AN ENGINEERING APPROACH TO THE ELIMINATION OF CONTAMINATED SEEPAGE FROM PROCESSED SHALE PILES

by

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INTRODUCTION

This paper presents the results of investigations which have been conducted into the nature of water movement in processed oil shale piles, in order to evaluate the best methods of eliminating contaminated seepage. The investigations have been specifically directed at the disposal of a direct-retorted, fine-grained processed shale in the Piceance Basin. However it is believed that the technology described is applicable to the disposal of a wide range of materials in similar climatic conditions.

Processed shale piles have the potential to become sources of contaminated groundwater as a result of long term leaching of salts and hydrocarbons liberated in the retorting process. As the flow of water in these piles is generally extremely slow, the direct testing of the long term effects of the piles is not feasible in the time spans that are available. The study reported in this paper sought to overcome this problem by developing a simple model of the flow in a processed shale pile, and using this model to evaluate possible seepage mitigation measures

A SIMPLE MODEL OF LONG TERM FLOW WITHIN THE PILE

The flow of water within a processed shale pile is complicated. The retorted shale is often emplaced in the pile at a temperature considerably above ambient temperature, and cools over a very considerable period of time. The processed shale may also be chemically active; it may have considerable pozzolanic activity, and it may also have a considerable quantity of leachable salts. In addition the processed shale is emplaced in an unsaturated state, and will in all probability remain unsaturated. Finally, the pile is made up of a mixture of waste rock from the mining process, and processed shale from the retorting.

From the point of view of the minimization of contamination due to seepage from the pile, the most critical period is after the pozzolanic activity has been satisfied by available and infiltrated water, and after the temperature has returned to equilibrium with the natural geothermal conditions. Before this condition is reached, both the chemical and temperature effects appear to delay the formation and discharge of contaminated seepage. Accordingly, the approach of this study is to ignore these temperature and chemical transients, thus resulting in a conservative analysis with respect to environmental impact of the pile.

The water movement in the pile can be divided into three distinct zones: the infiltration zone, the interior flow zone, and the exit zone. Each is considered below.

The Infiltration Zone

The infiltration zone is the portion of the pile where the partitioning of the incident precipitation occurs. Evaporation and transpiration absorb the majority of the incident precipitation, with a small portion escaping these processes and entering the deep flow system.

The processes that take place in the infiltration zone are the subject of a major discipline (soil physics), and have been dealt with in detail with respect to processed oil shale elsewhere (see for example Bond et al, 1982). The general conclusions which come out of the literature are:

1. Flow conditions in the infiltration zone are highly variable, and are determined by a complex interaction of meteorological, soil physics, thermodyamic, and biological phenomena.

2. The transient nature of these phenomena tends to disappear at depths of a few meters below the ground surface.

3. Regardless of how arid the region being considered is, some portion of the incident surface water always escapes from the infiltration zone and passes into the material below.

The quantification of the amount of infiltration which will actually occur is not possible in advance of the design of the pile, and of the vegetative cover that will be established on it. In general infiltration in natural systems has been found to be between 5% and 10% of the incident precipitation, when back analysed from flow models [see for example Weeks et al, 1974 (on infiltration in the Piceance Basin); and Reddell, 1967 (on infiltration to the Ogallala aquifer in Eastern Colorado)].

For the purposes of this evaluation the infiltration will be assumed to be a variable, with the best estimate being 25 millimeters (1 inch) per year, about 5% of the incident precipitation. This is the value computed by Weeks et al (1974) for the natural terrain in this area.

It is possible to evaluate the likelyhood that this flow can reach the interior flow zone, by evaluating the bounding saturated flow that the material could sustain. The saturated flow is governed by Darcy's Law (Darcy, 1856):

$$q = K\ i \qquad (1)$$

where q = volumetric flow per unit area
K = hydraulic conductivity
i = hydraulic gradient

The hydraulic conductivity of processed shale has been evaluated by several investigators. Some typical results are presented in Table 1.

Table 1. Hydraulic conductivities of processed oil shales.

Investigator, Date, and Material	Hydraulic Conductivity (meters/sec)
Bloomsburg and Wells, 1978	
Loose Paraho	2 E-06
Compacted Paraho	7 E-09
Colorado State, 1983	
Loose Lurgi	1 E-07
Compacted Lurgi	7 E-09

Thus the minimum hydraulic conductivity measured in these tests is 7 E-09 meters per second. If flow into the system is in the saturated mode, flow will occur under a gradient of unity. Inserting a value of unity into Equation 1 indicates that the numerical value of the infiltration rate will be equal to the vertical hydraulic conductivity. Converting this value indicates that the maximum infiltration rate that could be sustained through compacted processed shale is 220 millimeters per year. This is far in excess of the expected infiltration, so that there is no reason that 25 millimeters of infiltration could not enter the interior flow zone. A corollary of this is that compacting the shale to reduce its permeability will not be effective in limiting the infiltration to the pile.

Interior Flow Zone

The flow regime in the interior flow zone is divided into two regions. The lower region has flow that represents movement of moisture that was emplaced in the pile. This region thus reduces in size with time, as the moisture moves out of the base of the zone. Flow in the upper region of the zone results from infiltrated water, and is in general taking place at a different rate than in the lower region.

The interface between these two flow regions moves downward, at a rate that depends on the properties of the pile materials, the infiltration rate, and the initial processed shale moisture content. The interface is not, in reality, a sharp division, but a gradational change between the two zones of different moisture content. However in this study a sharp change has been assumed for simplicity. Using this simplification, the theoretical behavior of this interface has been developed by the authors, and results in the following equations:

$$T = Zo \frac{\left[\theta'' - \phi(q'/K)^{(1/n)} \right]}{\left[K(\theta''/\phi)^{(n-q')} \right]} \qquad (2)$$

where T = time for interface to traverse pile
Zo = height of pile
θ = Volumetric Wetness
φ = total porosity of medium
q = infiltration/exfiltration
K = saturated hydraulic conductivity
n = Brooks-Corey (1966) exponent
' = indicates upper region of pile
" = indicates lower region of pile

For the special case where the processed shale is disposed of dry ($\theta''=0$), this equation becomes:

$$T = \frac{Zo\ \phi}{\left[q'^{(1-1/n)}\ K^{(1/n)} \right]} \qquad (3)$$

The time for the interface to traverse the pile has been computed for various situations, and the results are presented in Figures 1, 2, and 3. Note that each set of analyses refers to a "base case". The "base case" is a best estimate of the actual conditions that will occur in a real pile made up of direct retorted, fine processed shale. The "base case" parameters are as follows:

Vertical hydraulic conductivity (K)	2.0 E-07 m/s
Porosity (φ):	0.48
Infiltration to interior (q'):	25 mm/year
Pile depth (Zo):	100 meters
Brooks-Corey exponent (n):	4
Initial volumetric wetness (θ"):	0.0

All these values are either reported in the literature or are reasonable for the case considered. As can be seen, the parameters that are varied in the analyses are vertical saturated hydraulic conductivity, infiltration rate, and initial volumetric wetness.

Figure 1 shows the time taken for the interface to move through a pile of processed shale 100 meters thick, assuming that it was initially dry. For the "base case" the time is about 800 years. Note that the time for this wetting front to arrive at the base of the pile is a weak function of saturated hydraulic conductivity and a linear function of infiltration. As the saturated hydraulic conductivity drops, there comes a point where the infiltration is controlled by the conductivity, rather than by the available infiltration. However, for a reasonable infiltration rate (25mm/year) this occurs at a vertical saturated hydraulic conductivity of 8 E-10 meters/second, which is well below achievable values in this material.

Figure 2 shows the time that the interface (between the original and the infiltrated water) takes to reach the base of the pile, as a function of the initial moisture content of the pile. Clearly, the time is a very strong function of the initial wetness, mainly because this parameter controls the available porespace in the processed spent shale. If the initial moisture content is 20%, the transit time for the interface is less than 100 years, for any reasonable infiltration rate.

Figure 3 shows the initial seepage rate from the base of the pile (ignoring chemical and temperature effects) for the base case with the initial volumetric wetness varying. The rate is expressed as an equivalent seepage rate (equivalent to an infiltration rate) and as a flow per unit area. Note that for initial moisture contents in excess of 9%, the theoretical seepage rate actually decreases when the interface reaches the base of the pile.

These figures show that the seepage from the base of the pile is a strong function of the initial wetness, and a weak function of the saturated vertical hydraulic conductivity of the processed shale. The long term steady state seepage from this zone is equal to the infiltration rate for reasonable material parameters. The time which is required to establish this steady state condition is a strong inverse function of the initial moisture content, a linear inverse function of the infiltration rate, and a weak inverse function of the saturated hydraulic conductivity.

Thus the control of seepage and leachate production within the pile is most closely tied to the control of initial moisture content, and control of infiltration.

Exit Zone

Once flow nears the lower boundary of the pile, consideration must be given to how the water will exit the pile. This depends very much on the conditions present in the foundation of the pile. Three conditions typify the possibilities:

1. A saturated foundation material, such as would exist if the foundation were below the water table.

2. A foundation which is not fully saturated with water, but where the air in the pore-space is saturated with water vapor. In this case, liquid water can flow through the foundation material.

3. A "dry" foundation, where the relative humidity in the foundation is kept low enough to ensure that all water entering the foundation material will evaporate.

In the first two cases, water can flow out of the pile in the liquid phase, carrying with it dissolved contaminants. On the other hand, in the last case the contaminants are left behind in the base of the pile, while the water exits as vapor.

An analysis was performed to evaluate the feasibility of moving the water out of the pile in the vapor phase, provided that the foundation materials could be kept at low humidities (this provision will be evaluated in the next section). The process is a diffusion process, so that the hydraulic conductivity of the material is irrelevant. The equation that results from this analysis is:

$$Zf = \frac{Dv\ (V'-V'')}{q'\ \ pw} \qquad (4)$$

Where Zf = distance above the base of the pile at which flow will be totally in the vapor phase

Dv = vapor diffusion coefficient

V = water vapor concentration

q = volumetric seepage rate

pw = density of water

' = indicates in base of pile

" = indicates in foundation

The thickness of the zone in which the flow is in the vapor phase is presented in Figure 4. This zone is defined as the "exit zone". The parameters used in the evaluation are:

Dv = 5.7 E-06 m2/sec
V' = 9 E-03 kg/m3
V" = 0 (approximately)
q' = 25 mm/year (varied)
pw = 1000 kg/m3

As can be seen from the figure, the exit zone is typically very narrow, generally less than 0.1 meter. Thus the evaporation of the flow will take place in a very small volume of material. The salts that were originally dissolved in the seepage will deposit in this area, creating a "caliche" layer at the base of the pile. This process will result in the reduction of both pore volume and saturated hydraulic conductivity of the material in this area. This will probably have the eventual effect of reducing the flux of vapor through the base of the pile, and of "armoring" the base of the pile against significant saturated flow if the foundation were to cease to be effective in removing the vapor flow.

FLOW IN THE FOUNDATION

As noted above, if the air in the foundation materials can be kept at a moisture content below that of the processed shale, then the water transfer out of the pile will be in the vapor phase, rather than the liquid phase, and will therefore not carry the dissolved solids. This section evaluates the feasibility of designing a foundation that is capable of achieving this condition.

The concept which has been developed is to engineer a foundation system that will cause ambient air to be drawn through the foundation materials at a flow rate adequate to evaporate all the seepage water.

The flow must be capable of being sustained in geologic timescales for the mitigation process to be truly effective. Thus the air flow must be self-sustaining after the processed shale pile has cooled and all cementation reactions have taken place. Two mechanisms appear to be significant in the long term for maintaining an air flow in the pile: air density changes due to humidification, and air density changes due to heating by geothermal sources.

The density of dry air is greater than the density of moist air. This somewhat surprising fact is a result of the relatively high vapor pressure exerted by water. As a result, as the air in the foundation absorbs the seepage water, the density drops, and it seeks to rise relative to the air outside the pile.

In addition, the temperature inside the pile will generally be higher than the average temperature outside the pile. Any air flowing into the pile foundation will therefore be heated, and as a result its density will also drop. This will create a bouyancy effect, helping to drive the air out of the foundation into the outside airmass.

The foundation design evaluated in this study is shown in Figure 5. It is essentially a combination of an underdrain and a chimney, with the processed shale taking the shape of a doughnut around the chimney. This system was analysed for the flow of dry air through the foundation materials as a result of the buoyancy induced solely by the natural geothermal gradient. In the Piceance Basin area this gradient is about 4.7°C per 100 meters of depth, which is somewhat higher than the global average (Tait, 1972). The resulting equation is as follows:

$$Q = \frac{\# \; r*r \; k \; p \; [RG + g] \; [1 - T'' \exp(-2gM/RT)]}{u \; (T'' - 1) \left[1 + \dfrac{r*r \; (RG + g) \; \ln(r'/r)}{m \; R \; T' \; (T'' - 1)} \right]} \qquad (5)$$

where Q = air flow rate
\# = pi
r = radius of chimney
r' = outer radius of pile
k = absolute permeability
p = average density of air
R = gas constant for dry air
G = geothermal gradient: (T - T') / M
g = acceleration due to gravity
T = air temperature outside pile
T' = air temperature inside foundation
T" = temperature ratio factor
m = thickness of foundation material
M = thickness of entire pile
u = absolute viscosity of air

The temperature ratio factor is found from the following equation:

$$T'' = \left(\frac{T}{T'} \right)^{2(RG + g)/RG} \qquad (6)$$

The parameters which apply to the foundation system of a processed shale pile located at Tract C-a are approximately as follows:

\# = 3.14159
r = 360 m
r' = 1800 m (equivalent to an area of 4 square miles)
k = 2.0 E-07 m2 (equivalent to a hydraulic conductivity of 2 m/s)
p = 0.96 kg/m3
R = 288.7 m2/s2-°K
G = -0.047 °K/m
g = 9.8 m/s2
T = 280 °K
T' = 284.7 °K
T" = 0.9908
m = 30 m
M = 100 m
u = 1.8 E-05 kg/m-s (180 micropoise)

Applying these parameters to the above equation produces an air flow of 1650 cu.m/sec. Despite the fact that this appears to be a large air flow (in more common units it is 3 million cubic feet per minute), the bulk velocity of air at the exit point of the chimney will be less than 0.01 meters per second, which will be barely detectable.

The corresponding flow of water is found by reference to psychrometric charts and computes to be 0.0091 cu.m/sec. The seepage rate from the pile is 0.0085 cu.m/sec for an infiltration rate of 25 millimeters per year. It is therefore clear that the system as shown is able to exhaust the seepage water which would occur if all the infiltration did in fact pass through the pile.

It should be noted that the flow computed above is doubly conservative. First, it ignores the bouyancy effect of the increased humidity of the air in the foundation of the pile. Second, it ignores the effects of the residual heat in the foundation as a result of the elevated temperature of the processed shale when deposited, and the heat generated by the exothermic reaction of the shale when water flows through it. Despite ignoring these potentially major effects, the long term ability of the pile to exhaust the infiltrated water seems assured.

ENGINEERED APPROACHES TO SEEPAGE REDUCTION

The above discussion gives a basis from which to judge the likely effectiveness of various possible methods of reducing contaminated seepage from processed shale piles in the west of the United States. These methods include the following:

1. Sealing the surface of the pile. This strategy is attractive, as the genesis of all long term seepage is infiltration. However to significantly reduce the infiltration below the present level (estimated at 25 millimeters per year) requires the installation of a cover material that has an hydraulic conductivity of less than 8E-10 meters per second, and will survive for geologic lengths of time. It is believed that this is an impossibly difficult specification to meet, using either natural or synthetic materials.

2. Reducing the permeability of the interior of the pile. There have been suggestions that if the permeability of the pile is reduced (usually by compaction) this will reduce the seepage through it. However, as mentioned above, the seepage transit time is only a weak function of the permeability of the material, and the ultimate seepage rate is not affected by the permeability at all unless it is below about 8E-10 meters per second. Thus this strategy is not likely to be effective.

3. Providing a liner on the base of the pile. The final strategy that is common in waste disposal projects is the provision of a liner beneath the facility, in order to create a physical barrier to seepage. Again, for the liner to be effective, it must meet the specification of having a hydraulic conductivity of less than 8E-10 meters per second, and of being effectively indestructible.

4. Providing a ventilated foundation to cause vapor transport of the seepage. This strategy appears to have the capability of allowing the inevitable seepage to the pile to pass from the base of the pile in the vapor phase, thus eliminating the transport of contaminants from the pile. As shown in this paper, careful design of the foundation can achieve this effect over geologic time without external power input.

CONCLUSION

It is possible to prevent the movement of dissolved solids from a processed shale pile to the environment by the provision of a carefully engineered foundation ventilation system. Such a system will ensure that all water leaves the pile in the vapor phase, and will therefore not transport any dissolved solids. This paper provides the theoretical justification for placing reliance on such a system for environmental protection against contaminated seepage.

REFERENCES

Bloomsburg, G.L., and Wells, R.D., 1978, "Seepage Through Partially Saturated Shale Wastes," U.S. Bureau of Mines

Bond, F.W., Freshley, M.D., and Gee, G.W., 1982, "Unsaturated Flow Modelling of a Retorted Oil Shale Pile," Pacific Northwest Laboratory, Richland.

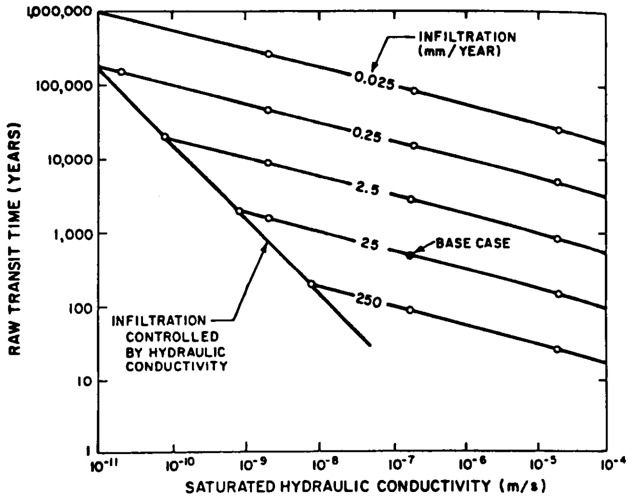
Colorado State University, 1983, Personal communication on results of ongoing testing of processed shales.

Darcy, H., 1856, "Les Fontaines Publiques de la Ville de Dijon - Exposition et Application des Principles a Suivre et des Formules a Employer dans les Questions de Distribution d'Eau," Libraire des Corps Imperieux des Ponts et Chaussees et des Mines, Paris.

Reddell, D.L., 1967, "Distribution of Groundwater Recharge." Masters thesis CET66- 67DLR37, Colorado State University, Fort Collins, Colorado.

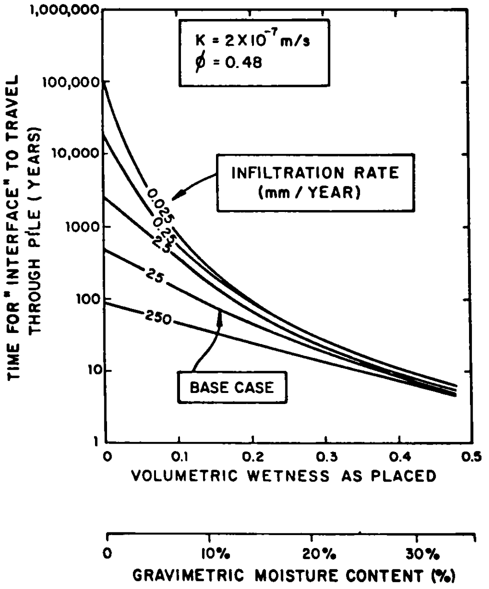
Tait, D.B., 1972, "Geohydrology of the Piceance Creek Basin, Colorado." Colony Development Operation, Denver, Colorado.

Weeks, J.B., Leavesley, G.H., Welder, F.A., and Saulnier, G.J., 1974, "Simulated Effects of Oil Shale Development on the Hydrology of the Piceance Basin, Colorado." U.S. Geological Survey Professional Paper 908.



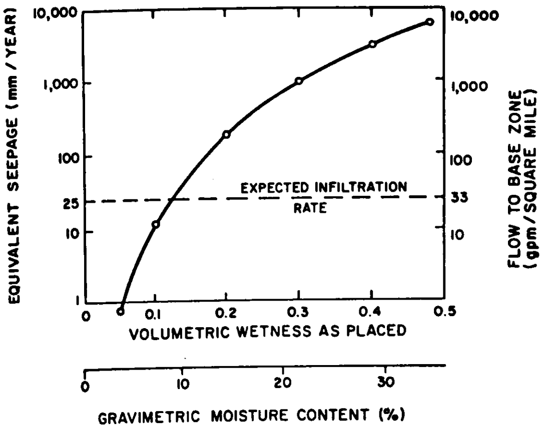
TIME FOR THE INTERFACE TO MOVE THROUGH A 100 METER THICK PILE

Figure 1



EFFECT OF INITIAL MOISTURE CONTENT ON INTERFACE TRANSIT TIME

Figure 2

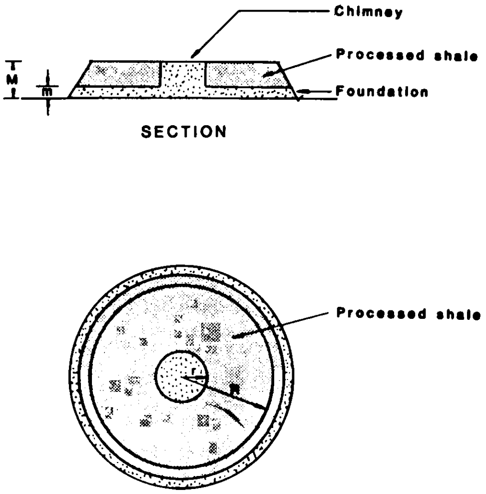


BASE PARAMETERS-$K_s = 2 \times 10^{-7}$ m/s

$\phi = 0.48$

INITIAL SEEPAGE RATE
FROM THE INTERIOR FLOW ZONE

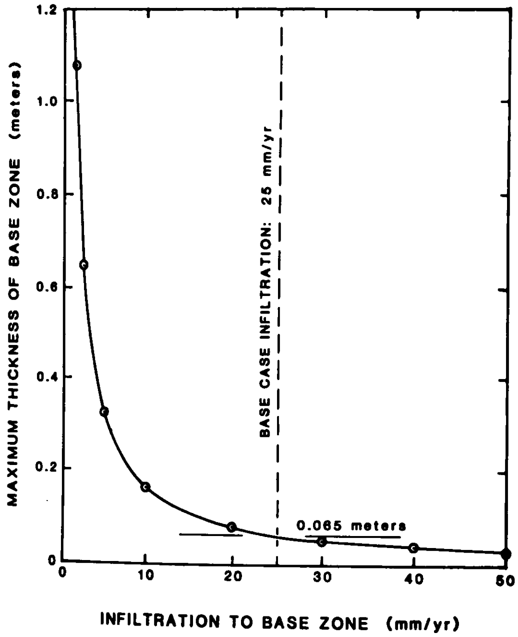
Figure 3



PLAN

CONCEPTUAL PROCESSED OIL SHALE PILE
DESIGN WITH VENTILATED FOUNDATION

Figure 5



THICKNESS OF EXIT ZONE

Figure 4