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EFFECTIVENESS OF SECONDARY LINERS IN REDUCING PHOSPHOGYPSUM STACK POST-CLOSURE LIABILITIES

FINAL REPORT

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FINAL REPORT

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PERSPECTIVE

The use of an intermediate liner in a phosphogypsum stack as a means of reducing the process water content of the stack in order to have less process water to treat when the stack is closed has been the subject of much discussion and analysis by the Process Water Technical Advisory Committee. There was never any doubt that there were advantages to utilizing this technique but it was obvious that the extent of the advantages would be site-specific and that the water balance at each site would be the primary factor in determining how well this approach worked. With the installation of an intermediate liner there is a significant increase in the volume of water that must be handled and unless the plant had a negative water balance before the installation, provisions would have to be made to handle this extra water that would be draining from the stack from under the liner. Under these conditions it is essential that the situation at each stack be analyzed in detail before a liner is installed to insure that the plant operation is not impaired.

G. Michael Lloyd, Jr.
Director of Research Programs

ABSTRACT

Active phosphogypsum stacks are almost entirely saturated with acidic process water. In fact, approximately half of the pore water entrained within the gypsum stack is in “temporary storage” and will eventually drain once the stack is closed. Closure of a typical phosphogypsum stack requires consumption and/or management and treatment of approximately 4 billion gallons of drainable pore water. The objective of this research study was to evaluate the potential effectiveness of secondary liners in reducing costs and environmental liabilities related to treatment of post-closure phosphogypsum stack pore water drainage. In particular, a secondary liner could potentially enable the plant to consume drainable pore water from the lower “capped” portion of the stack during active operation of the upper stack above the secondary liner. Preliminary estimates had suggested that the reduction in process water treatment costs, via partial consumption of the stack pore water during plant operation, and the corresponding savings exceeded construction costs associated with incorporating a secondary liner at mid-height of the stack.

The use of secondary liners, installed when a gypsum stack achieves a height greater than mid-height of the stack and preferably when the stack rises to a higher elevation corresponding to two-thirds the design height, was determined to be a planning tool or a design feature that can effectively reduce costs and environmental liabilities at terminal closure of a given facility. In order for this design feature to be cost-effective, the plant must have a negative water balance and must be capable of consuming pore water that drains from the lower “capped” portion of the stack prior to terminal closure, i.e., prior to plant shut-down.

Use of a secondary liner will increase the useful life of a stack by promoting consolidation of the *in situ* gypsum and will also provide an opportunity for the plant to recover P_2O_5 that would otherwise be lost. The quantity of post-closure drainable pore water requiring treatment will also be significantly reduced as a result. In order for the intermediate liner design feature to be cost-effective, the plant must be capable of consuming pore water that drains from beneath the secondary liner prior to terminal closure. The secondary liner, if installed when a gypsum stack rises to two-thirds the design height, is expected to yield significant savings in post-closure liabilities at unit treatment costs in the range of $15 to $25 per thousand gallons of acidic process water. At these unit rates, use of such a secondary liner on a typical stack is likely to net financial liability savings on the order of 20 to 32 million dollars (in 2006 dollars) as a direct result of the reduced quantity of process water requiring treatment after closure.

Considering P_2O_5 recovery benefits in the range of $150 to $175 per ton with 1 to 2% P_2O_5 in the pore water consumed prior to terminal closure, and using typical costs for liner system installation, cost/benefit analyses indicate that an intermediate liner installed at two-thirds the design height of the stack is likely to net cost savings on the order of 15 to 40 million dollars. A breakeven point wherein the intermediate liner will no longer be cost-effective would occur if emerging technologies lead to a reduction in the cost of treating process water to low-end range of $5 to 7 per thousand gallons.

ACKNOWLEDGEMENTS

The support and sponsorship provided by the Florida institute of Phosphate Research to conduct this investigation is gratefully acknowledged. The assistance and input received from Dr. Paul Clifford, Mr. G. Michael Lloyd and the Process Water Technical Advisory Committee are particularly appreciated.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol	Description
BGal	Billion gallons
e	Void ratio
EOC	End of Construction (i.e., when the phosphogypsum stack achieves its design height and its storage capacity for waste disposal is depleted)
ELTC	End of Long Term Care (i.e., end of 50-yr. long-term care period after closure)
gpm	Gallons per minute
G_s	Specific gravity
HDPE	High density polyethylene
k_v	Saturated vertical hydraulic conductivity
k_h	Saturated horizontal hydraulic conductivity
n	Total porosity
n_e	Effective porosity
σ_v'	Vertical effective stress
γ_d	Dry Density

INTRODUCTION AND RESEARCH OBJECTIVES

STATEMENT OF PROBLEM

Active phosphogypsum stacks are almost entirely saturated with acidic process water. For a typical overall average phosphogypsum stack *in situ* dry density of 80 to 85 lb./ft.^{3}, the entrained pore water accounts for approximately 40% of the total volume of the stack. Seepage of pore water from a closed phosphogypsum stack occurs as a result of consolidation and long-term creep settlements and by gravity drainage, resulting in a gradual lowering of the phreatic water surface within the stack, and a reduction in the phosphogypsum moisture content from saturated to field capacity conditions. The field capacity moisture content of phosphogypsum is typically on the order of half the saturated moisture content. Accordingly, approximately half of the acidic pore water entrained within the gypsum stack is in "temporary storage" since it will eventually drain once the stack is closed. Hence, closure of a typical phosphogypsum stack, having a base area on the order of 400 acres and height of about 200 feet, would require consumption and/or management and treatment of approximately 4 billion gallons of drainable pore water (even discounting infiltration through the slopes and additional pore water that will drain from the stack as a result of post-closure secondary compression or drained creep).

The rate of post-closure pore water drainage from a typical phosphogypsum stack depends on many factors, including foundation soil permeability and/or bottom liner, if any, type and number of underdrains and internal drains, if any, stack size, age and height, and the phosphogypsum permeability and drained creep characteristics. Post-closure drainage studies undertaken by Ardaman & Associates, Inc. for phosphogypsum stacks worldwide indicate typical drainage rates of approximately 500 to 2,000 gallons per minute (gpm) during the first year of closure, and overall gross average drainage rates during the first 5 years of closure on the order of 200 to 500 gallons per minute.

Depending on the plant water balance and process water storage capacity, an active facility may be able to consume process water draining from a closed phosphogypsum stack. Conversely, long-term water management (i.e., during and after final closure of a phosphogypsum stack system and upon chemical plant shut-down) will almost certainly require significant quantities of process water treatment at substantial rates. Considering a two-stage lime treatment cost ranging from $15 to $25 per thousand gallons for acidic process water, treatment costs for final closure of a typical phosphogypsum stack could exceed 60 to 100 million dollars.

Rule 62-673.640 of the Florida Administrative Code (F.A.C.) requires the owner or operator of a phosphogypsum stack system to provide the Florida Department of Environmental Protection (FDEP or Department) proof of financial responsibility for final closure and long-term care of the phosphogypsum stack system. The Department has recently promulgated significant revisions to the financial responsibility requirements of Rule 62-673. These amendments to the Rule became effective on July 2, 2005 and require including the treatment of any process water at terminal closure as a financial liability. The cost of closure and long-term care of a stack system is in fact highly dependent upon the cost of treatment of the process water inventory at the time of and after plant closure. Long-term water management (i.e., during and after final closure of a stack system and upon shut-down of the chemical plant) will, therefore, normally require water treatment at considerable expense.

STUDY OBJECTIVES

An original funding was granted by the Florida Institute of Phosphate Research (FIPR) in February 2003 to perform a limited study in order to evaluate the potential effectiveness of secondary liners in reducing costs and environmental liabilities related to treatment of post-closure phosphogypsum stack pore water drainage. The purpose of that study, funded under FIPR 03-01-180, was to preliminarily evaluate the effectiveness of a design feature that could potentially be incorporated in a phosphogypsum stack management plan to reduce costs and environmental liabilities at terminal closure. In particular, the objective was to undertake model simulations of pore water drainage from a gypsum stack that incorporates a secondary liner, installed at about mid-height of the stack (or at a higher elevation as illustrated in Figure 1), to enable plant consumption of drainable pore water from the lower "capped" portion of the stack during active operation of the upper stack above the secondary liner (i.e., provided the water balance of the active facility can accommodate management and consumption of pore water drainage from the lower stack). Preliminary estimates had suggested that the reduction in process water treatment costs, via partial consumption of the stack pore water during plant operation, and the corresponding savings exceeded construction costs associated with incorporating a secondary liner at mid-height of the stack.

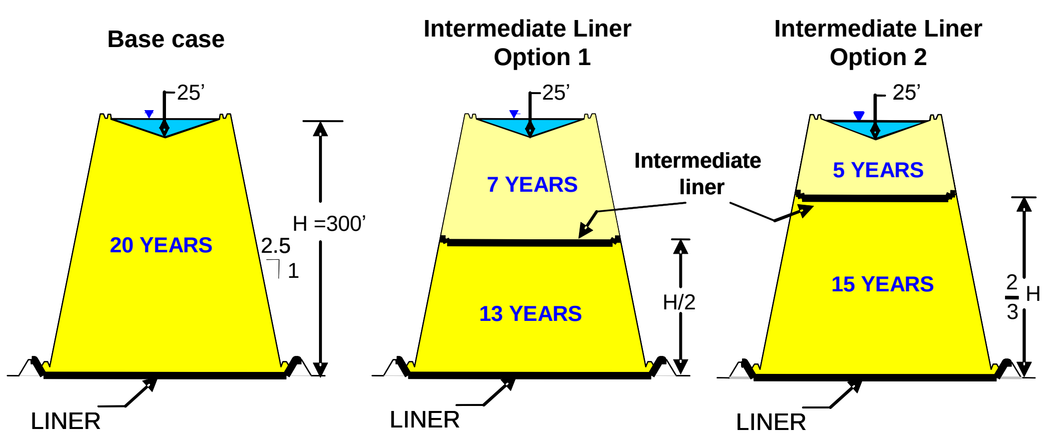


Figure 1. Installation of Intermediate Liners.

A more comprehensive study was funded by FIPR in October 2004 (FIPR 04-01-190) to evaluate the effect of specific process changes and water balance improvements on Financial Responsibility for Closure of a Phosphogypsum Stack System. The latter study was focused on reducing the volume of drainable pore water at final closure of the system by implementation of various measures, including process changes at the plant, early closure of certain portions of the facility, as well as installation of an intermediate liner on the gypsum stack as it is being raised to promote early dewatering of drainable pore water. That research study is being evaluated using results from a water balance model and stack dewatering model applied to a "typical" phosphogypsum stack system, with particular emphasis on the remaining water inventory at the end of plant life. The water balance analyses were to be performed over a 40-yr. life with differing cyclical rainfall scenarios, and with the facility transitioning from an unlined 200-ft.-high gypsum stack to a lined 300-ft.-high gypsum stack some 20 years prior to terminal closure (as illustrated by the schematics in Figure 2). Results of the study, when completed, may be used as a guide by individual chemical plants to determine site–specific measures based on site-specific water balance analyses that each individual plant can implement in order to optimize its financial responsibility requirements.

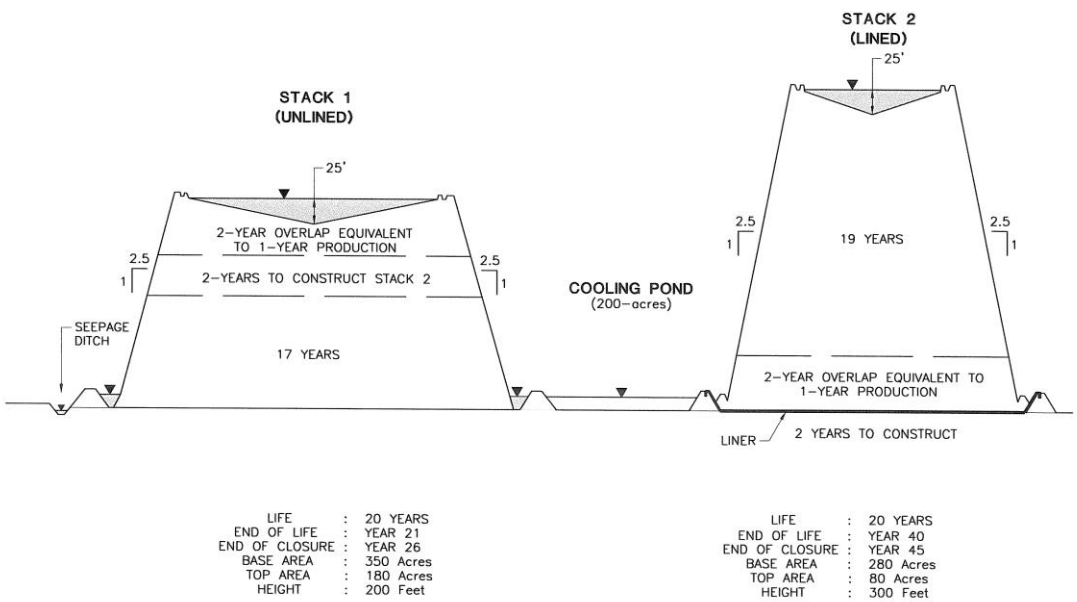


Figure 2. Model Phosphogypsum Stack System.

Because the dewatering aspects of the evaluation of FIPR Contract No. 04-01-190 titled "Study to Evaluate the Effect of Process Changes and Water Balance Improvements on Financial Responsibility for Closure of a Phosphogypsum Stack System" are directly related to the objectives of FIPR Contract No. 03-01-180 titled "Study to Evaluate the Effectiveness of Secondary Liners in Reducing Costs and Environmental Liabilities Related to Post-Closure Phosphogypsum Stack Pore Water Drainage", the dewatering results from both of these projects are combined and presented herein. It should be noted that the more comprehensive research project (FIPR 04-01-190) involved performing extensive model simulations of pore water drainage from a gypsum stack, and because that study relied in part on results from the other project (FIPR 03-01-180), the two projects were coordinated and conducted concurrently to the benefit of both research studies.

PHOSPHOGYPSUM PROPERTIES

Field and laboratory data from prior phosphogypsum stack explorations and studies conducted by Ardaman & Associates, Inc. were compiled, reviewed and evaluated for selection of representative physical properties pertinent to estimating drainable pore water volumes and drainage rate characteristics of a "typical" phosphogypsum stack in Florida.

DRY DENSITY

The range of in-situ dry density versus depth measured at 22 phosphogypsum stacks located at 16 facilities is presented in Figure 3. As shown, there is significant variability at any given depth. For example, at a depth of 40 ft., the *in situ* dry density ranges from a low of 60 lb./ft.^{3} to a high on the order of 100 lb./ft.^{3} Because the *in situ* dry density of phosphogypsum has a significant impact on water balance during the active life of the plant and on the volume of drainable water after closure of the stack, such variations in dry density could have a very significant effect on the results of cost/benefit analyses pertaining to use of secondary liners.

A significant part of the variability in measured dry densities at a given depth (say changes up to 15 lb./ft.^{3}) is a result of variations attributed to plant operations, such as:

- crystal morphology (e.g., stubby versus elongated gypsum particles, rosettes vs. individual particles, etc.)
- rock source and chemical process (e.g., hemihydrate vs. dihydrate process, etc.)
- defoaming agents (i.e., relative quantity of "black gypsum" versus light gray gypsum)
- flocculant use, if any
- entrained treatment sludges with the gypsum slurry, if any

Much of the variability, on the other hand (say up to 25 lb./ft.^{3}), is attributed to the physical characteristics and management of the phosphogypsum disposal area, including:

- design features (e.g. unlined vs. lined systems, drains, etc.)
- rate of rise and plant production history
- desiccation/saturation and wet/dry cycles
- age of stack
- height of stack
- consolidation and creep or time-dependent settlements
- closure and dewatering

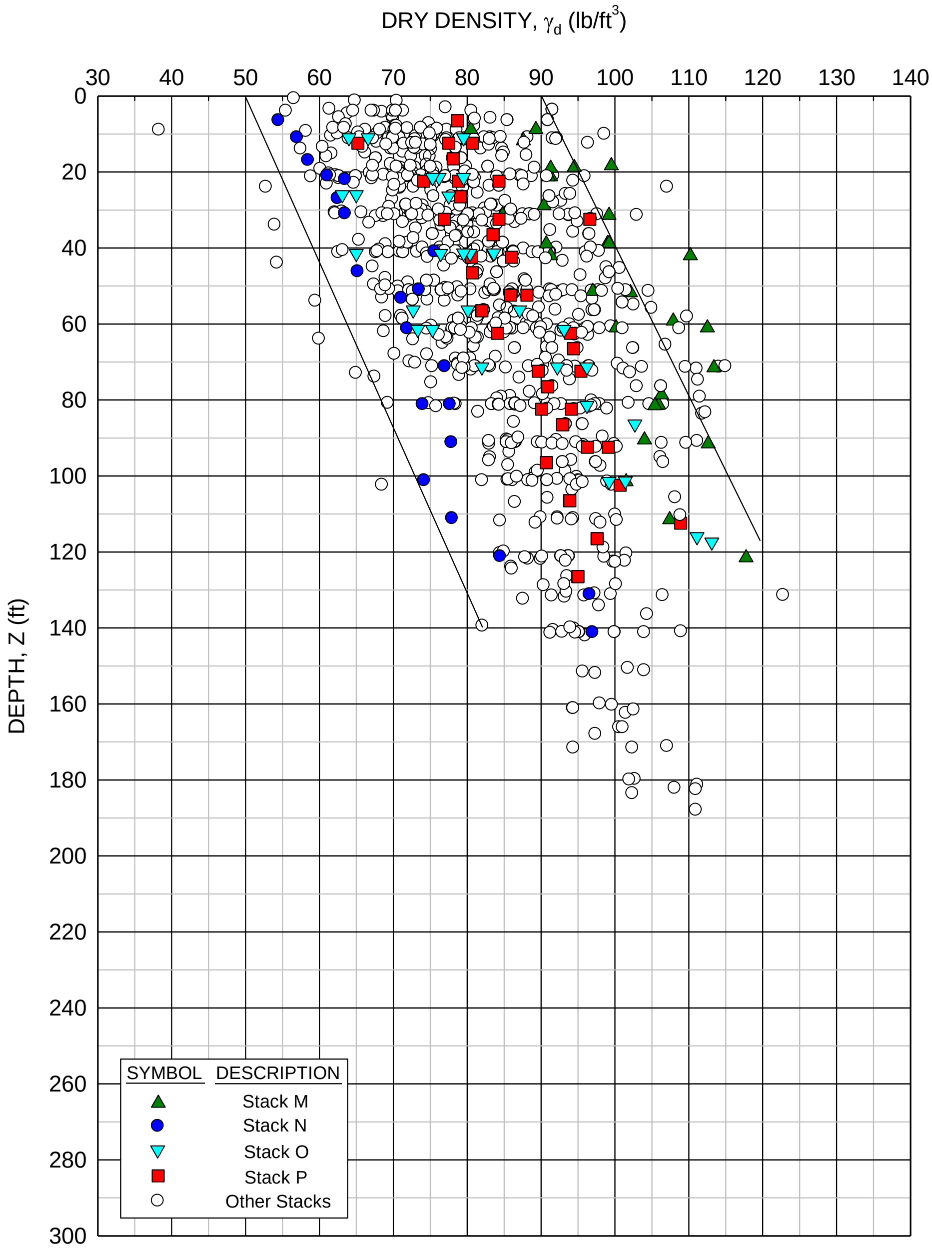


Figure 3. Range of Dry Density Versus Depth from Gypsum Industry Data.

In spite of the observed variability, there is a clear trend of increasing dry density with depth for any given stack (see Figure 3). Note also that, because of the lower effective stresses, a stack with a bottom liner is expected to exhibit somewhat lower dry densities than a stack founded on a relatively pervious foundation.

The End-of-Construction (EOC) dry density (γ_d) relationships for both the lined and unlined stacks used in the FIPR study are presented and compared to measured data in Figure 4. The "terminal" densities selected to represent ultimate post-closure conditions at the End of the Long Term Care (ELTC) period are depicted by the "upper bound" profile in Figure 4. While this "upper bound" profile was chosen in this study to conservatively represent ultimate conditions 50 years after closure, dry densities at the end of the long-term care period are probably better represented by a relationship lying somewhere between the "lower bound" and "upper bound" ELTC density profiles presented in Figure 4, i.e., with a corresponding maximum dry density somewhere between 112 lb./ft.^{3} and 120 lb./ft.^{3} In fact, it would not be unreasonable to expect the lower ELTC "terminal" density profiles to correspond to the lower EOC *in situ* dry densities.

CREEP AND STRAIN RATES

The EOC dry density relationships in Figure 4 and the rate of rise of the stack(s) in Figure 2 (considering an assumed P_2O_5 production rate of 1 million tons per year, and a gypsum/P_2O_5 ratio of 5) were used to generate a relationship between strain rate and initial void ratio. This relationship is illustrated by the red line in Figure 5. A series of power function curves were then fitted through this line at the corresponding vertical effective stress (σ'_v) to allow for modeling the creep behavior of the phosphogypsum as a function of stress level and void ratio. These relationships were used to predict the change in dry density over time and the corresponding time-dependent settlement of the stack.

HYDRAULIC CONDUCTIVITY

Measured vertical hydraulic conductivity data, k_v, on undisturbed phosphogypsum samples collected from phosphogypsum stacks located at 16 facilities are presented as a function of void ratio (e) in Figure 6. As shown, there is significant variability in the measured data. Nevertheless, the FIPR study relationships presented in Figure 6 and selected for use with void ratios greater than and less than 0.50, respectively, appear to provide reasonable fits to the measured vertical hydraulic conductivity data.

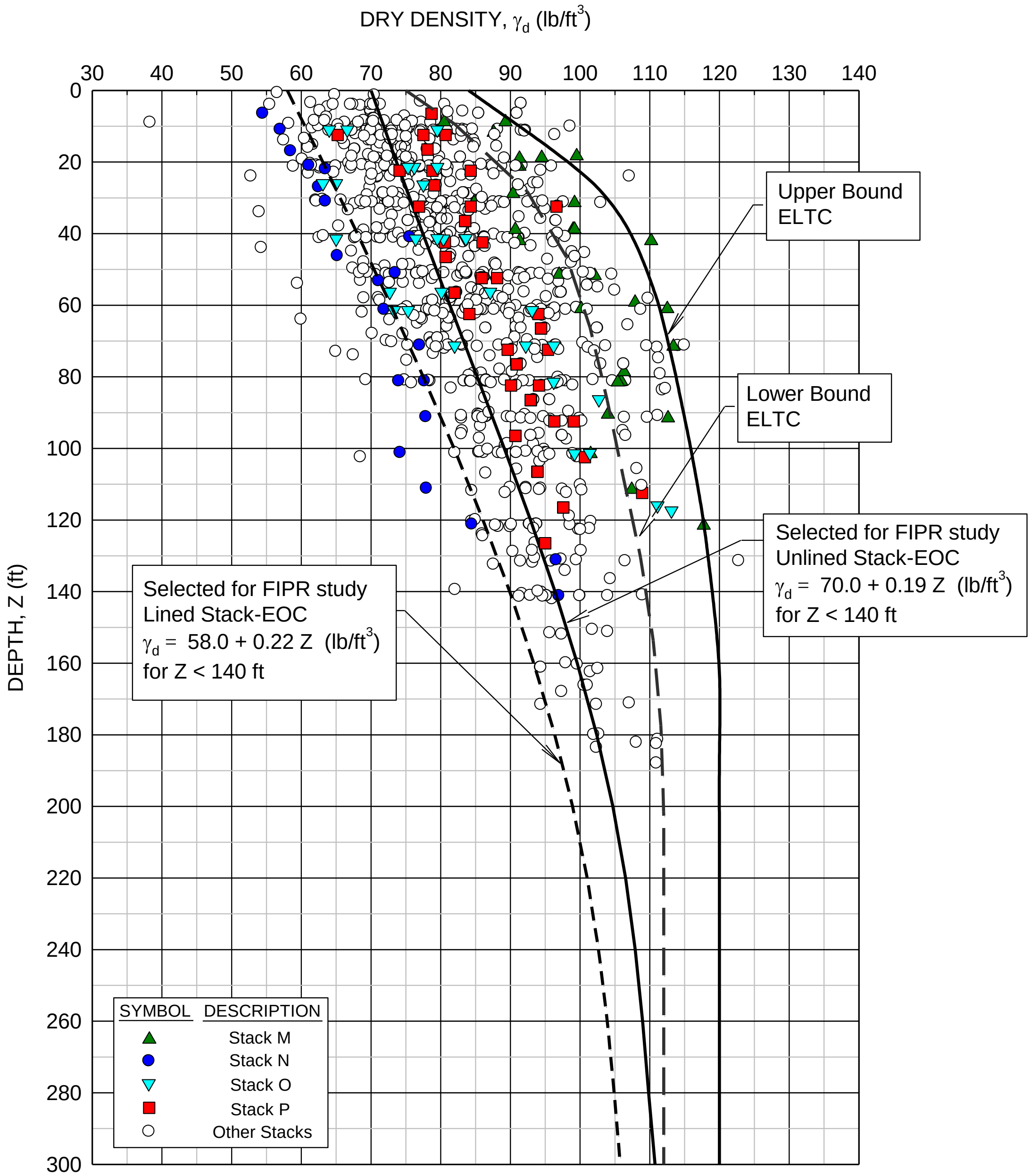


Figure 4. Dry Density Versus Depth Relationships Based on Gypsum Industry Data.

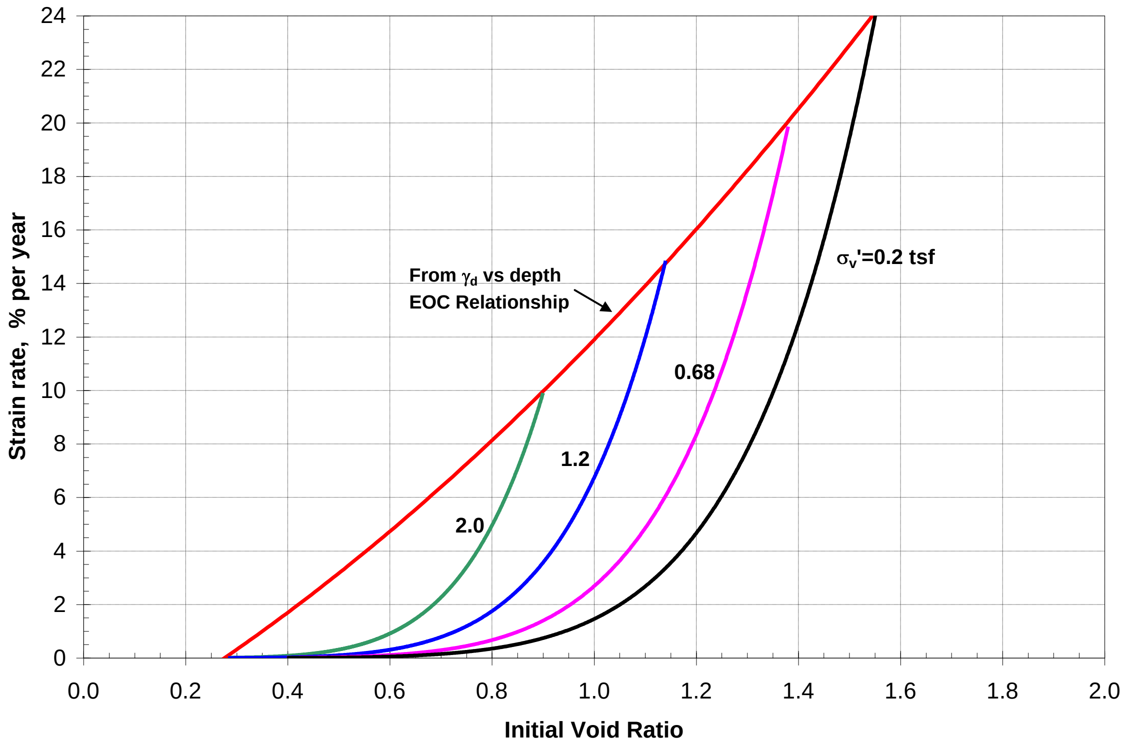


Figure 5. Creep Rate Curves.

The relationships providing a good fit to the data yield the following saturated vertical coefficients of permeability as a function of dry density:

Table 1. "Typical" Values of k_v for Different Dry Densities.

Dry Density, γ_d, lb/ft.^{3}	Vertical Hydraulic Conductivity, k_v, cm/sec
60	1.5×10^{-3}
70	5.0×10^{-4}
80	8.0×10^{-4}
90	6.0×10^{-5}
100	1.5×10^{-5}
110	3.0×10^{-6}
120	4.0×10^{-7}

Based on Ardaman & Associates, Inc.'s experience in modeling phosphogypsum stacks, the *in situ* phosphogypsum was assumed to be anisotropic with a coefficient of permeability in the horizontal direction, k_h, selected for the FIPR study to be equal to 3 times the coefficient of permeability in the vertical direction, i.e., $k_h/k_v = 3$.

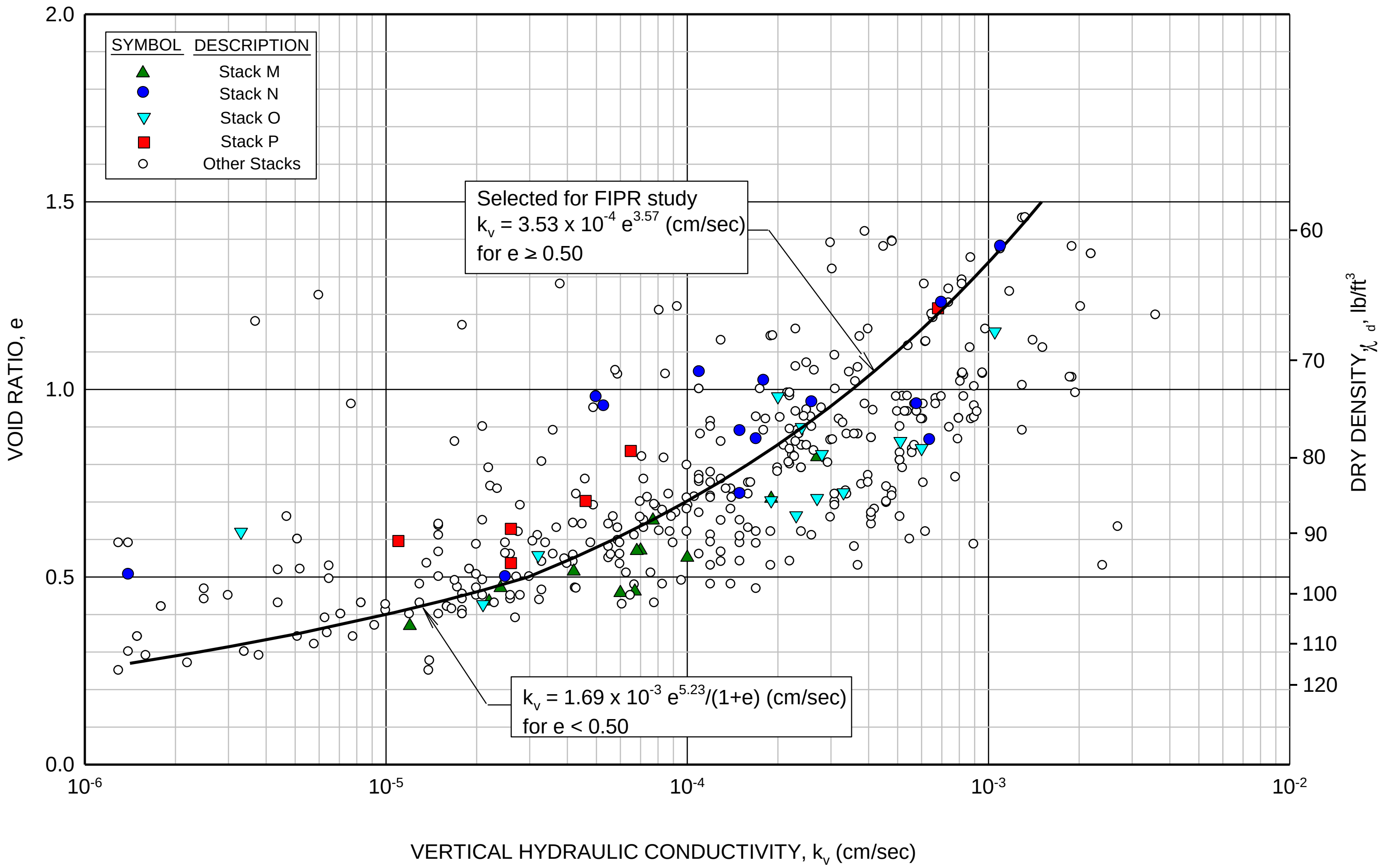


Figure 6. Hydraulic Conductivity Versus Void Ratio from Gypsum Industry Data.

EFFECTIVE POROSITY

The range of effective porosity measured on undisturbed samples of phosphogypsum from 10 stacks at 9 facilities is presented in Figure 7 as a function of dry density. As shown, although there is significant variability in the data, a representative relationship was selected for use in the FIPR study. Note that effective porosity is the drainable porosity which actually represents the fraction of the total volume of the stack that will dewater by gravity. On the other hand, total porosity represents the fraction of the total volume of the stack occupied by pore water some of which will be retained indefinitely within the gypsum mass by capillarity. As illustrated in Figure 7, as the dry density of the gypsum increases, the effective porosity relationship deviates further away from the total porosity until a lower bound effective porosity is reached at a dry density on the order of 105 lb./ft.^{3} The total and effective porosity relationships yield the following values as a function of dry density:

Table 2. "Typical" Values of Total and Drainable Porosities at Various Dry Densities.

Dry Density, γ_d, lb./ft.^{3}	Total Porosity, n	Drainable Porosity, n_e
60	0.58	0.53
70	0.52	0.36
80	0.45	0.22
90	0.38	0.13
100	0.31	0.06
110	0.24	0.04
120	0.18	0.04

Based on the above, at an average dry density of 80 lb./ft.^{3}, 45% of the volume of the stack consists of pore water, but only 22% of the total volume represents drainable pore water subject to the financial responsibility requirements of Rule 62-673. At a much higher dry density of 100 lb./ft.^{3}, 31% of the volume of the stack consists of pore water and only 6% of the total volume represents drainable pore water. Such reduced drainable pore water volume can represent a considerable favorable improvement in post-closure liability.

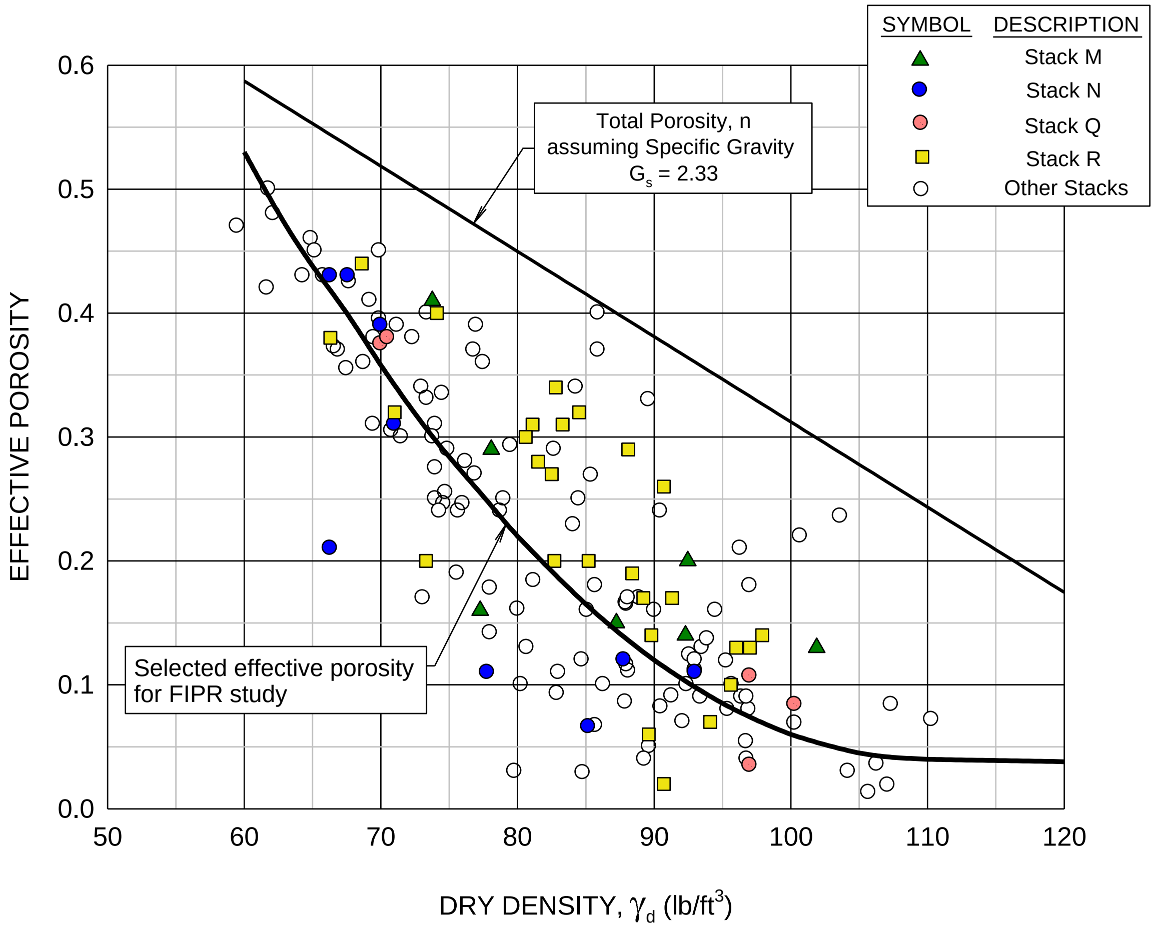


Figure 7. Effective Porosity Versus Dry Density from Gypsum Industry Data.

GYPSUM STACK DEWATERING MODEL

DEWATERING PROGRAM

Dewatering of the gypsum stacks was simulated using MODFLOW. MODFLOW is a three-dimensional (3D), cell-centered, finite difference, saturated flow model developed by the United States Geological Survey (McDonald & Harbaugh, 1988). MODFLOW can perform both steady state and transient flow analyses and has a wide variety of boundary conditions and input options.

A special version of MODFLOW is distributed with the Department of Defense Groundwater Modeling System (GMS). GMS is a comprehensive graphical user-friendly environment for performing groundwater simulations, which supports MODFLOW as a pre- and post-processor. The input data for MODFLOW are generated by GMS and saved to a set of files. These files are read by MODFLOW when MODFLOW is launched from the GMS menu. The output from MODFLOW is then imported to GMS for post-processing. The GMS interface was developed by the Environmental Modeling Research Laboratory of Brigham Young University in partnership with the U.S. Army Engineer Waterways Experiment Station.

GMS Version 6.0 (which incorporates MODFLOW 2000) was used for the analyses presented in this report.

For illustration purposes, the following figure (Figure 8) shows a representative cross section of one of the simulated stacks (300 ft. high) founded on an impervious liner with three concentric rings of drains placed beneath the stack slopes.

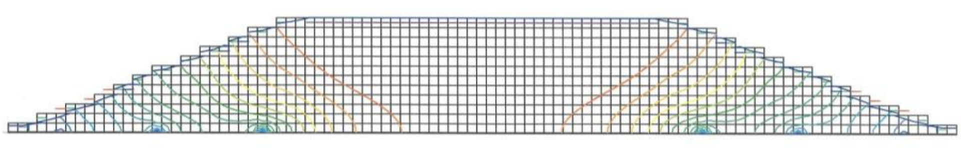


Figure 8. Typical Cross Section in MODFLOW.

Figure 9 represents an oblique 3D view of the stack. Up to about 200,000 elements, distributed over up to 12 horizontal layers, were used in the simulations. A maximum of about 40 sets of different "materials" with differing hydraulic properties (permeability and effective porosity) were assigned to each of the gypsum stacks as explained in the following sections. The values of these properties were revised up to 10 times during the course of the analyses to simulate changes in density with time and load.

A total of about 250 time steps were adopted in the simulations. This proved to be sufficient to ensure adequate numerical accuracy and convergence of the results.

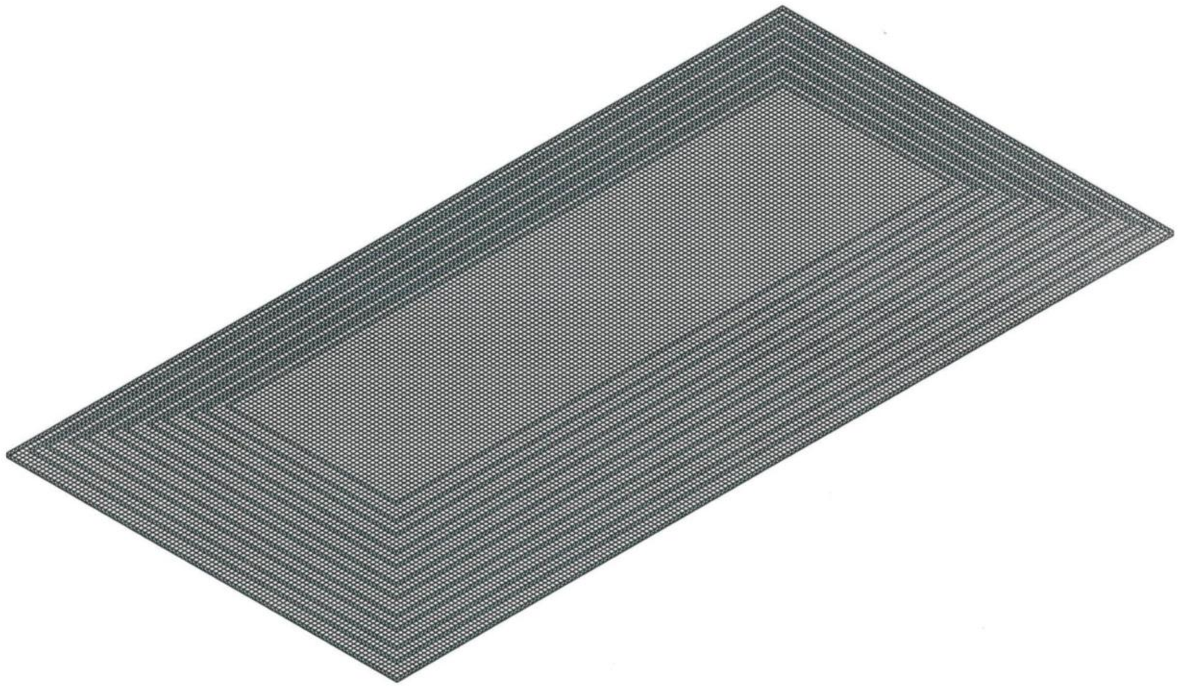


Figure 9. Tri-Dimensional View of 300-Ft.-High Stack in MODFLOW.

CONSOLIDATION AND CREEP MODEL

The rate and amount of dewatering from a gypsum stack is directly related to the hydraulic properties of the gypsum. However, as evidenced in Figures 4, 5, 6 and 7, these properties are not unique, i.e., their magnitude changes as the stack compresses due to both primary and secondary consolidation (creep). This stress and time dependent compression also results in the gradual expulsion of water from the void spaces, which ultimately adds to the total water expelled from the stack.

In order to simulate and predict the amount of compression with stress and time, as well as the changes in the magnitude of the hydraulic properties, a consolidation/creep model was developed. The model is based on the *in situ* density versus depth relationships (at end of construction, EOC) presented in a preceding section (see Figure 4), the rate of gypsum production (considering an assumed P_2O_5 production rate of 1 million tons per year, and a gypsum/P_2O_5 ratio of 5), and the geometry of the stack. These "parameters" or EOC conditions provide a basis to backfigure a series of points or stain rates (%/yr.) as a function of initial void ratio and vertical effective stress level (σ'_v) represented by the red line depicted in Figure 5. Also shown on this figure are a number of power curves that indicate the variation in strain rate at constant vertical effective stress (i.e., creep). These curves are obtained assuming that, at any particular σ'_v level, the strain rate intersects the EOC strain rate void ratio stress line, and asymptotically approaches zero as the dry density of the gypsum increases.

Due to the nature of the power curves, the strain rates above the EOC line increase steeply, sometimes resulting in unrealistically high strain rates under certain loading conditions (e.g., gypsum beneath a secondary liner). Since no data was available for such conditions, a maximum limit to the strain rate was set so that, at any particular void ratio, the strain rate was never higher than 1.5 times the rate indicated by the EOC line at that void ratio. This approach yielded reasonable changes in the density profiles with time, and was consistently applied to all the modeled stacks to ensure full compatibility of the results.

INFILTRATION

An average rate of rainfall infiltration into the side slopes of 4 in./yr. was used in the majority of the analyses presented in this report. This infiltration rate is based on observations by Fuleihan and others (2005), who found this to be a typical average infiltration into a side slope final cover comprised of *in situ* amended or leached gypsum with seeded or sodded grass, for regions with average annual rainfalls on the order of 51 to 55 in./yr. (as is characteristic of many Florida areas).

A limited number of simplified simulations were also carried out, for comparison purposes, assuming zero infiltration and up to 8 in. of infiltration per year through the side slopes.

MODELING METHODOLOGY

As mentioned in the preceding sections, MODFLOW was used to simulate the dewatering of the gypsum stacks. Use of MODFLOW requires that the consolidation and creep of gypsum be uncoupled from the gravity dewatering and related flow simulations; in other words, stress, deformation and pore water pressure changes are not simultaneously accounted for by MODFLOW. Therefore, the consolidation/creep model was independently used to estimate the compression of the gypsum due to changes in effective stresses and time (creep), and the resulting changes in hydraulic properties, i.e., permeability and effective porosity, were manually inputted to MODFLOW at various times.

The properties and thickness of each of the layers were revised up to 10 times during the analyses, so as to reflect the variations in hydraulic properties as the stack settled and drained.

At the same time, the pore water that was theoretically expelled as a result of this compression during each of the time periods was added back as recharge in the MODFLOW simulation, to ensure that the rate of dewatering reflected the need to drain this water volume during the corresponding time interval. Furthermore, these consolidation/creep water volumes had to be carefully evaluated and adjusted so as to account for only those gypsum elements in the finite difference model that were submerged, and therefore, that would expel water, rather than air, as the void spaces reduced.

The gypsum stacks were divided into a number of different areas in order to reflect the variations in density, and therefore hydraulic properties, across the stack. These variations result from two main factors, namely the initial differences in stress levels and ages within the stack and the different hydraulic gradients that progressively develop around the areas of influence of drains. Figure 10 presents a partial cross-section through a typical model stack, which was divided into 4 areas and 12 horizontal layers. In the core area, the gypsum layers are initially denser than in the shoulders due to higher effective stresses, as illustrated in Figure 11, which shows the initial (i.e., EOC or end of construction) density profiles assigned to each of these areas, along with the weighted average density curve. In each of the slope areas designated B1, B2 and B3 in the figure, the hydraulic gradients also vary due to the drains located atop the liner at the bottom of the stack.

From the above, a total of up to 40 sets of hydraulic properties (hydraulic conductivity and effective porosity) were assigned simultaneously during each time period, to each of the MODFLOW simulations. Moreover, an anisotropy permeability factor $k_h/k_v = 3$ was used in all the analyses.

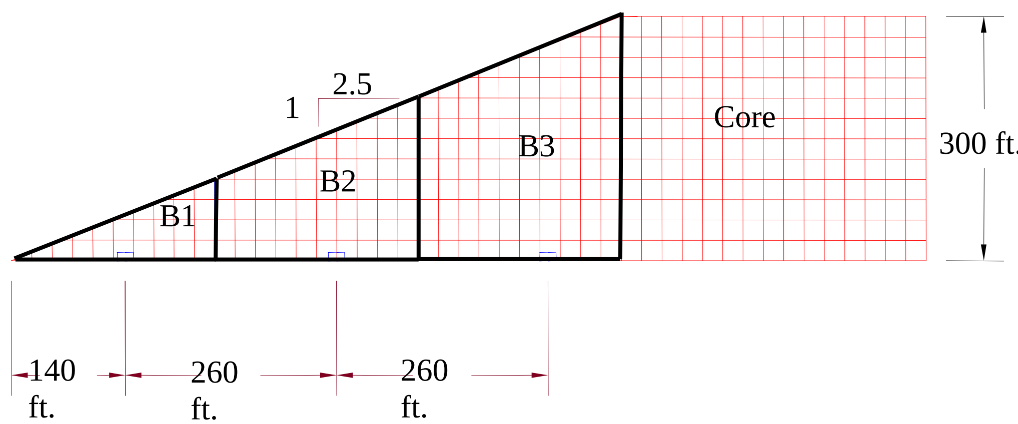


Figure 10. Partial Cross-Section with Different Hydraulic Properties.

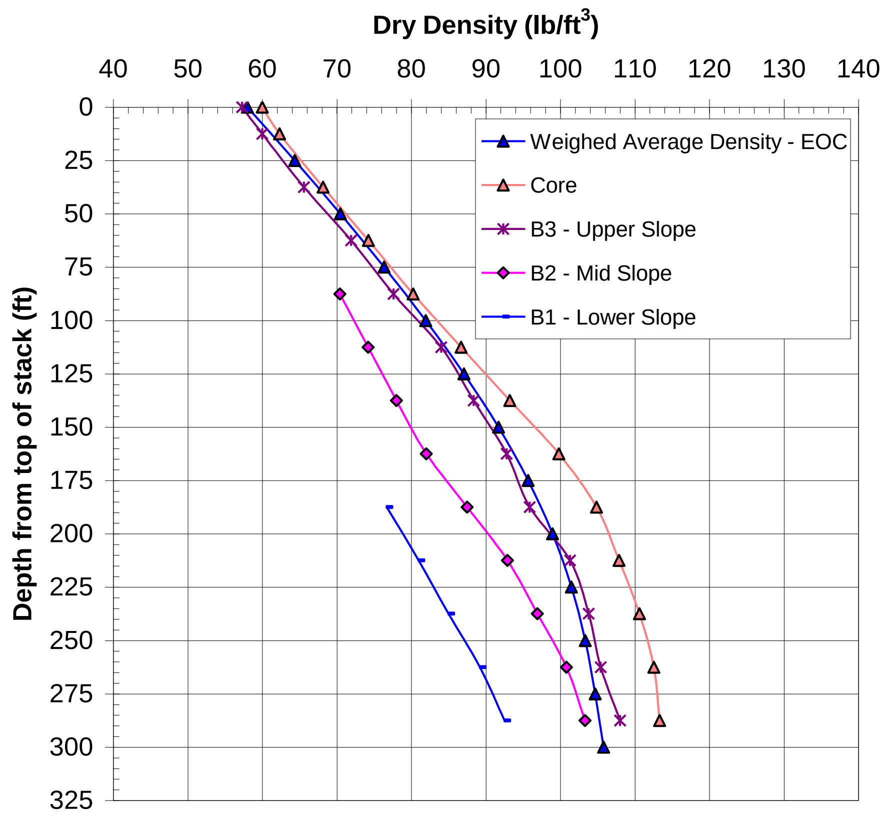


Figure 11. Initial Dry Density Profiles Assigned to a "Typical" Stack.

One limitation of MODFLOW is that elements become inactive once the water table has dropped below the bottom of the finite difference cell. In certain instances, when the stack undergoes significant compression as a result of rapid increases in stress levels due to the placement of a secondary liner, the consolidation/creep water volume added to the model as recharge below the intermediate liner is not allowed to drain out through the inactive cells beneath the slope, and unrealistic pore water pressures are generated as a result. To prevent this from occurring, the uppermost active cells in the stack just below the intermediate liner were assigned a temporary drainage boundary.

Another important aspect of the model is the full recreation of the staged construction sequence of the stacks. It will be shown later that at the end of construction, the stacks have a particular geometry and density profile which should coincide with the average density curves described above. In the case of the stacks with intermediate liners, it was fundamental to progressively model the layers below and above the liner so that full consistency persisted among the various models. This was achieved by simulating the layered construction of each of the lined and unlined stacks, from bottom up, and fully considering the associated consolidation and creep of each of the gypsum layers.

An example of this is depicted in Figure 12. The first case corresponds to the stack lined at the bottom, whose cross-section geometry at EOC is as shown. The second illustrates how the portion of the stack below the intermediate liner has changed, before placement of the liner and at the EOC. Notice how the slope goes from 2.0 Horizontal:1.0 Vertical (2H:1V) to 2.7H:1V and the height reduces from 162 to 117 ft. The modeling technique was such that if the intermediate liner is obviated, the same exact geometry of the first stack is obtained.

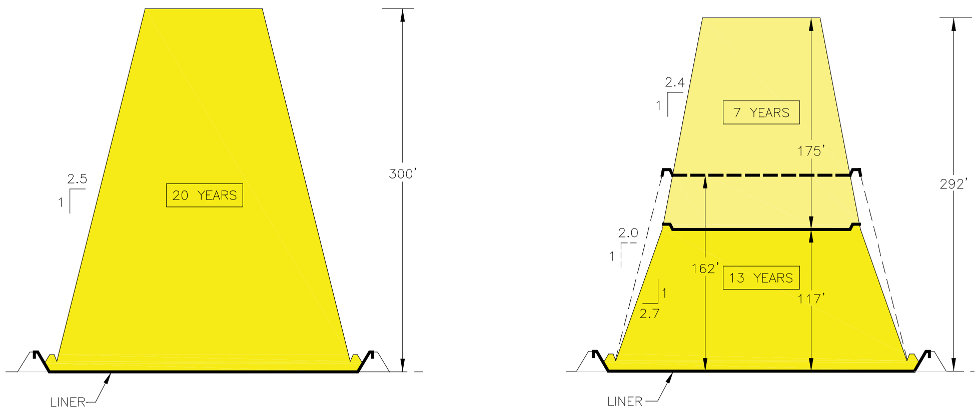


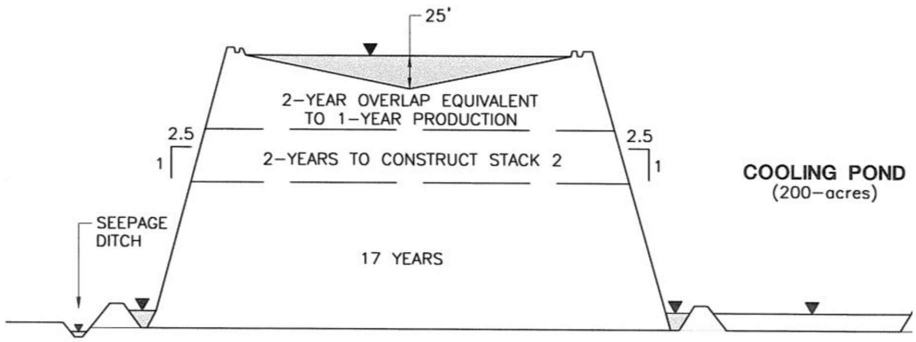
Figure 12. Changes in Geometry of Gypsum Stacks During Construction.

All the stacks were assumed initially fully saturated, and were allowed to drain through the side slopes and through any drainage boundary at the base (drains for lined stacks, or underlying foundation sands for unlined stack).

For purposes of this evaluation, a simplifying assumption was made that closure occurs instantaneously at the EOC, i.e., as soon as the phosphogypsum stack achieves its design height. In reality, closure typically takes around 5 years and will be modeled as such in the water balance analyses (FIPR 04-01-190).

DEWATERING OF A STACK ON RELATIVELY PERVIOUS FOUNDATION

Figure 13 summarizes the geometry of the gypsum stack founded on a relatively pervious foundation and with no bottom liner (previously introduced in Figure 2). The base and top areas are 350 and 180 acres, respectively, with a total height of 200 ft. and average side slopes of 2.5H:1V.



Stack 1

LIFE	:	20 YEARS
END OF LIFE	:	YEAR 21
END OF CLOSURE	:	YEAR 26
BASE AREA	:	350 Acres
TOP AREA	:	180 Acres
HEIGHT	:	200 Feet

Figure 13. Geometry of Unlined Stack at EOC.

The permeability, k_v, of the stack core initially reflected the average density profile described in Figure 4 for the unlined stack at EOC; the permeability decreased during the simulations with gradual increases in density to the upper bound ELTC density profile (with k_v ranging from about 3.2×10^{-4} to 6.0×10^{-7} cm/sec, depending on time and position within the stack). The foundation was modeled using a constant $k_v = k_h = 3.5 \times 10^{-4}$ cm/sec. (1 ft./day), and a total thickness of 35 ft. The water permeating through the foundation was collected in perimeter seepage ditches, where the water level was maintained one foot above the natural ground surface.

The cumulative pore water volume expelled with time for this model is presented in Figure 14. The total reached a maximum of just over 4.3 billion gallons at the ELTC, with 2.0 billion and 1.43 billion coming from storage/dewatering and creep/consolidation, respectively. It is clear from trends in the figure that most of the water flowing out of the stack 20 years after closure (i.e., 20 years after EOC) is rainfall water that infiltrates through the slopes (at the assumed rate of 4 in./yr.), and that compression of the stack is not very significant after this 20-yr. period.

This observation is further supported by the results in Figure 15, where it is evident that about 85% of the 31 ft. of total settlement experienced by the stack occurred during the initial 20 years after the EOC. During this same 20-yr. period, the elevation of the phreatic line drops more dramatically, reaching an elevation of 8.5 ft. (measured at the center of the stack, relative to the natural ground level) compared to the final 4.5 ft. at ELTC (a total drop of 195.5 ft.), at which point the phreatic line has fallen 164 ft. below the top of the settled stack surface.

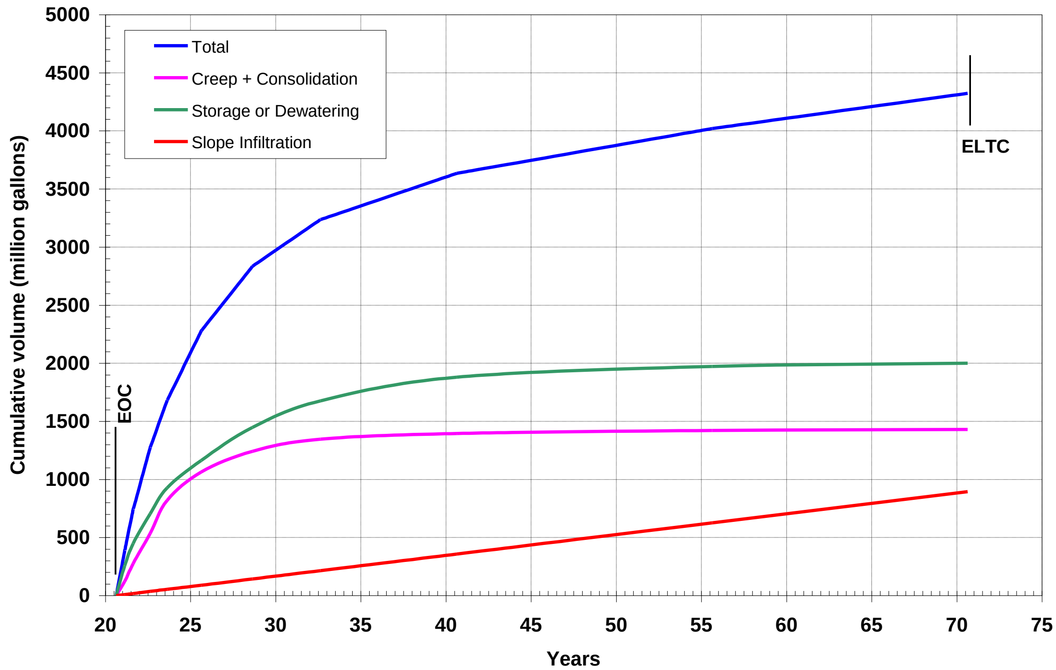


Figure 14. Cumulative Water Volume Drained from Unlined Stack.

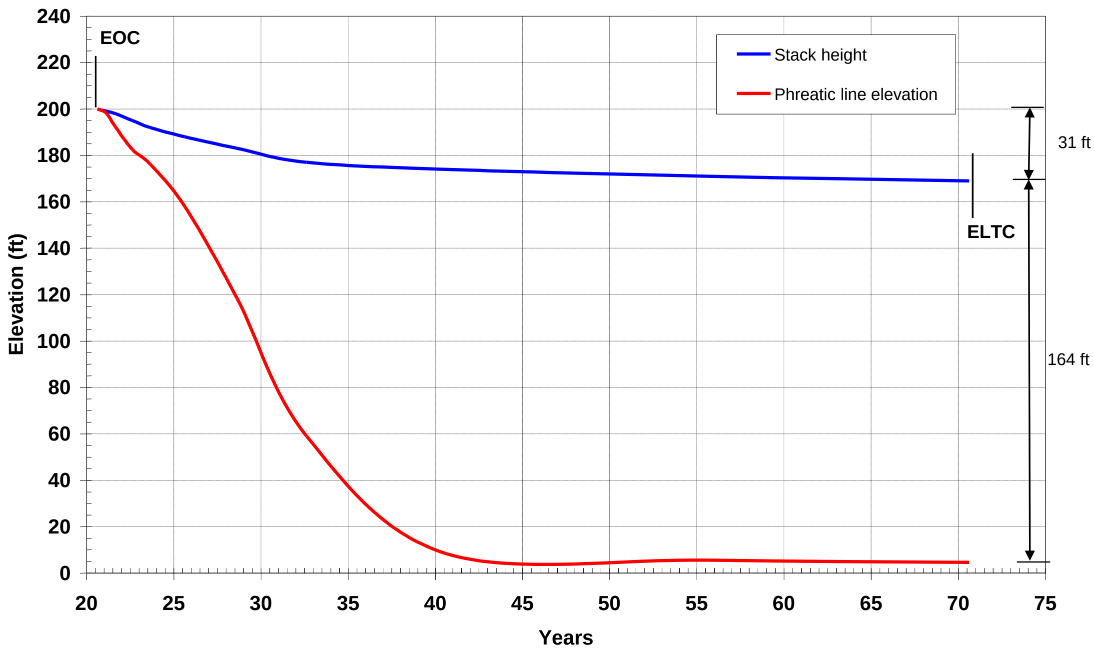


Figure 15. Elevation of Unlined Stack and Phreatic Line (@ Center of Stack).

The drainage or flow rate from the unlined closed stack as a function of time is shown in Figure 16. It decreases from an instantaneous peak of about 2600 gpm (average of 1340 gpm during the first year) to just under 500 gpm within the first five years after EOC, and then the rate declines more gradually towards 34 gpm at ELTC as the compression of the stack slows down. The main source of drainage water is then rainfall infiltration through the side slopes.

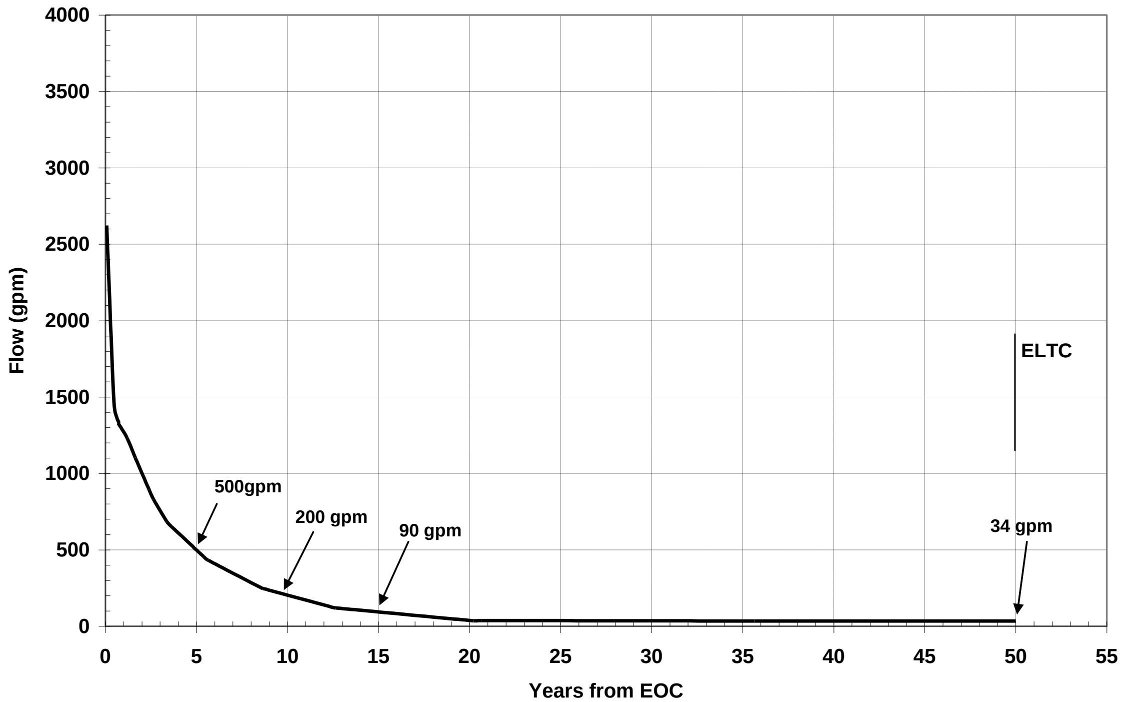
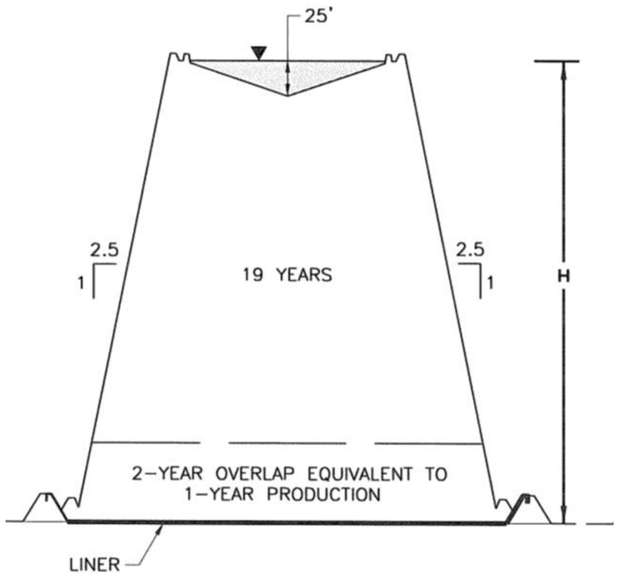


Figure 16. Flow Rate from Unlined Stack.

It should be emphasized that these results cannot be generalized to other gypsum stacks as the conclusions are highly dependent on the stack geometry, assumed dry density profiles, hydraulic properties of the gypsum and foundation soils, and infiltration rate through the side slopes of the closed stack.

DEWATERING OF A STACK WITH A BOTTOM LINER

Figure 17 shows the cross-section geometry of the gypsum stack with a bottom liner. The base and top areas are 280 and 80 acres, respectively. Total height is 300 ft. with average side slopes of 2.5H:1V.



Stack 2

TOTAL LIFE	:	20 YEARS
END OF LIFE	:	YEAR 40
END OF CLOSURE	:	YEAR 45
BASE AREA	:	280 Acres
TOP AREA	:	80 Acres
HEIGHT	:	300 Feet

Figure 17. Geometry of Lined Stack at EOC.

Bottom drains have been positioned as indicated in Figure 18. These are located atop the liner in the shoulder area beneath the slope at 140, 400 and 660 ft. from the toe of the stack.

The initial average density profile at EOC is depicted in Figure 19. This figure also includes density curves at 2, 10, 25 and 50 years after EOC. Note that these analyses were done using the upper-bound terminal density profile in Figure 4.

The total cumulative water drained from this stack at ELTC is just over 4.6 billion gallons (Figure 20). Almost 50% of this water volume comes from compression of the stack (as it consolidates and creeps) during the initial 25 years following the EOC, with the majority of the other half being contributed by pore water coming out from storage (i.e., dewatering). Most of the water seeping through the stack after this 25-yr. period comes from rainfall infiltration into the side slopes.

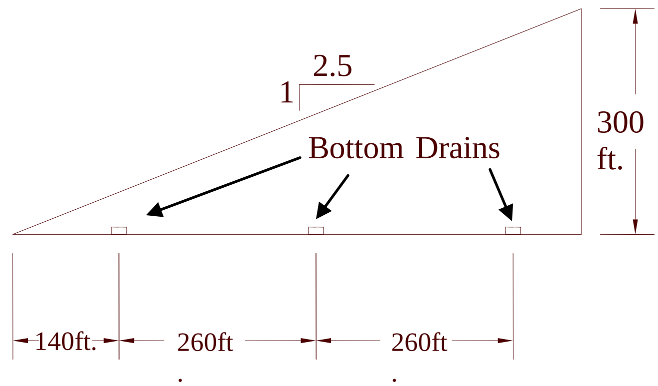


Figure 18. Schematic Position of Bottom Drains in Lined Stack.

The phreatic line at the center of the stack dropped by a total of nearly 90 ft. by the ELTC, as shown in Figure 21 (where elevations are measured from the bottom of the stack). However, because the total settlement at this point was a significant 56 ft. (almost 20% of the total height), the difference in elevation between the phreatic line and the top of the stack is only 33 ft. at ELTC. After this point, the phreatic surface seems to continue on its downwards trend, although at a relatively slow pace.

The flow rate from the lined stack starts at about 3500 gpm at the EOC (average of about 2200 gpm during the first year) and drastically decreases to about 300 gpm after 5 years (Figure 22). At the ELTC, the flow rates reach a steady state value of 44 gpm, which is essentially the rate of rainfall infiltration into the side slopes. Note that over time, the quality of leachate attributed to rainfall recharge is expected to improve. Ultimately, the seepage water will become free of most chemical constituents except for calcium sulfate, with dissolved solids concentrations corresponding to the solubility of gypsum in fresh water.

Figure 23 shows a schematic representation of the final (ELTC) cross-sectional geometry of the lined stack, including the phreatic water level. The dashed line represents the original section at EOC. The water mound at the center of the stack of the ELTC is about 211 ft. high, compared to the 244-ft. height of the settled stack. It is worth noting that despite the seemingly high phreatic water level because of the assumed high density and low permeability of the gypsum (i.e., upper bound ELTC *in situ* dry density), and hence low effective porosity, the total volume of drainable pore water at that time is only 0.44 billion gallons.

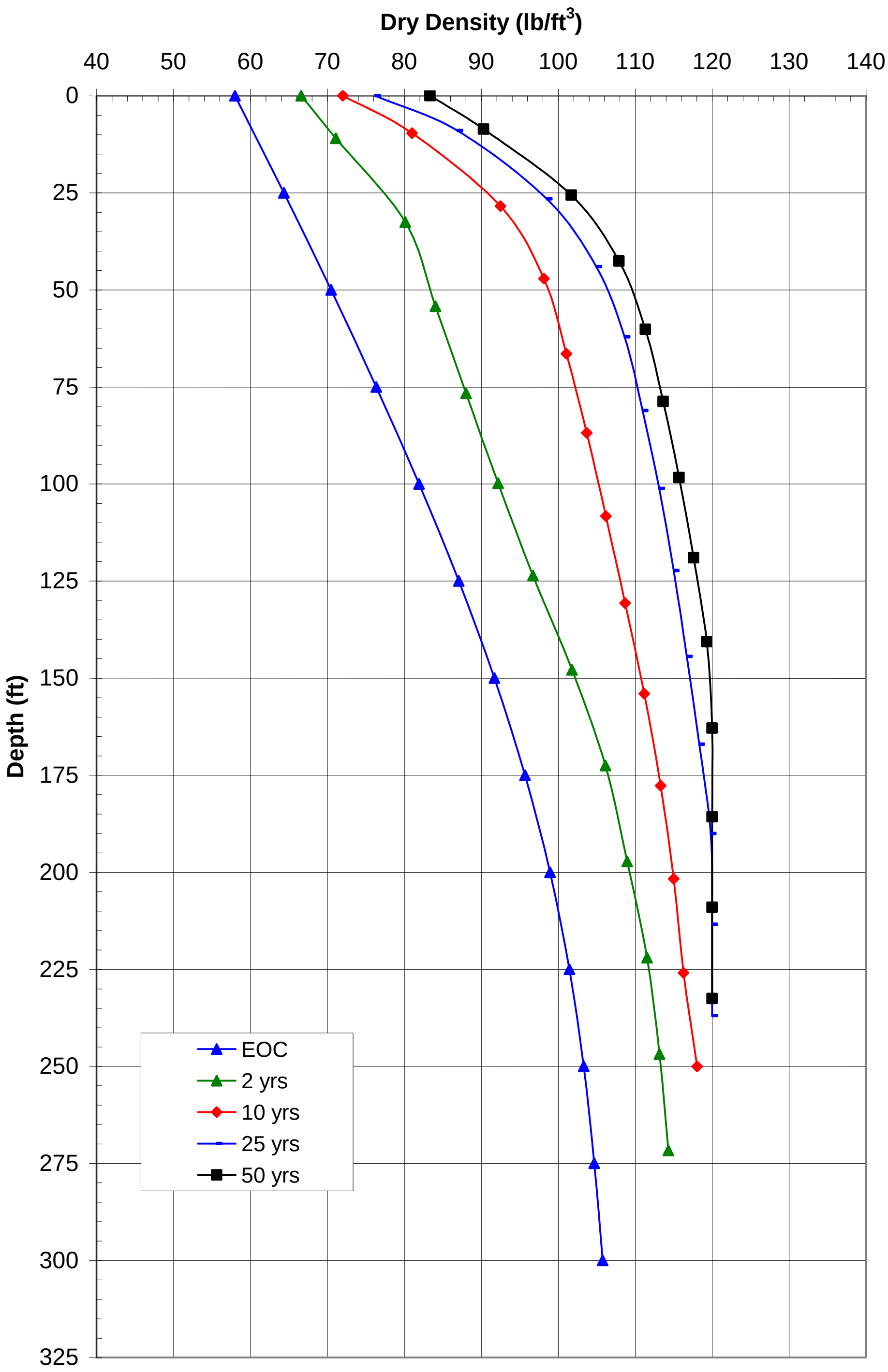


Figure 19. Density Changes of Lined Stack with Time (@ Center of Stack).

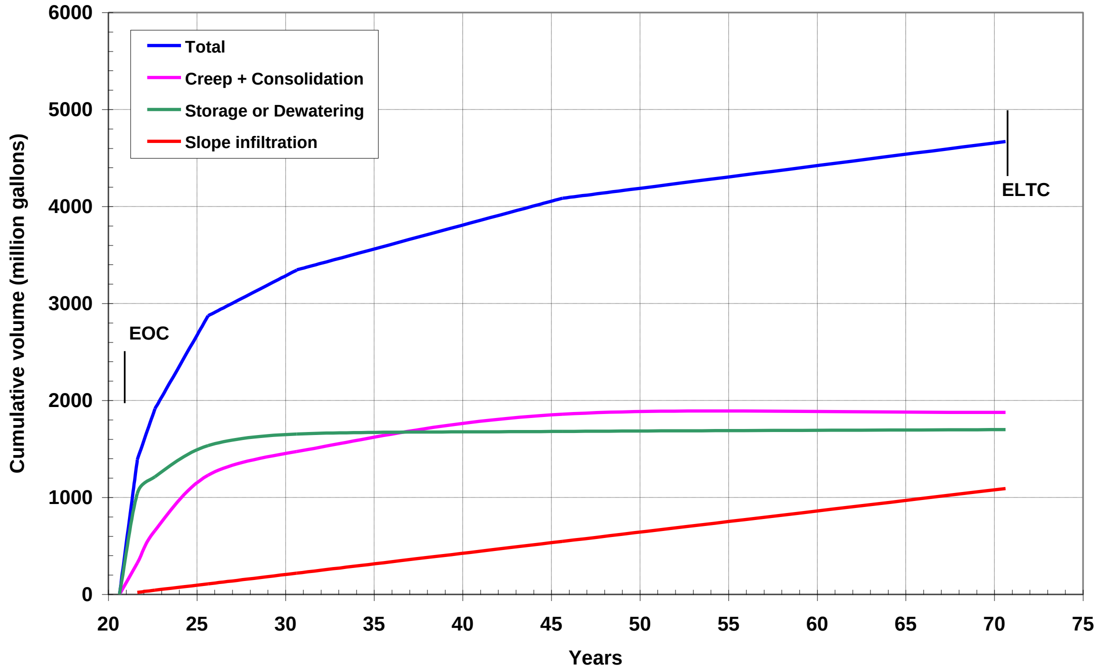


Figure 20. Cumulative Water Volume Drained from Lined Stack.

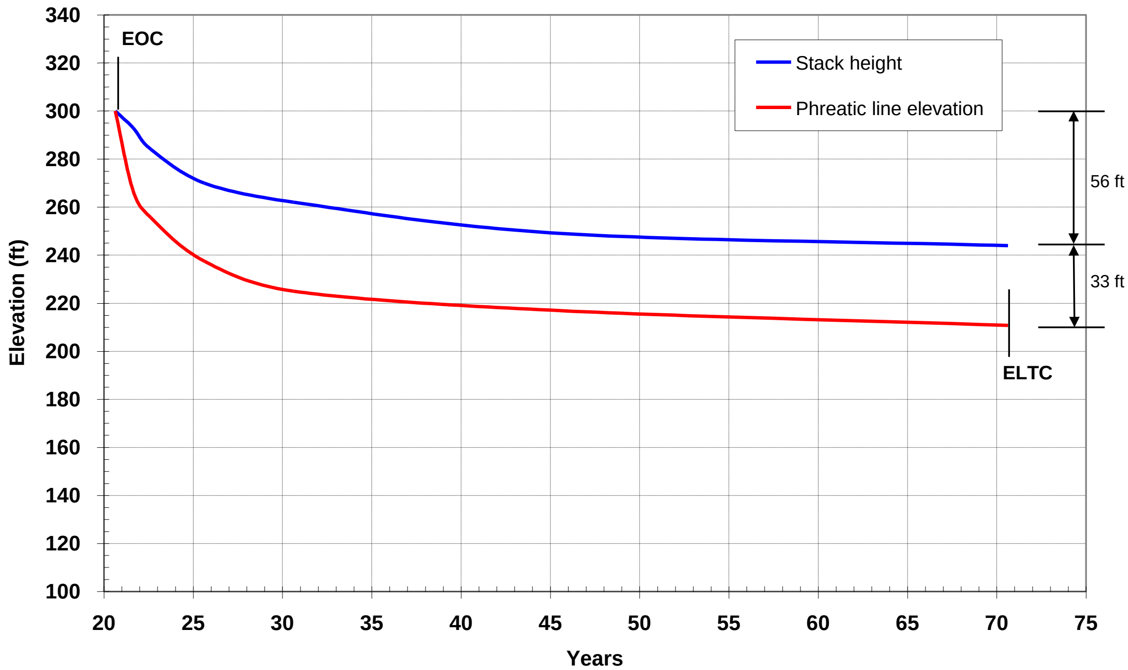


Figure 21. Elevation of Lined Stack and Phreatic Line (@ Center of Stack).

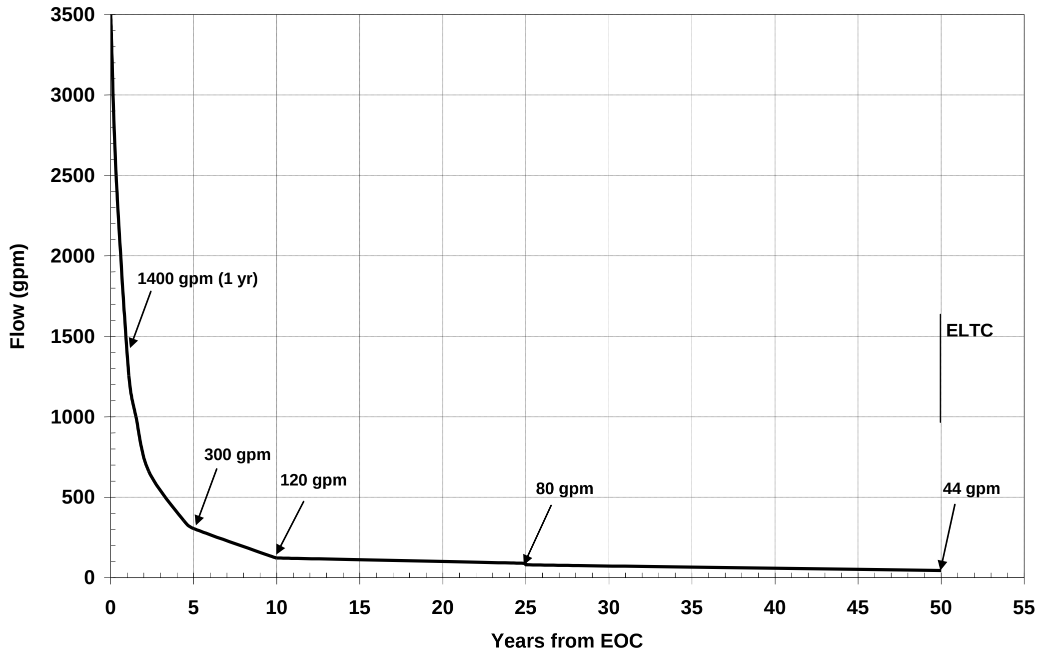


Figure 22. Flow Rate from Lined Stack.

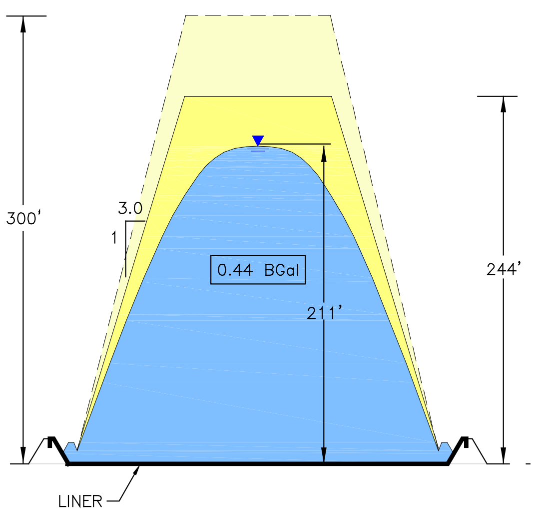


Figure 23. Schematic Representation of Lined Stack and Phreatic Line at ELTC with Upper Bound Densities.

The apparently high elevation of the water table, even 50 years after closure, is a result of the very low permeability that was assumed to prevail throughout the stack, a consequence of using the upper-bound terminal density profile and of extrapolating the permeability relationship to very low void ratios beyond the range of measured data (see Figure 6). At the highest density of 120 lb./ft.^{3} towards the bottom of the stack, the permeability used in the model is in the order of 4×10^{-7} cm/sec., which is one order of magnitude lower than measured on dense undisturbed gypsum samples, and which approaches the permeability of clays. At these levels, the drainable pore water is also very low (with an effective porosity as low as 4%), which further contributes to the retention of pore water within the stack.

Even though these low densities may occur in the field, particularly for high, aged stacks with a high initial EOC density profile, use of the lower-bound ELTC density profile (instead of the upper bound ELTC profile), as shown on Figure 4, can have a dramatic effect on the dewatering of the stack, as evidenced by the results in Figure 24. Figures 25 and 26 show that even though the total drained volume with the lower-bound density profile is only 0.4 billion gallons lower than in the base case with the upper-bound ELTC density profile (Figure 25), the elevation of the phreatic line in the center of the stack decreases significantly from 211 ft. in the latter case to around 53 ft. (Figure 24), with a trend of decreasing water table elevation at ELTC suggesting an even lower longer term water mound of about 30 to 40 ft. (Figure 26). The drainable pore water at ELTC also decreases from 0.44 billion gallons to 0.18 billion gallons when the lower bound ELTC density is adopted (Figures 23 and 24).

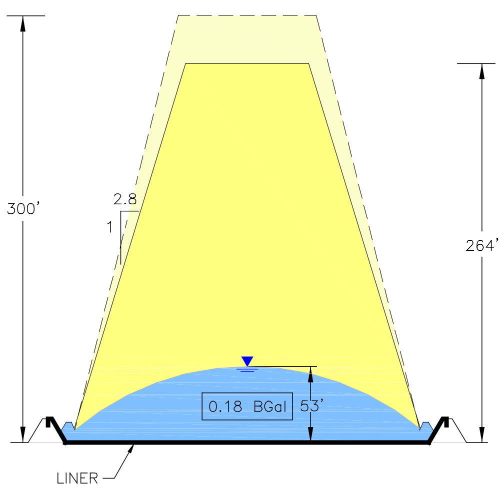


Figure 24. Schematic Representation of Lined Stack and Phreatic Line at ELTC with Lower Bound Densities.

A more moderate settlement of the stack is also noted with the lower bound ELTC density profile, with a final height of 264 ft. compared with 244 ft. for the base case.

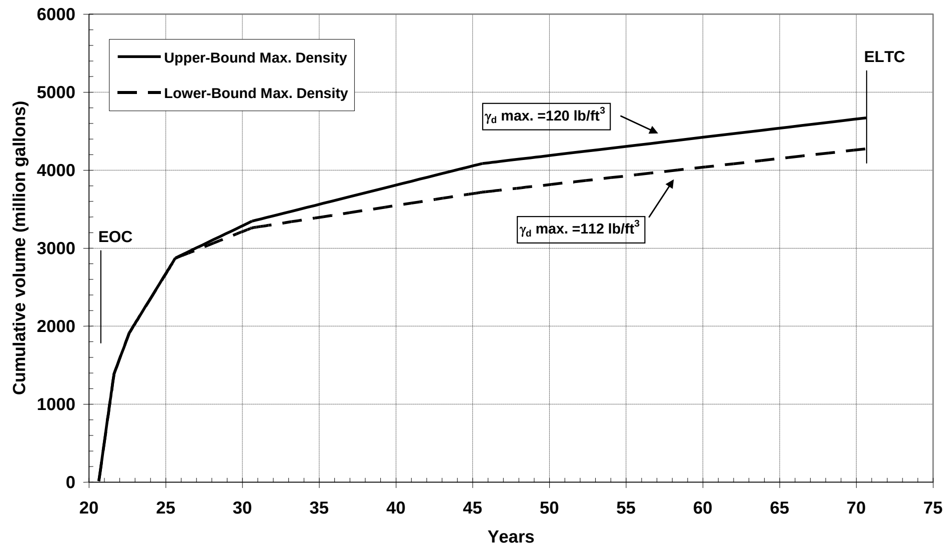


Figure 25. Cumulative Water Volume Drained from Lined Stack for Upper and Lower Bound Density Profiles.

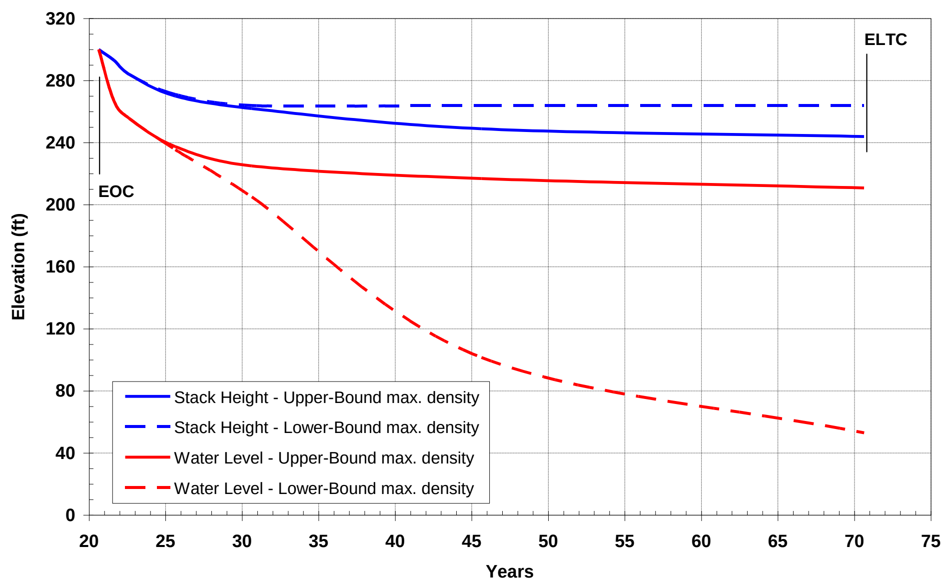


Figure 26. Elevation of Lined Stack and Phreatic Line for Upper and Lower Bound Density Profiles.

Figure 27 depicts how the rate of rainfall infiltration into the side slopes affects the phreatic water table elevation in the center of the stack. Eight in./yr. of infiltration with the lower-bound density profile would result in a water table mound about 15 ft. higher than with an assumed infiltration rate of 4 in./yr. Eliminating infiltration completely from the stack with the upper-bound density profile would result in an additional water table drop of 35 ft. compared to the base case with 4 in./yr. of infiltration. Moreover, dewatering would continue beyond the ELTC period for the case without any slope infiltration.

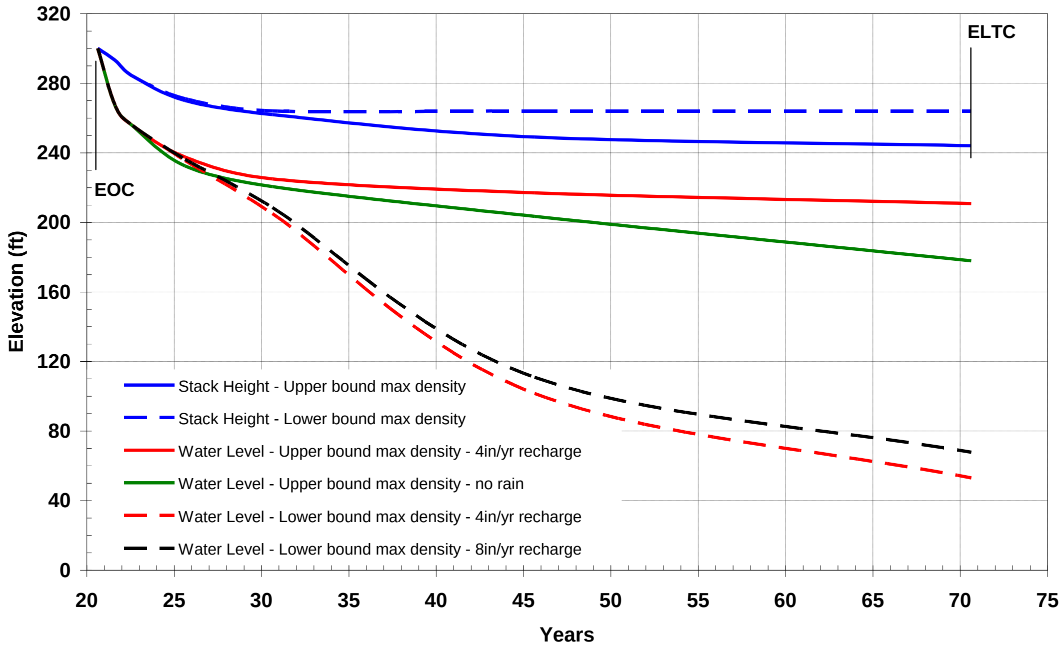


Figure 27. Elevation of Lined Stack and Phreatic Line for Various Infiltration Rates.

It should be emphasized that these results cannot be generalized to other gypsum stacks as the conclusions are highly dependent on the stack geometry and location of drains, assumed dry density profiles, hydraulic properties of the gypsum, and infiltration rate through the side slopes of the closed stack.

EFFECT OF SECONDARY LINERS ON PORE WATER DRAINAGE

Figure 28 presents the geometry of two cases with intermediate liners (Options 1 and 2) that were evaluated and compared to the base case stack with a bottom liner. The dashed line indicates the geometry of the stack before placement of the secondary liner and subsequent construction of the upper portion of the stack. All these evaluations were made assuming the relatively conservative upper bound ELTC density profile in Figure 4.

As expected, the total stack heights (292 ft. and 288 ft., respectively) of Option 1 (13+7 yr. stack) and Option 2 (15+5 yr. stack) at EOC are lower than the 300-ft. height of the base case 20-yr. lined stack. Extension of these two stacks to 300 ft. would potentially add some 3 and 4 months of additional life to Option 1 and Option 2, respectively. Alternatively, a reduction in base area of about 5 and 7 acres, respectively, could have been made while maintaining the same 20-yr. life.

Typical dry density profiles in the center of the stack for Option 2 are shown in Figure 29. The dashed blue line represents the EOC of the 15-yr. section below the secondary liner, whereas the solid blue lines correspond to the EOC density of the combined stack at maturity. It is clear that the stack section under the liner has a higher density that results from the increased total vertical stresses imposed by the 5-yr. stack above the intermediate liner. Note that the density of the lower stack below the liner has reached the maximum upper-bound value of 120 lb./ft.[3] The same trends characterize the density profiles for Option 1.

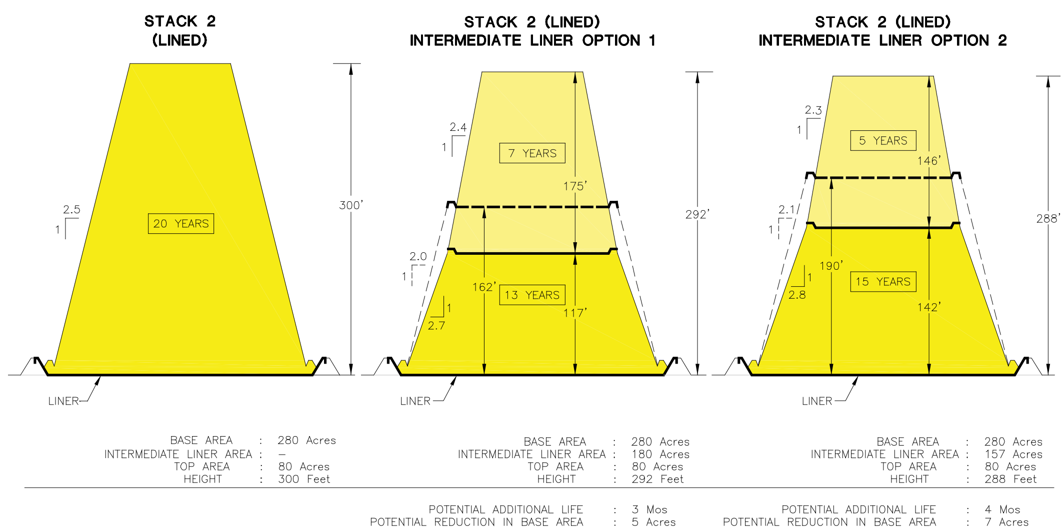
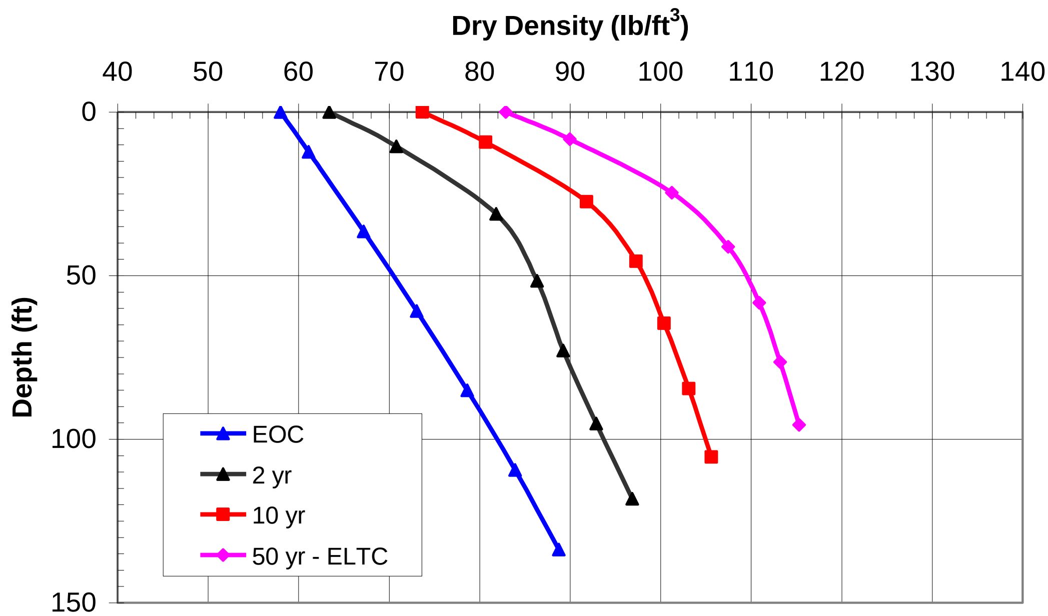
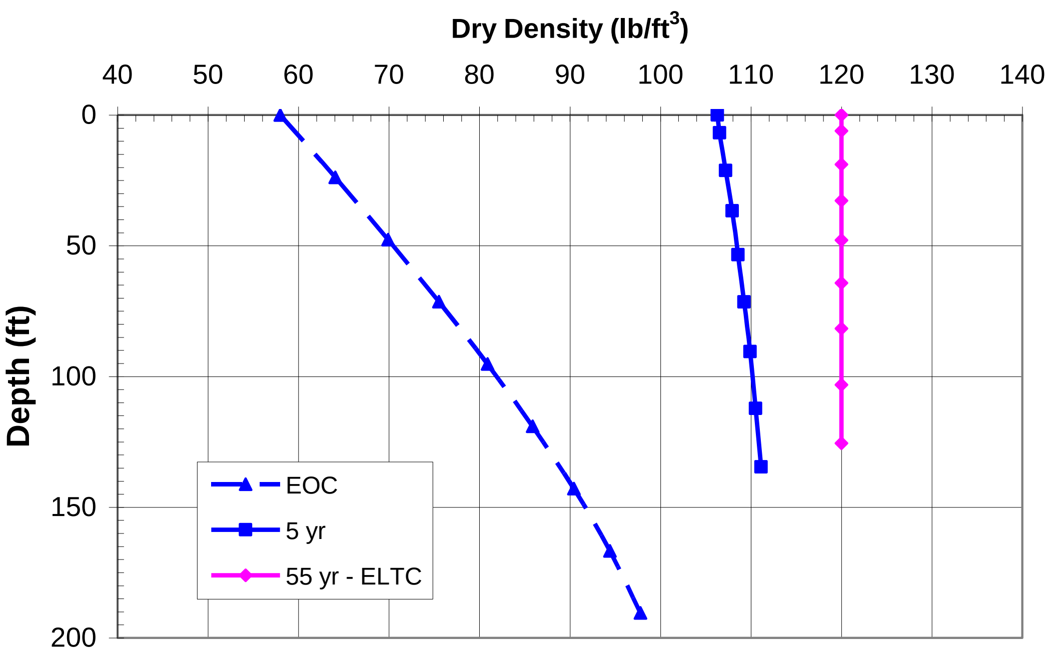


Figure 28. Intermediate Liner Options.



(a)



(b)

Figure 29. Density Changes of Lined Stack with Intermediate Liner with Time: (a) 5-Yr. Stack Above Secondary Liner; (b) 15-Yr. Stack Below Secondary Liner.

Figure 30 illustrates more clearly the effect of the intermediate liner on the density profile. A steep jump in density occurs at the boundary where the secondary liner is located, which explains the lower heights of these stacks, relative to the base case without an intermediate liner, for the same 20-yr. life.

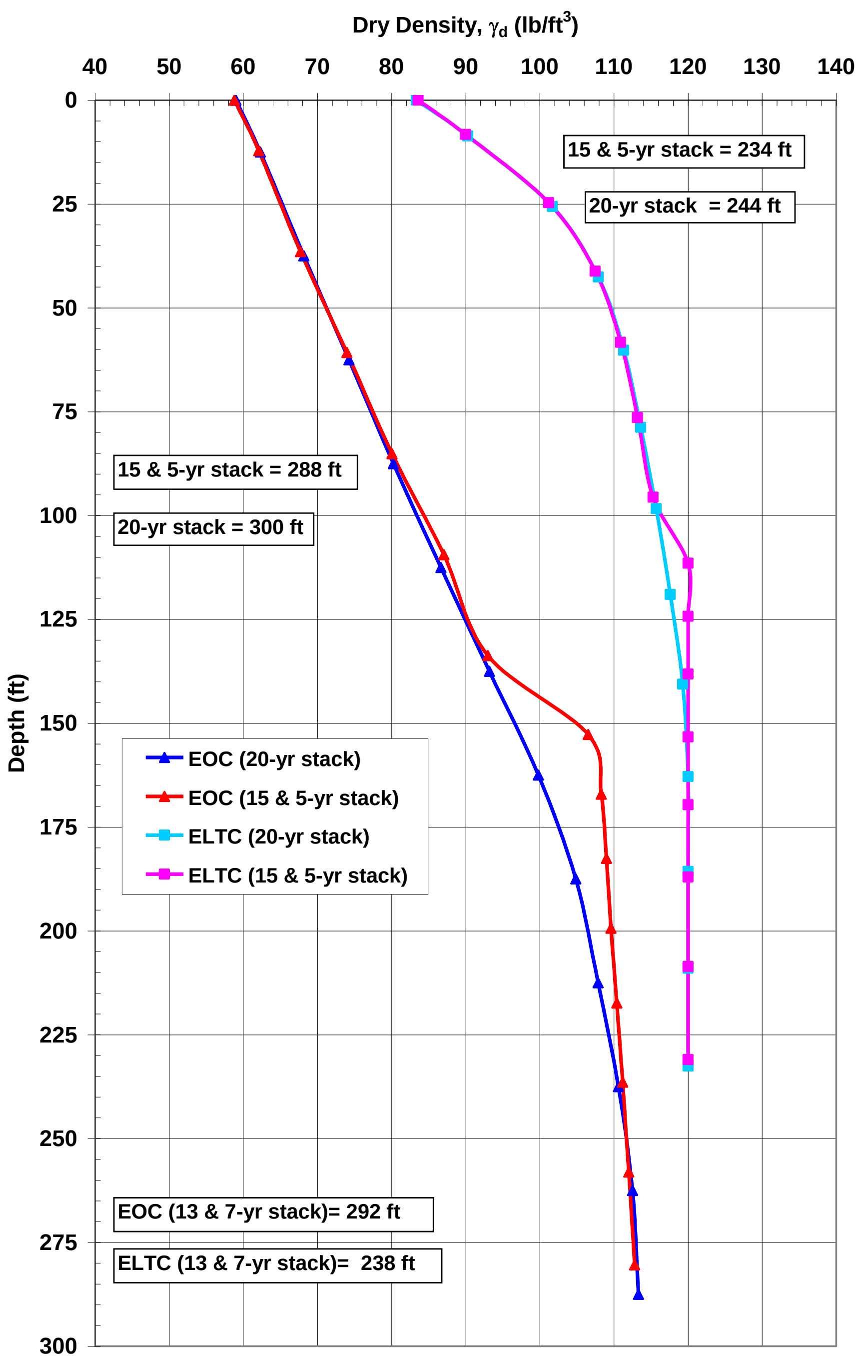


Figure 30. Initial and Final Density Profiles.

Drains for the stack section below the intermediate liner have been positioned above the bottom liner using the same configuration illustrated in Figure 18. For the stack section above the secondary liner, perimeter drains have been located in the shoulder area beneath the slopes, as depicted in Figure 31.

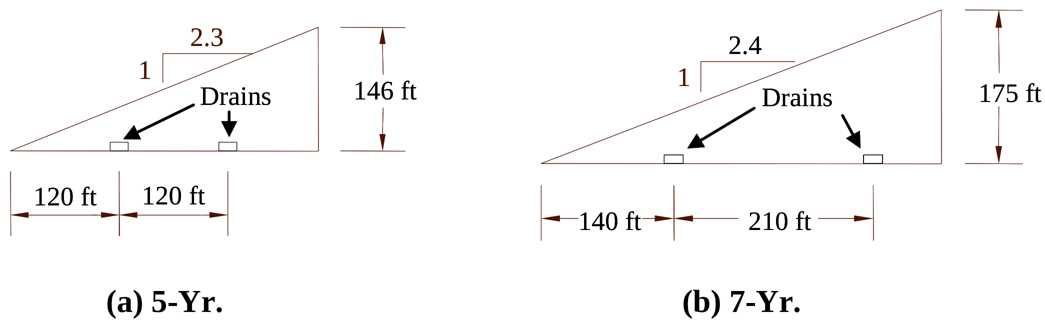


Figure 31. Schematic Position of Drains in Stacks Above Secondary Liner.

The cumulative water drained from each of the lined stacks is shown in Figure 32. Figure 33 considers only the water volumes drained after final closure.

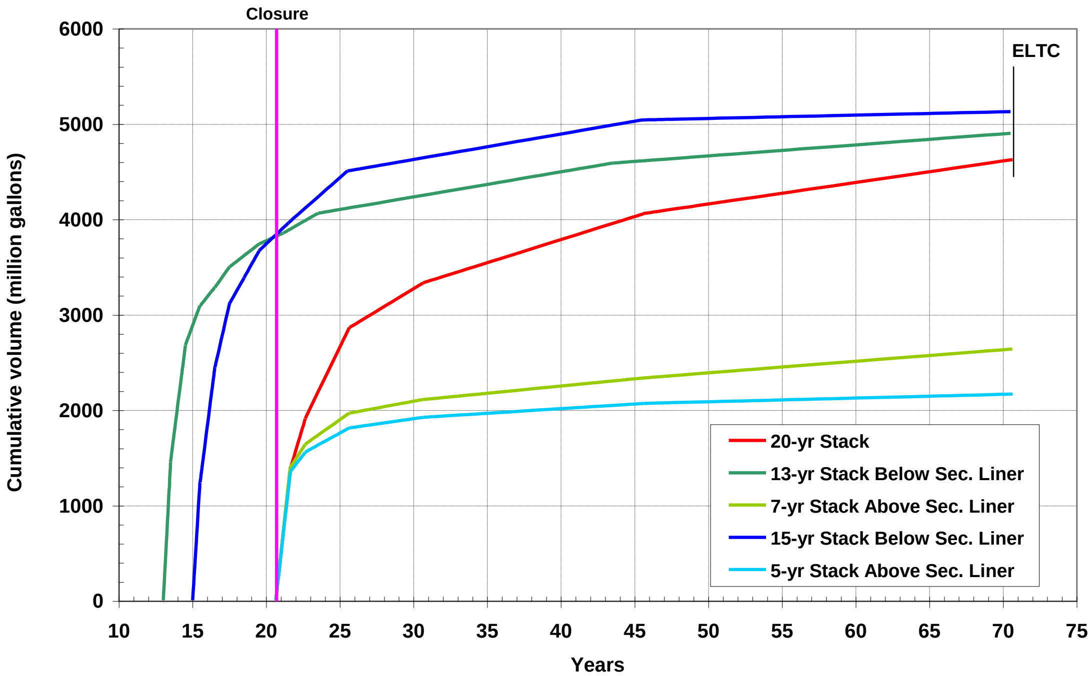


Figure 32. Cumulative Water Volume Drained from Stacks with Secondary Liner.

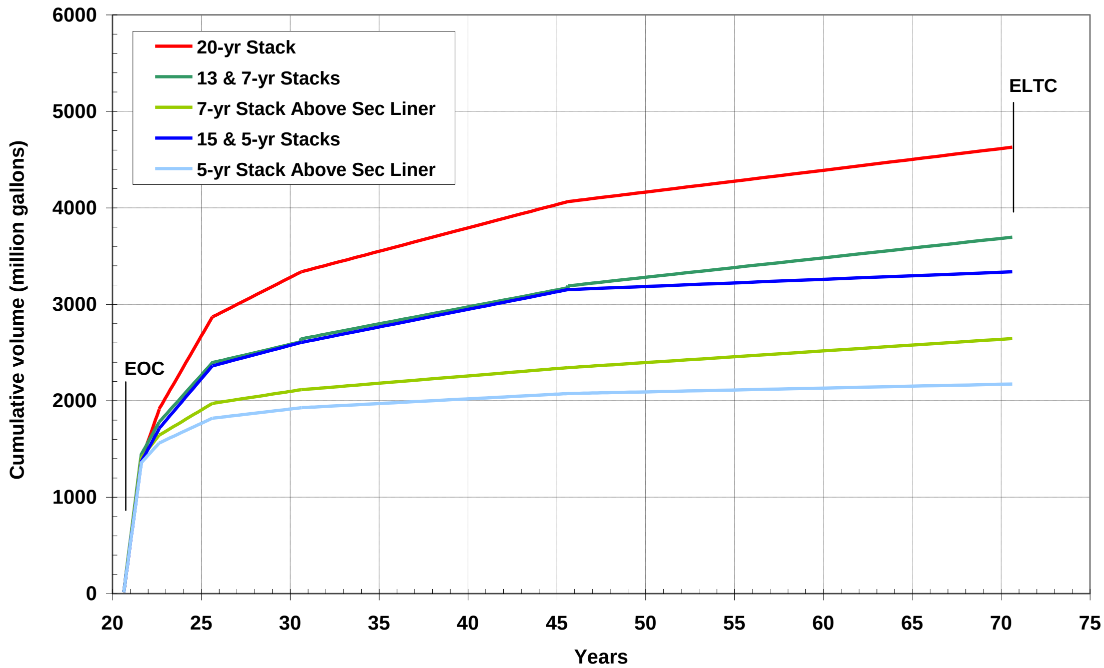


Figure 33. Cumulative Water Volume Drained After Closure of Stacks with Secondary Liners.

Table 3 summarizes results of the effects of the intermediate liner on the volume of drainable pore water. During construction of the 5-yr. and 7-yr. stacks above the secondary liner, 3.91 and 3.85 billion gallons, respectively, of water drains out from the stacks below the intermediate liner, compared to 2.66 and 2.44 billion gallons that would "drain" during an equivalent time period from the base case 20-yr. lined stack. This results in 1.19 and 1.47 billion gallons of additional pore water that is expelled, pre-closure, from the Option 1 (13 + 7-yr.) and Option 2 (15 + 5-yr.) stacks compared to the 20-yr. base case. Drainable water post-closure is actually 0.94 and 1.28 billion gallons lower for the Option 1 (13 + 7-yr.) and Option 2 (15 + 5-yr.) stacks, respectively, compared to the 20-yr. base case.

Table 3. Effect of Intermediate Liner on Drainable Pore Water.

Gypsum Stack	Additional Drainage Pre-Closure Relative to 20-Yr. Stack (Billion Gallons)	Post-Closure Drainable Water Through ELTC (Billion Gallons)	Net Additional Water "Consumed" During Plant Life (Billion Gallons)	Remaining Pore Water @ ELTC (Billion Gallons)
20-yr.	-	4.63	-	0.44
13 + 7-yr.	3.85 - 2.66 = 1.19	3.69	0.94	0.3
15 + 5-yr.	3.91 - 2.44 = 1.47	3.35	1.28	0.3

At the ELTC period, the Option 1 (13 + 7-yr.) and Option 2 (15 + 5-yr.) stacks still have about 0.3 billion gallons of remaining drainable water, or 0.14 billion gallons less than the 20-yr. base case. This is schematically illustrated in Figure 34, along with the final cross-section geometries and phreatic water table elevation at ELTC for each of the stacks.

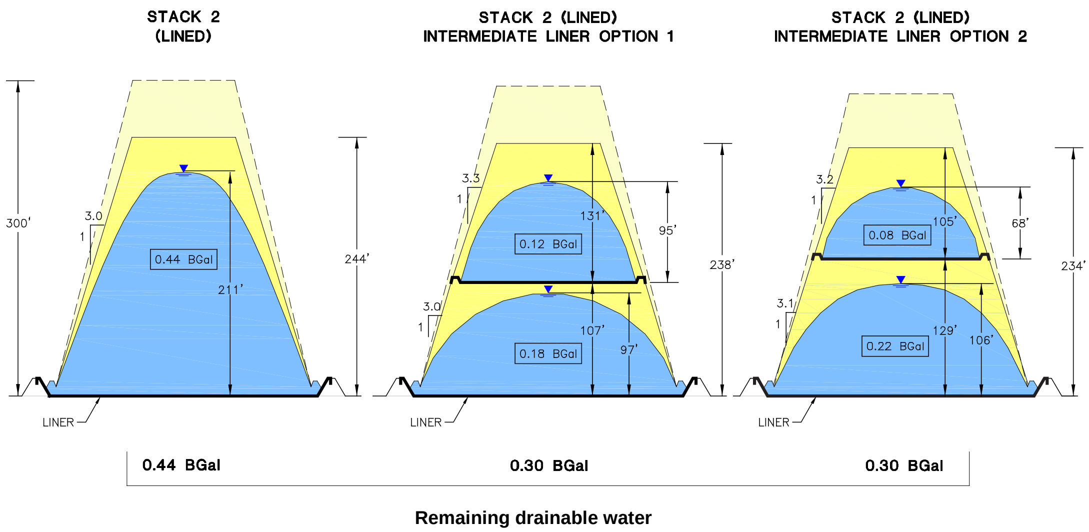


Figure 34. Phreatic Water Line Elevation and Remaining Drainable Water at ELTC.

The results presented above were used in cost/benefit analyses (that are presented in the following section) to assess the effectiveness of secondary liners in reducing costs and environmental liabilities related to treatment of phosphogypsum stack pore water drainage after closure.

COST/BENEFIT ANALYSES OF SECONDARY LINERS

As illustrated by the results in Figure 28, use of a secondary liner installed at about mid-height and at about two-thirds of the design height of a typical gypsum stack will increase the useful life of the stack by approximately 3 and 4 months, respectively, by promoting consolidation of the *in situ* gypsum beneath the secondary liner. As a result, the initial base area of the stack could be reduced by about 5 and 7 acres, respectively, with potential capital expenditure savings during initial construction on the order $625,000 to $875,000 (using a typical construction cost for the lined area including base preparation and associated stabilization drains and appurtenances of about $125,000/acre in 2006 dollars).

More importantly, use of a secondary liner will allow a significant quantity of P_2O_5 rich pore water to drain from the lower "capped" portion of the stack during active operation of the upper stack above the secondary liner, thus enabling plant consumption of the drained water, and leading to a significant reduction in the cost of treatment provided the water balance of the active facility can accommodate management and consumption of pore water drainage from the lower stack during the active life of the plant. Moreover, an equally important benefit of the secondary liner emerges from the fact that the plant will have an opportunity to recover P_2O_5 from the drained pore water that would otherwise be lost.

Table 3 summarized the results of dewatering models for a lined stack including the effect of a secondary liner. As shown, approximately 1.19 and 1.47 billion gallons of additional pore water are projected to drain during the active life of the upper stack relative to drainage from the base case stack when the secondary liner is installed at mid-height and at two-thirds of the design stack height, respectively. Assuming that the pore water contains 1 to 2% P_2O_5 (corresponding to phosphate concentrations on the order of 4,500 mg/l to 8,900 mg/l, respectively), every 1,000 gallons of additional pore water drained from the stack amounts to a potential recovery of approximately 85 to 170 pounds of P_2O_5. At an assumed product price of $150 to $175 per ton of P_2O_5, the potential cost savings (i.e., benefit) due to P_2O_5 recovery are approximately $6.38 to $14.87 per 1,000 gallons of pore water. The total potential savings would, therefore, be on the order of 7.6 to 17.7 million dollars for the stack with the secondary liner at mid-height, and on the order of 9.4 to 21.9 million dollars for the stack with the secondary liner at about two-thirds of the design stack height.

As shown by the results in Table 3, the volume of post-closure drainable water through the ELTC period from the stacks with secondary liner at mid-height and at two-thirds the design height is projected to be about 0.94 and 1.28 billion gallons less than the corresponding drainage from the base case stack, respectively. Considering a two-stage lime treatment cost (including sludge handling) ranging from $15 to $25 per 1,000 gallons of acidic pore water, the reduced post-closure pore water drainage amounts to cost savings on the order of 14.1 to 23.5 million dollars for the stack with the secondary liner at mid-height, and on the order of 19.2 to 32.0 million dollars for the stack with the secondary liner at two-thirds of the design stack height.

Assuming a typical unit cost for the secondary liner system installation (including base preparation and associated stabilization drains and appurtenances) of $60,000 to $70,000 per acre,* the total cost of the secondary liner system would be on the order of 10.8 to 12.6 million dollars for the 180-acre mid-height secondary liner system, and on the order of 9.4 to 11.0 million dollars for the 157-acre two-thirds height secondary liner system†. Table 4 summarizes the costs and benefits of secondary liners.

Table 4. Cost/Benefit of Secondary Liners.

Secondary Liner	Cost of Secondary Liner System (million dollars)*	Potential Savings (million dollars) *			Total Savings (million dollars)*	Total Net Savings (million dollars)*	Cost/ Benefit Ratio
		Increased Life or Reduced Base Area	P_2O_5 Recovery**	Reduced Treatment Volume ***			
None	0	0	0	0	0	0	0
@ Mid-height	10.8 to 12.6	0.6	7.6 to 17.7	14.1 to 23.5	22.3 to 41.8	11.5 to 29.2	0.48 to 0.30
@ Two-thirds Height	9.4 to 11.0	0.9	9.4 to 21.9	19.2 to 32.0	29.5 to 54.8	20.1 to 43.8	0.32 to 0.20

* 2006 dollars.
** Assumed P_2O_5 recovery benefit: $6.38 to $14.87 per 1,000 gallons of acidic pore water.
*** Assumed treatment cost: $15 to $25 per 1,000 gallons of acidic pore water.

As shown, the secondary liner is expected to yield significant savings considering P_2O_5 recovery benefits in the range of $6.38 to $14.87 per thousand gallons of pore water consumed, and treatment costs in the range of $15 to $25 per thousand gallons of pore water treated and discharged. At these unit rates, the secondary liner is projected to result in total net cost savings on the order of 12 to 29 million dollars if installed at mid-height of the stack, and as much as 20 to 44 million dollars if installed at two-thirds the design height. Considering that the cost of the secondary liner can be readily justified by the

*The unit costs of the secondary liner installation was arrived at using the following estimated unit costs for construction of various components of the liner system based on recent 2006 experience with similar construction projects:

60-mil HDPE liner:	$0.70/ft.^{2}
Stabilization drain:	$150/l.f.
Gypsum earthwork including base preparation:	$6/cyd

†Note that the upstream slope of the perimeter gypsum dike adjacent to the secondary liner need not be lined in this case because the stack already incorporates a bottom liner, and the only purpose of the secondary liner is to promote dewatering of the lower portion of the stack prior to closure.

P_2O_5 recovery benefit as long as the plant can consume the drained pore water, the reduction in financial liability at terminal closure would essentially be equivalent to the reduction in post-closure treatment costs which is very significant, i.e., on the order of 14 to 23 million dollars for the intermediate liner at mid-height, and as much as 19 to 32 million dollars for the intermediate liner at two-thirds the design height. The cost/benefit ratio for the latter intermediate liner alternative is in the range of 0.2 to 0.3, which is quite advantageous.

Table 5 presents costs and benefits of secondary liners normalized to the dollar values at the end of construction (EOC) considering the time value of money and using an assumed net discount/interest rate of 5%/yr.* When the costs and benefits are normalized to dollar values at the end of construction, the secondary liner is shown to result in still significant but somewhat reduced total net cost savings on the order of 5 to 22 million dollars if the liner is installed at mid-height of the stack, and as much as 15 to 38 million dollars if installed at two-thirds the design height. The net reduction in financial liability at terminal closure would then equal 11 to 18 million dollars and 15 to 25 million dollars for these two intermediate liner options, respectively, when normalized to values at the EOC.

Table 5. Cost/Benefit of Secondary Liners with Time Value of Money.

Secondary Liner	Cost of Secondary Liner System† (million dollars)	Potential Savings (million dollars)			Total Savings (million dollars)	Total Net Savings (million dollars)	Cost/ Benefit Ratio
		Increased Life or Reduced Base Area††	P_2O_5 Recovery**	Reduced Treatment Volume***			
None	0	0	0	0	0	0	0
@ Mid-height	16.0 to 18.6	1.6	9.0 to 21.0	11.0 to 18.4	21.6 to 41.0	5.6 to 22.4	0.74 to 0.45
@ Two-thirds Height	12.6 to 14.7	2.4	10.6 to 24.7	15.0 to 25.1	28.0 to 52.2	15.4 to 37.5	0.45 to 0.28

Note: All costs and benefit amounts have been normalized to the dollar value at the end of construction (EOC) considering the time value of money and using an assumed net discount/interest rate of 5% per year.
† Future value of investment after 5+1 years and 7+1 years for the intermediate liner at two-thirds the height and at mid-height, respectively.
†† Future value after 20 years from incurring capital investment for bottom liner.
** Future value of P_2O_5 recovery at EOC (after 2.5 to 3.5 years).
*** Present worth of savings in post-closure treatment costs discounted over 5 years to EOC.

*An assumed net discount rate of 5% corresponds approximately to a 7% discount rate with 2% inflation. Conversely, a net interest rate of 5% per year basically reflects a 7% interest rate with about 2% deflation. Note that new process water treatments technologies are currently being developed and refined and the emerging treatment methods may ultimately lead to a reduction (as opposed to increase) in the unit cost for treating process water. In light of this and in the interest of keeping the cost/benefit analyses relatively simple, a net discount/interest rate of 5% was used (with zero inflation).

Clearly, the secondary liner, installed preferably when a gypsum stack rises to an elevation corresponding to two-thirds the design height, can effectively reduce costs and environmental liabilities at terminal closure of a gypsum stack. In order for this design feature to be effective, however, the plant must have a negative water balance and must be capable of consuming pore water that drains from the lower portion of the stack prior to terminal closure, i.e., prior to plant shut-down. A comprehensive study funded by FIPR (FIPR 04-01-190) is currently underway to evaluate the effect of specific process changes and water balance improvements on financial liability of a closed phosphogypsum stack system. That study is focused on reducing the volume of drainable pore water at final closure of the system by implementation of various measures, including process changes at the plant, early closure of certain portions of the facility, as well as installation of a secondary liner on the gypsum stack as it is being raised to promote early dewatering of drainable pore water. Results from that study will provide insight into whether the plant is capable of consuming all pore water that drains from the phosphogypsum stack prior to terminal closure.

PRACTICAL IMPLICATIONS

The use of secondary liners, installed when a gypsum stack achieves a height greater than mid-height of the stack and preferably when the stack rises to a higher elevation corresponding to two-thirds the design height, appears to be a planning tool or a design feature that can effectively reduce costs and environmental liabilities at terminal closure of a given facility. In order for this design feature to be cost-effective, the plant must have a negative water balance and must be capable of consuming pore water that drains from the lower "capped" portion of the stack prior to terminal closure, i.e., prior to plant shut-down.

Use of a secondary liner will increase the useful life of a stack by promoting consolidation of the *in situ* gypsum and will also provide an opportunity for the plant to recover P_2O_5 that would otherwise be lost. The quantity of post-closure drainable pore water requiring treatment will also be significantly reduced as a result. In order for the intermediate liner design feature to be cost-effective, the plant must have a negative water balance and must be capable of consuming pore water that drains from beneath the secondary liner prior to terminal closure. The secondary liner, if installed when a gypsum stack rises to two-thirds the design height, is expected to yield significant savings in post-closure liabilities at unit treatment costs in the range of $15 to $25 per thousand gallons of acidic process water. At these unit rates, use of such a secondary liner on a typical stack is likely to net financial liability savings on the order of 20 to 32 million dollars in 2006 dollars as a direct result of the reduced quantity of process water requiring treatment after closure.

Considering P_2O_5 recovery benefits in the range of $6.38 to $14.87 per thousand gallons of pore water consumed prior to terminal closure and typical costs for liner system installation, cost/benefit analyses indicate that an intermediate liner installed at two-thirds the design height of the stack is likely to net cost savings on the order of 15 to 40 million dollars. A breakeven point wherein the intermediate liner will no longer be cost-effective would occur if emerging technologies lead to a reduction in the cost of treating process water to the low-end range of $5 to $7 per thousand gallons.

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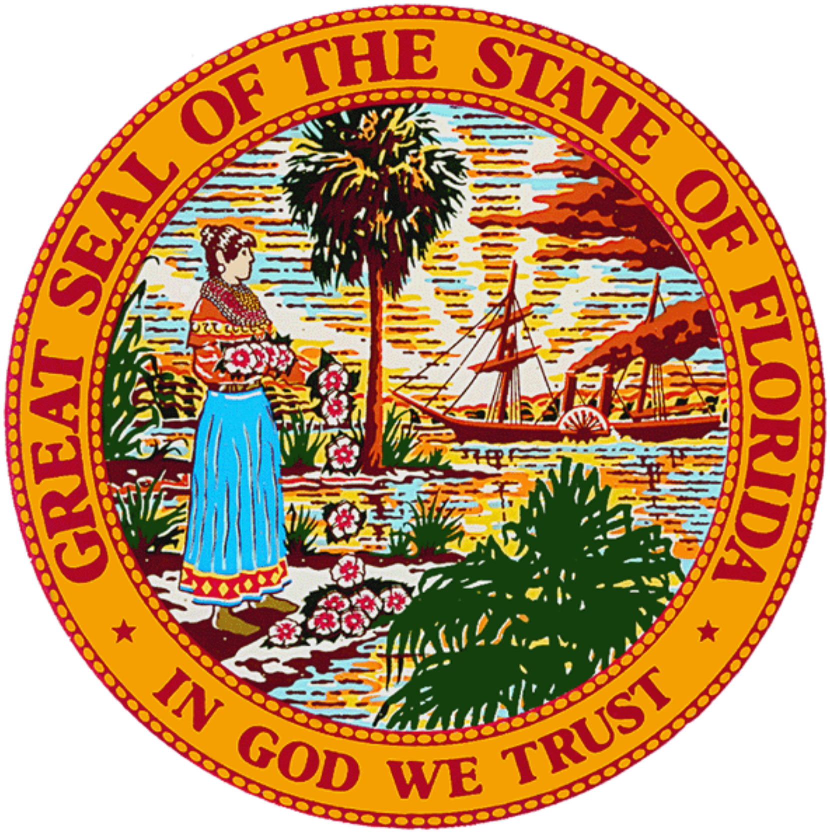
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