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

by

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ABSTRACT

This paper presents the results of continuing investigations into the nature of the behavior of seepage through a processed shale pile, and of the engineering steps that appear attractive to reduce or eliminate the transport of saline minerals from a processed shale pile by that seepage. This work is a continuation of research presented in the 17th Symposium which suggested that transport of contaminants could be eliminated by pile foundation design that encouraged water to leave the base of the pile in the vapor phase.

This paper presents the results of investigations into the energetics of this process, particulary the identification of possible sources for the energy required to evaporate the water in the pile. The results of the evaluation show that geothermal and residual pile heat are inadequate to vaporize the water, but that cooling of air drawn into the foundation system is able to provide the required energy. Based on this finding, a design for the pile and its foundation has been developed.

INTRODUCTION

Seepage of saline leachate from processed shale piles has been and remains an important concern of those who are involved in the development and regulation of oil shale production. This paper reports the current status of a long term investigation into the feasibility of engineering a processed shale pile that would prevent the discharge of saline leachate into the environment.

The engineered control concept which has evolved during this investigation involves the provision of a highly permeable foundation for the processed shale which allows the vaporization of any seepage through the pile, and the removal of the water vapor to the atmosphere. Any saline minerals which are dissolved in the seepage will remain in the base of the processed shale pile, forming a "caliche" layer which may impede subsequent flow from the pile.

The general concept of the engineered system was first published in the 17th Oil Shale Symposium. The present paper examines the thermodynamic feasibility of the concept.

This study is part of the continuing environmental protection activities funded by Rio Blanco Oil Shale Company in the development of their Federal Oil Shale Tract C-a. While the paper is specifically applicable to Rio Blanco Oil Shale Project's C-a Tract processed shale disposal area, on 84 Mesa in the Piceance Basin, it is believed to have general applicability to other waste disposal activities in arid areas.

CURRENT STATUS OF THE PROJECT

The status of the project at the start of the activities described in this paper was as follows:

1. The physics of the flow system in a processed shale pile under conditions of constant temperature and constant infiltration had been evaluated. This evaluation confirmed that there would always be some net infiltration into the processed shale pile, and that this infiltration would, in time, exit the base of the pile either as high salinity groundwater, or as essentially deionized water vapor.
2. A conceptual processed shale pile design was developed to create the conditions needed to allow vapor phase discharge of water from the base of the pile. This design involved the provision of a thick, high permeability layer beneath the processed shale, which was connected to a "chimney" in the center of the pile. The concept for the removal of moisture from the pile was to take advantage of the density contrast between the moist, cool air in the foundation and the generally warmer air outside the pile to cause airflow within the foundation. This flow would remove air saturated with seepage water vapor from the foundation material, and replace it with relatively dry air. This design and vapor removal concept was reported in Brown et al, 1984.
3. A check was performed to evaluate the validity of the thermodynamics of the vaporization of the water at the base of the pile. This evaluation is presented in this paper.

Ongoing work is examining the effects of temporal changes in pressure and temperature inside and outside the pile, to develop an understanding of the effects of these changes on the performance of the proposed environmental protection system.

EVALUATION OF THERMODYNAMICS OF VAPORIZATION

SYSTEM EVALUATED

The system evaluated in this paper is approximately as shown in Figure 1, which is the system that was suggested as a result of the previous paper on this subject by the authors (Brown et al, 1984). In this design, processed shale is placed in a pile which also has a very coarse drainage layer at some location within it. The processed shale is generally fine, hot, and relatively dry. The drainage layer is expected to be constructed of pit run waste rock.

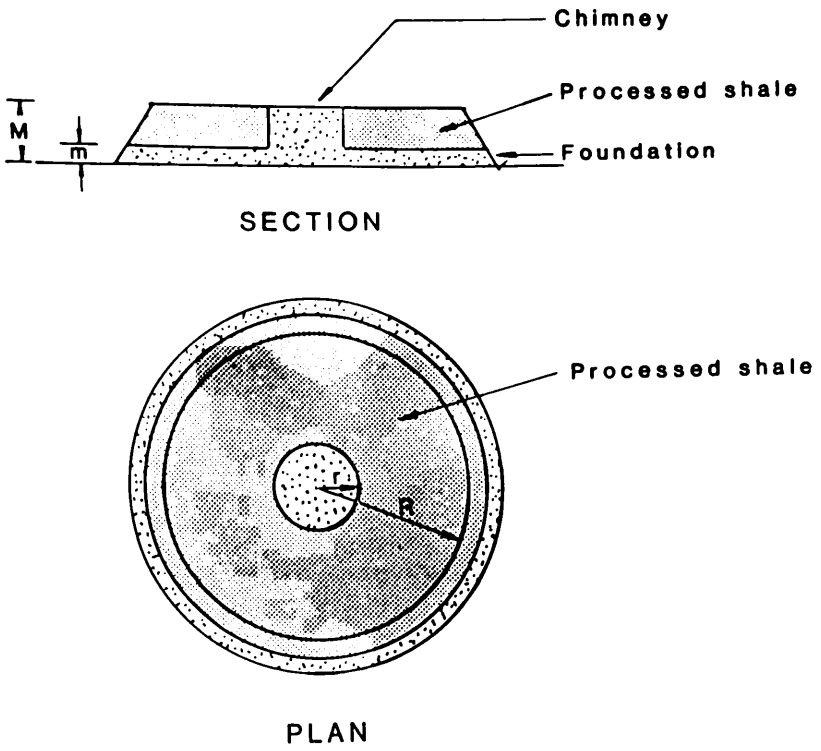

Figure 1. Schematic of initial processed shale pile design used in this paper (Brown et al, 1984)

HEAT REQUIRED TO EVAPORATE WATER

There is a considerable amount of heat required to evaporate the water that infiltrates into the pile. Consider a square meter of pile area. The infiltration of incident precipitation to that area has been estimated at 25 millimeters per year (Brown et al, 1984, Weeks et al, 1977). Using this infiltration rate, the total water flow rate to the foundation material is:

$$q = \text{infiltration} \times \text{area}$$

$$= 2.5\text{x}10^{-2}\ \text{m}^3/\text{m}^2/\text{year}$$

The density of water is 10^3 kilograms per cubic meter. Thus the mass of water to be vaporized is:

$$m = \text{flow rate} \times \text{density}$$

$$= 25\ \text{kilogram/m}^2/\text{year}$$

The latent heat of vaporization of water at 7^{o}C is 593 kilocalories per kilogram. Thus the heat required to vaporize the water flowing to the foundation is:

$$h = \text{mass flow rate} \times \text{latent heat of vaporization}$$

$$= 1.48\text{x}10^7\ \text{calories/m}^2/\text{year}$$

As one calorie is equal to 4.186 Joules (the mechanical equivalent of heat), the power required for the vaporization of the seepage is:

$$p = \text{heating rate} \times \text{mechanical equivalent of heat}$$

$$= 6.2\text{x}10^7\ \text{Joule/m}^2/\text{year}$$

Noting that 1 Joule per second is equal to one Watt, the power needed to vaporize the seepage is:

$$p = 2.0\ \text{Watt/m}^2$$

The area of the processed shale pile assumed throughout this study is 1000 hectares (equivalent to 4 square miles). Using this area, the total amount of water flowing is:

$$Q = \text{infiltration rate} \times \text{area}$$

$$= 8\ \text{kilograms per second (8 l/sec; 130 gpm)}$$

The total power required to evaporate the water is:

$$P = \text{power per unit area} \times \text{area}$$

$$= 20\ \text{megawatts (27,000 horsepower)}$$

which is a very considerable amount of power.

VAPORIZATION USING TERRESTRIAL HEAT SOURCES

Geothermal heat flow

The most obvious source of heat is the heat flowing through the earth's crust. While this heat flux varies, a reasonable global average is 70 milliwatts per square meter. This is about 4% of the heat required for the evaporation of the seepage water (2 watts per square meter). It is clear from this evaluation that the power available from geothermal sources is inadequate to evaporate the seepage on its own. The power available over the entire area of the pile from geothermal sources is:

$$P_g = \text{geothermal heat flux} \times \text{area}$$

$$= 0.7\ \text{megawatts}$$

This amount of power is still considerable, and would be adequate to conduct the moist air out of the foundation material.

Internal heat of the processed shale pile

The processed shale will be placed in the pile at a temperature which will range from 40 degrees celcius to 100 degrees celcius. The heat energy trapped in the pile will be available for the evaporation of water in the foundation.

Consider the maximium amount of water that this heat can evaporate. If it is assumed that:

1. the processed shale pile is 100 meters thick,
2. its initial temperature averages 100^{o}C,
3. it cools to a final temperature of 7^{o}C,
4. the specific heat of processed shale is 0.21 calories per gram per degree celcius, and
5. the density of processed shale is 1300 kilograms per cubic meter,

then the heat lost is:

$$h = \text{volume} \times \text{density} \times \text{temperature change} \times \text{specific heat}$$

$$= 2.5\text{x}10^6\ \text{kilocalories/m}^2$$

If it is further assumed that there is no heat loss from the surfaces of the processed shale, and that all heat in the pile goes to evaporation of seepage water, then the maximum amount of water that can be evaporated using this heat is:

m = available heat/specific heat of vaporization

= 4.2×10^3 kilograms of water/m^2

The time for this amount of water to seep through the pile (from the time of first arrival of the seepage at the base of the pile) for a mass flow rate of water of 25 mm per year (or 0.025 cubic meters per square meter per year) is:

t = mass of water / mass flow rate

= 170 years

Accordingly, it is clear that the maximum time that the heat available at emplacement of the pile would be able to evaporate the seepage water would be less than 170 years. While this is useful additional protection, it is not significant when compared to a reasonable containment period, for example the period to the next ice age, projected to be perhaps 10,000 years. By that time, the performance of the seepage control system in the pile will likely be irrelevant.

It is worthy of note that the energy available from the heat in the pile is significant. The energy can be computed from:

E = heat/unit area x area x mech. equiv. of heat

= 1.1×10^{17} Joules

which is, of course, equal to the energy available from a 20 megawatt source over 170 years.

VAPORIZATION USING ATMOSPHERIC HEAT SOURCES

The vaporization of water as it enters the foundation of the pile requires a considerable amount of heat. One source of this heat is the air that could be made to flow through the foundation. Assume for the present that air is flowing in the foundation. As the water evaporates, the air is cooled in order to provide the heat of vaporization of the water. As a result of the cooling, the density of the air increases. As a result of the increase of density, the air in the drainage system flows downward, drawing more air into the foundation system, and forcing the more saturated air out the base of the pile. Note however that there is a somewhat compensating decrease of density due to the increased humidity of the air. The physics of the flow system has already been considered in Brown et al, 1984.

To evaluate the effectiveness of this mechanism, consider the following analysis. Assume that 5000 cubic meters of air enters the center of the drain at 7 °C, and flows from the center of the pile drain to the periphery. Also assume that there is a total of 25 mm per year of infiltration, all of which is reaching the drain. At the drain, the water evaporates, saturating the flowing air with water vapor, and cooling the air.

The heat lost by the water is:

H = mass flow rate x heat of vaporization

= 4.3×10^3 kilocalories/second

The specific heat at constant pressure of air at these temperatures is about 0.17 calories per gram per degree celcius. The temperature drop due to the evaporation of the water is given by:

dT = heat withdrawal rate /
(mass air flow rate x specific heat)

= 5°C

The air temperature in the foundation would drop to close to freezing in this case. At these temperatures, the water carrying capacity of saturated air is quite low, about 0.0045 times the mass flow rate of air, based on psychrometric charts. As some water is introduced in the intake air (these computations assume 50% relative humidity), the net mass removal rate of water is only about 0.0016 times the mass flow rate of air. The seepage rate in the pile is 8 kg per second. In order to remove this mass flow rate of water, the mass flow rate of air must be 5000 kg per second, which is why this rate has been used above.

The question then must be asked as to whether the density change induced by this temperature change is adequate to cause this air flow. Based on the evaluation performed in Brown et al, 1984, the equivalent hydraulic conductivity of the foundation materials would need to be in the order of 10 meters per second. This is equivalent to a coarse gravel or cobble rock drain, which is achievable with materials available on site (waste mine rock).

FEASIBILITY OF VAPORIZATION PROCESS

In order to check the feasibility of the vaporization process described above, the process was evaluated using the second law of thermodynamics. This law states that (Perry, 1984):

> "The entropy change of any system and its surroundings, considered together, resulting from any real process is positive and approaches a limiting value of zero for any process that approaches reversibility."

Based on this law, an equation for the change in entropy of any open system can be developed:

$$S_{in} - S_{out} + (Q/T)_{in} - (Q/T)_{out} + S_{gen} = 0$$

where: S_{in} = sum of mass flow rate times specific entropy of inputs to system
S_{out} = sum of mass flow rate times specific entropy of outputs from system
Q/T_{in} = sum of heat flow/temperature for heat inputs to system
Q/T_{out} = sum of heat flow/temperature for heat outputs from system
S_{gen} = rate of generation of entropy by the system.

If the rate of generation of entropy by the system is positive, then the process is possible.

The system considered is indictated in Figure 2. The boundary across which the entropy change is evaluated is also indicated. The terms in the above equation are computed as shown in the following subsections.

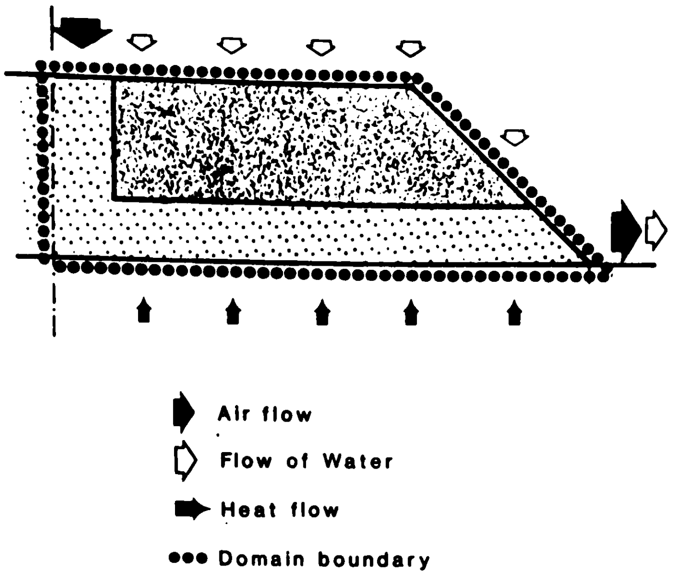

Figure 2. Boundary of thermodynamic system

Basic parameters

The basic parameters used in the analysis are as follows:

	Parameter	Value
1.	Elevation at site	2130 meters
2.	Atmospheric pressure	782 millibar
3.	Density of air	0.9933 kg/m^3
4.	Average ambient temperature	7^{o}C
5.	Average ambient humidity	50%
6.	Water infiltration	8 kg/sec
7.	Air flow through pile foundation	5000 kg/sec
8.	Output air humidity	95%
9.	Geothermal heat flow	0.070 W/m^2

In addition, it is assumed that there is no net heat loss across the boundary of the pile, once it has reached steady state (i.e. the temperature of the pile has equilibrated after its initial cooling).

Entropy of input streams

The input water stream is a result of infiltration, which is estimated to be at a rate of 8 kg of water per second. The specific entropy of water at 7^{o}C is 0.103 kilojoule/(kilogram ^{o}K). Thus the rate of input of entropy due to the water stream is:

$$S_{in}(\text{water}) = \text{mass flow rate x specific entropy}$$
$$= 0.8\ \text{kJ/(sec.}^o\text{K)}$$

The entropy input due to the flow of air is computed similarly. The specific entropy of moist air at 7^{o}C and 50% humidity is 0.1226 kJ/(kg.^{o}K). The rate of introduction of entropy into the system as a result of the air intake is therefore:

$$S_{in}(\text{air}) = \text{mass flow rate x specific entropy}$$
$$= 613.0\ \text{kJ/(sec.}^o\text{K)}$$

The total input entropy associated with material streams is therefore:

$$S_{in} = S_{in}(\text{air}) + S_{in}(\text{water})$$
$$= 613.8\ \text{kJ/(sec.}^o\text{K)}$$

Entropy of input heat

In addition to the input of materials, entropy is injected into the system by the geothermal heat flux from beneath. The heat flux is assumed to be injected at the ambient temperature equivalent to 100 meters below the surface of the earth, approximately 9^{o}C. The entropy added due to the total heat flux (0.7 megawatts) is:

$$(Q/T)_{in} = \text{heat flux / temperature}$$
$$= 2.5\ \text{kJ/(sec.}^o\text{K)}$$

Entropy of output moist air stream

The output air stream is the only way in which entropy can leave the system, as it is assumed that there is no heat loss from the pile. The air stream flow rate is 5008 kilograms per second, and is assumed to be at 95% relative humidity. Based on psychrometric tables adjusted for the altitude of the site, the temperature of the output stream of moist air will be 3.6 ^{o}C. The specific entropy of air at 95% humidity and this temperature is 0.1254 kJ/(kg.^{o}K). The entropy of the stream is therefore:

$$S_{out} = \text{mass flow rate x specific entropy}$$
$$= 628.0\ \text{kJ/(sec.}^o\text{K)}$$

Net change in entropy

The net rate of change in entropy for the process is thus computed as:

$$S_{gen} = -(S_{in} - S_{out} + Q/T_{in})$$
$$= +11.7\ \text{kJ/(sec.}^o\text{K)}$$

The process is thus possible under the above assumptions, but it is close to reversible. Accordingly it is likely to be subject to interruption due to temperature changes and other transient effects.

The final humidity of the air in the foundation is open to speculation. The above computations assume a humidity of 95%. It is important that the air reach this humidity, both because of the need to carry the maximum amount of water from the system in the vapor phase, and because the process is not self-sustaining if the humidity is significantly lower. The actual humidity that will be experienced in the field will be a function of the rate at which the evaporation will take place. This is the subject of ongoing research being performed at Colorado State University under Dr. McWhorter.

IMPLICATIONS FOR DESIGN OF THE PILE

The mechanism described above could be used to drive a seepage prevention system. The design of the foundation would be modified from that presented in

Brown et al, 1984, in that the foundation drain would be constructed so as to slope towards the periphery of the pile, generally as shown in Figure 3. This slope would allow the best airflow conditions for the system, as the temperature of the air would presumably drop fairly steadily from intake to exit.

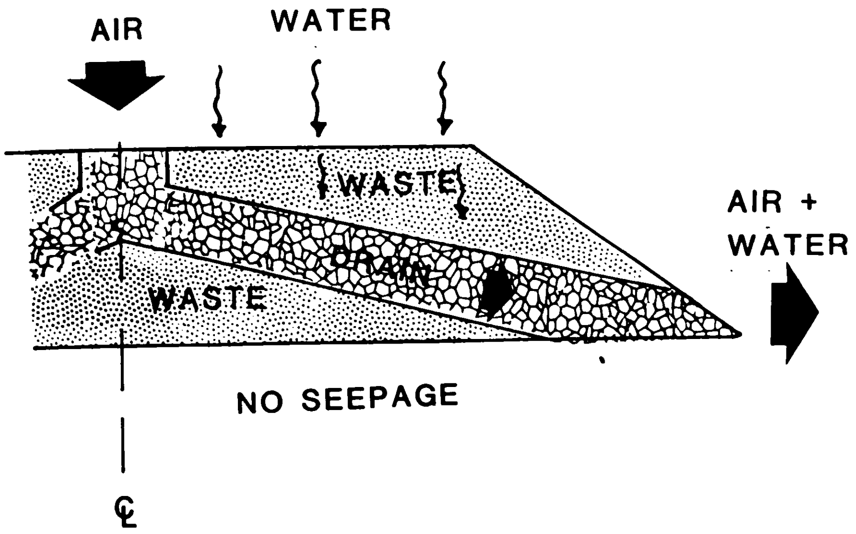

Figure 3. Schematic of modified processed shale pile design.

An alternative design approach would be to have the drain above all of the processed shale. In this way the evaporation takes place before any leachate has been created. It should be borne in mind that the only requirement of the seepage collection system is that it vaporizes and exhausts the water in the vapor form before it seeps from the pile.

CONCLUSIONS

The overall objective of the Processed Shale Seepage Project is to develop a processed shale disposal technique that includes a passive seepage control system that will be effective over several thousands of years. The theoretical work done to date has suggested that such a system is feasible. There is an adequate source of energy for the vaporization required in the system, and the process appears to be capable of being self-sustaining.

More work is required to establish the feasibility of the concept in detail, particularly with respect to the effects of daily and seasonal temperature and barometric changes. In addition, field testing is needed to provide some "real" performance against which to assess the analytical evaluations.

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