined without taking into account vapor movement. A more advanced model is required to account for vapor movement in the waste profile.

Applied to Tanks 104-BY and 105-TX, the model showed that the surface of saltcake in Tank 104-BY would have about 12 wt\% water content, whereas that of Tank 105-TX would be dried to the residual of 5 wt\% . The height of the saltcake profile appears to be the primary variable determining whether surface dryout will occur for given hydraulic parameter values.

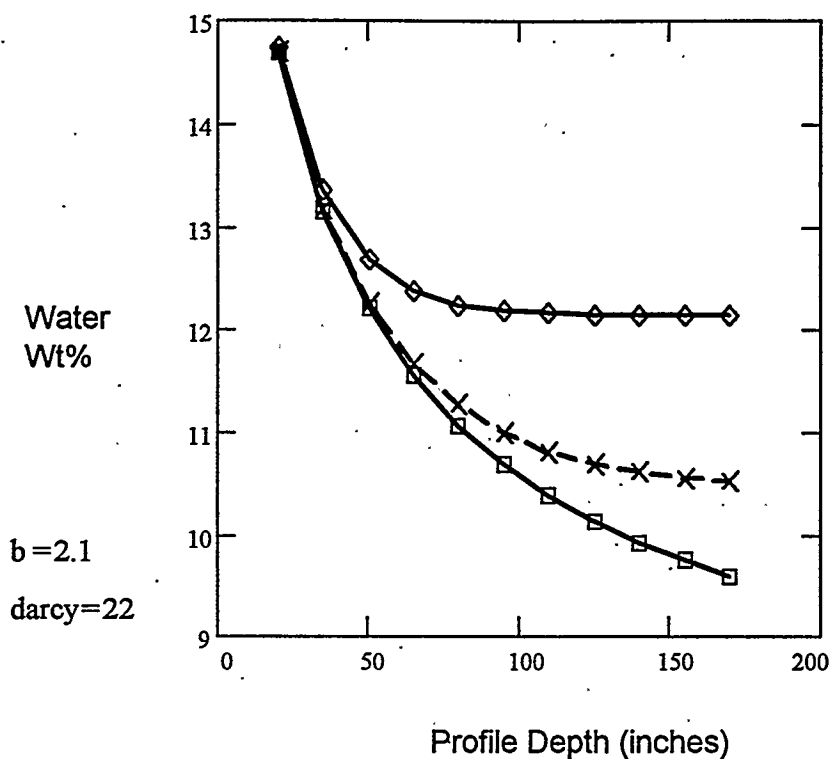


Figure 18. Surface Moisture Content in a Tank with a Homogeneous Saltcake Profile Under Conditions of Steady Liquid Input. Input flux is 0.1 W/m^2 (squares), 2 W/m^2 (X), and 20 W/m^2 (diamonds) of water vapor transfer. Equivalent brine liquid flows, respectively, are 3 kg/day, 60 kg/day, and 550 kg/day into the tank waste surface area of 410 m^2 . Profile depth is the depth from the surface to the interstitial liquid level.

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Appendix A

Steady Upward Unsaturated Flow in a Layered Porous Profile

Darcy's Law

The permeability of a porous medium is $k = (Q/A) \mu L / \Delta P$
where

Q is flow rate or discharge rate (cm^3/s)

A is flow area (cm^2)

L is flow length (cm)

P is pressure (atmospheres)

μ is liquid viscosity (centipoise)

and

$q = Q/A$ is specific discharge rate or Darcy velocity (cm/s).

Permeability is expressed in units of darcies. A permeability of 1 darcy produces a specific discharge of 1 cm/sec for a liquid with 1 cP of viscosity under a hydraulic gradient, $\Delta P/L$, of 1 atm/cm . Permeability is equivalent to a flow area of 10^{-8} cm^2 in cgs units.

For pressure expressed in terms of liquid head, h , Darcy's law becomes

$$q = - (k \rho g / \mu) \Delta h / L$$

where

$K = k \rho g / \mu$ is the liquid's hydraulic conductivity (cm/sec)

ρ is liquid density (g/cm^3)

g is acceleration of gravity, 980 cm/s^2

h is liquid height (cm)

μ is liquid viscosity (centipoise) for 1 poise = 1 dyne-sec/cm^2

If pressure is expressed in terms of water head, h_w , then

$$\Delta P 10^{+6} = \rho_w g \Delta h_w = \rho g \Delta h$$

and the hydraulic conductivity, K_w , is based on the water density, ρ_w .

Note that the hydraulic conductivity, using pure water, can not be determined for a soluble porous medium such as saltcake. A saltcake-saturated solution must be used to find K . This is because pure water would dissolve the pore structure and change the intrinsic permeability, k .

Unsaturated Flow

By taking into account the total hydraulic potential, which equals the sum of the matric and gravitational potential, Darcy's law becomes

$$q = -K (dh/dz + 1) = -K_w (dh_w/dz + \rho/\rho_w) \quad (A.1)$$

Here q is positive for upward flow with the vertical coordinate, z , as positive when downward.

For unsaturated flow, h is the matric suction head, which is the height of liquid that can be held up against gravity by capillarity in a porous matrix. Matric suction head is the capillary pressure divided by the weight density, ρg , of the liquid, and it is a positive (non-negative) quantity above the reference point where the liquid pressure equals the atmospheric pressure. Suction head is also the negative of the liquid's local matric potential energy per unit weight. By this convention, h would be negative when corresponding to positive hydrostatic pressure in the saturated zone below the reference point.

In the unsaturated state, the matric suction, h , and liquid conductivity, K , are functions of the local volumetric liquid content, θ . A conventional constitutive relationship between h , K and θ is the Brooks-Corey model for the unsaturated hydraulic properties:

$$h = h_s \cdot S^{-b} \quad K = K_s \cdot S^\beta \quad (A.2)$$

where S is the relative degree saturation defined by

$$S = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (A.3)$$

Here the subscripts "s" and "r" refer to saturated and residual liquid content, respectively. The liquid conductivity vanishes at residual liquid content and capillary pore flow ceases. Parameters of the model are the holdup height, h_s , the saturated conductivity, K_s , and the pore-size index, b . Ideally, $\beta = 2b + 3$, by a capillary pore flow theory (Campbell 1985).

Using equations (A.1) and (A.2), Darcy's law for flow can be expressed entirely in terms of the variable h . The conductivity employed in equation (A.1) is

$$K(h) = K_s \cdot \left(\frac{h_s}{h} \right)^C \quad \text{for} \quad h \geq h_s \quad (A.4)$$

and K equals K_s otherwise, when h is less than h_s , and where $C = 2 + 3/b$.

For steady, upward flow conditions, q is a nonnegative constant, and the porous region is $z > 0$ below the surface at $z = 0$. Using equation (A.4) substituted into equation (A.1), the solution for $h(z)$, within a part of the profile where the model parameters remain the same, i.e., a layer, is given by integration:

$$Z_0 - Z = \int_{h_0}^h \frac{1}{\left(\frac{R}{Kr(h)} + 1\right)} dh \quad (A.5)$$

for $R = q/K_s$, where $Kr(h) = K(h)/K_s$ is the relative conductivity; Z_0 is a reference depth for a specified h_0 .

Equation (A.5) determines h implicitly as a function of z . Once $h(z)$ is calculated, it is substituted into the liquid retention relation of (A.2) to determine S at each depth and the θ profile.

Heterogeneous Layered Profiles

Let

$$Zf(h, h_0, a) = \int_{h_0}^h \frac{1}{\left(\frac{R}{Kr(h)} + 1\right)} dh \quad (A.6)$$

where $a = (R, b, h_s)$ is the set of model parameters for each material layer. Starting at the profile bottom with the first layer, the value of h_1 at the top of that first layer is determined by

$$Z_0 - Z_1 = Zf(h_1, h_0, a_1)$$

where the layer thickness is

$$\delta Z_1 = Z_0 - Z_1 \quad \text{and} \quad \delta Z_i = Z_{i-1} - Z_i \quad (\text{layer } i).$$

The sequence of solutions to the top of each layer is found by repeating the calculation:

$$\delta Z_i = Zf(h_i, h_{i-1}, a_i) \quad (A.7)$$

The profile for $h(z)$ within each layer is then found by solving for each z up to Z_i

$$(Z_{i-1} - z) = Zf(h(z), h_{i-1}, a_i) \quad (A.8)$$

A complication to solving equation (A.7) is that h becomes infinite if a layer is too thick to sustain the given flux q . For certain functions $Kr(h)$, the integral (A.6) can be calculated as an analytical expression. However, in general, the integral must be obtained numerically for the Brooks-Corey model (A.2). Also, the integral (A.6) is difficult to calculate because h may vary over many orders of magnitude.

A transformation of variable is used to facilitate calculation of equation (A.6). Let $\eta = \ln(h)$. Then

$$q = (-1) \cdot J(\eta) \cdot \left(\frac{d}{dz} \eta + e^{-\eta} \right) \quad (A.9)$$

where

$$\begin{aligned} J(\eta) &= J_s \cdot \exp[-\lambda(\eta - \eta_s)] & \eta \geq \eta_s \\ J(\eta) &= K_s \cdot e^{\eta} & \eta < \eta_s \end{aligned} \quad (A.10)$$

with $\lambda = C - 1$ and

$$J_s = K_s \cdot e^{\eta_s} \quad \eta_s = \ln(h_s)$$

Expressed in terms of the transformed variable η , the integral of equations (A.5) or (A.6) becomes

$$Zf(\eta, \eta_o, a) = \int_{\eta_o}^{\eta} \frac{1}{\left(\frac{q}{J(\eta)} + e^{-\eta} \right)} d\eta \quad (A.11)$$

where

$$\eta_o = \ln(h_o)$$

$$\frac{q}{J(\eta)} = R \cdot \exp \left[[(\lambda + 1) \cdot \Phi(\eta - \eta_s) - 1] \cdot (\eta - \eta_s) \right] \quad (A.12)$$

with

$$R = \frac{q}{J_s} \quad \lambda = 1 + \frac{3}{b}$$

$\Phi(x)$ equals 1 when x is non-negative and equals 0 otherwise. Parameters of equation (A.11) are now $a = (R, \lambda, \eta_s)$. Note that the integral can be evaluated analytically when η becomes sufficiently large because the term $\exp(-\eta)$ vanishes relative to $R \exp(\lambda(\eta - \eta_o))$ in the integrand of equation (A.11).

For sufficiently small $\varepsilon > 0$, let η_c satisfy

$$\eta_c > \eta_s \quad \text{and} \quad \frac{e^{-\eta}}{R \cdot \exp[\lambda \cdot (\eta - \eta_s)]} \leq \varepsilon$$

when $\eta > \eta_c$ Then

$$\eta_c = \frac{\lambda \cdot \eta_s - \ln(R \cdot \varepsilon)}{\lambda + 1} \quad (\text{A.13})$$

The approximate integration of equation (A.11) is then found as

$$Zf(\eta, \eta_c, a) = \frac{1}{R \cdot \lambda} \left[\exp[-\lambda \cdot (\eta_c - \eta_s)] - \exp[-\lambda \cdot (\eta - \eta_s)] \right] \quad (\text{A.14})$$

The exact integral is between equation (A.14) and (A.14) multiplied by $1/(1+\varepsilon)$. Thus, the maximum layer thickness is given by

$$\text{Max} \delta Z = Zf(\eta_c, \eta_o, a) + Zf(\infty, \eta_c, a) \quad (\text{A.15})$$

when $\eta_c > \eta_o$

Otherwise, equation (A.14) with η_o substituted for η_c can be used to calculate equation (A.11).

For points z , less than $Z_o - \text{Max} \delta Z$, the liquid content is at the residual value. However, for z greater than $Z_o - \text{Max} \delta Z$ (i.e., below the layer surface of maximum thickness), $h(z)$ has a finite value associated with $\theta(z)$ greater than θ_r .

Moisture Content Conversion

Given the volumetric liquid content $\theta(z)$ at each profile depth z , the weight percent water is found as follows.

$$\text{Wt\%}(\theta) = \frac{P_w \cdot \rho_L \cdot \theta}{\rho_p \cdot (1 - \theta_s) + \rho_L \cdot \theta} \quad (\text{A.16})$$

where

ρ_L is liquid density

ρ_p is particle grain density

P_w is percent water in liquid

θ_s is saturated volumetric liquid content.

Note that the particle density and saturated liquid content would vary for each layer.

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