

LEACHING AND RECOVERING COPPER FROM AS-MINED MATERIALS

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**PROCEEDINGS OF THE LAS VEGAS SYMPOSIUM
FEBRUARY 26, 1980**

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Chapter 2

A MODEL OF THE DUMP LEACHING PROCESS THAT INCORPORATES OXYGEN BALANCE, HEAT BALANCE, AND TWO DIMENSIONAL AIR CONVECTION

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ABSTRACT

A mathematical model describing the leaching of low grade industrial waste dumps is developed and solved by finite difference techniques. The leaching behavior of model dumps of different sizes, permeabilities, and waste characteristics, under different operating conditions, is then investigated using the model. It is shown that leaching is fastest for dumps 50—100 feet (15—30m) high, that permeability is very important for the effective leaching of large dumps, that slow leach kinetics of the waste may not be detrimental, and that the leaching of large dumps may be facilitated if leach solutions are preferentially applied to the hot, near-edge portions of the dump.

Introduction

Previous publications have discussed the development (1) and testing (2,3,4) of a finite difference model of copper leaching in low grade industrial sulfide waste dumps. Copper leaching from low grade waste piles surrounding porphyry copper mines in the southwestern United States and elsewhere is a process of considerable economic significance. Such leaching is an important secondary source of copper; recently some mine operations have been based entirely on leaching although in these cases mainly non-sulfide, acid soluble copper, was leached. The models reported to date have considered the leaching of mixed sulfide/non-sulfide waste and have incorporated oxygen balance, heat balance, temperature dependent mixed oxidation kinetics, bacterial catalysis, and one dimensional (vertical only) air convection. The modeling and testing of the vertical air flow model has helped identify factors that are important to efficient dump leaching. It has been found, for example, that there is an optimum dump height (40-70 ft), that decrepitation of a waste during leaching promotes more rapid leaching by avoiding the inhibition that would otherwise be caused by growth of a leach rim surrounding 1-5 cm fragments of waste, that much more acid is produced and neutralized by pyrite oxidation within a dump than has been conventionally (or could be practically) added to leach solutions applied to the dump surface, and that much more iron is leached and precipitated within a typical dump than is added to the solutions in the process of recovering copper by iron precipitation. It has also been found that the average yearly rate at which leach solutions are applied to a dump can have an important impact on the rate of leaching. The ambient temperature at the dump location can also be an important factor. Many of these factors have clear implications for optimum design and operation of waste dumps.

The models previously developed are unrealistic, however, in requiring or assuming only vertical air flow through a dump (see Figure 1). Since a dump rests on ground that is much less permeable (effectively impermeable), air must convect horizontally into the dump before it can circulate upward. Since air convection carries the oxidant required for leaching (1,3), allowing for horizontal air flow could change some of the predictions made by the model. We will find this is in fact the case. The purpose of this article is to show how a model can be developed that allows for horizontal as well as vertical air flow and to explore some of the predictions of such a model.

Development of the Model

The development of the two dimensional model closely parallels the development of the one dimensional model previously reported (1,2). For this reason our discussion here will be brief. The reader is referred to the previous papers for the details omitted. Symbols are defined in the glossary.

Physically, the model simply requires conservation of mass (air and oxygen), momentum (describes air flow), and energy (heat balance):

Conservation of mass

$$\nabla \cdot q = 0 \text{ (effect of depletion of } O_2 \text{ ignored)} \quad (1)$$

$$\frac{d[O_2]}{dt} = R_{O_2} \quad (2)$$

Conservation of momentum

$$-\nabla p + \rho g - \frac{\nu}{k} q = 0 \text{ (Darcy's law for flow through porous media)} \quad (3)$$

Conservation of energy

$$\rho_m c_m \frac{dT}{dt} = K_m \nabla^2 T - \nabla \cdot (qT + q_1 c_1)T + A \quad (4)$$

Equation (4) simply states that the heat flow required to change the temperature of the dump must be supplied by conduction, the flow of air (first part of the second term on right), the flow of water (second part of second term on right), or volumetric heat sources in the dump (i.e. the exothermic sulfide oxidation reactions).

Equation (3) is converted to a more usable form by letting $q = \nabla \times \psi \hat{x}$. We ignore the consumption of air due to oxygen depletion (i.e. assume equation (1) holds) as a small price to pay for a major simplification in the equations. Substituting this expression for q in equation (3) and taking the curl of the whole expression to eliminate p results in:

$$\nabla \cdot \frac{\nu}{k} \nabla \psi - \frac{d\rho}{dy} = 0. \quad (5)$$

ψ is the so-called stream function. Air flow will occur parallel to lines of constant ψ and will be faster where the streamlines are closer together. The air convection is driven by horizontal gradients in air density, ρ .

Finally, the total derivative in equation (2) is expanded and quasi-steady state oxygen profiles through the dump assumed (i.e. $\partial[O_2]/\partial t = 0$). Then approximating ρ as ρ_0 :

$$\frac{1}{\rho_0} q \cdot \nabla [O_2] = R_{O_2} \quad (6)$$

Along a streamline, s , $a \cdot \nabla[O_2^g] = q_s \frac{\partial[O_2^g]}{\partial s}$, so

(6) can be integrated from the point of entry of air into the dump:

$$[O_2^g] = [O_2^g]_{\text{ambient}} - \int_{\text{streamline}} \left(\frac{ds}{q_s} \right) R_{O_2} \rho_o \quad (7)$$

Equations(4), (5), and (7) are the mathematical expressions of the dump leaching model. We now discuss how the parameters in these equations are obtained.

As in previous papers (1,3) the heat generated, oxygen consumed, and copper produced as a result of leaching are derived from chemical equations describing the leaching process. Considering the chemistry of the dump leaching process as a whole (including iron added in the process of removing copper by iron precipitation), it can be shown (1) that the grams of oxygen consumed per gram of copper leached, OXCU, and the calories produced per gram of copper leached, ACU, may be expressed:

$$OXCU = 1.75 + 1.91 \text{ FPY} \quad (8)$$

$$ACU = 2.89 + 5.41 \text{ FPY} \quad (9)$$

If the rate of copper leaching is given by $\partial X / \partial t$, where X is the fraction of sulfide (X_S) or non-sulfide (X_{NS}) copper remaining at any time, the rate of copper leaching, R_{Cu} , oxygen consumption, R_{O_2} , and heat production, A , are then given by:

$$R_{Cu} = \rho_m G_s H([O_2^g]) \frac{\partial X_S}{\partial t} + \rho_m G_{NS} \frac{\partial X_{NS}}{\partial t} \quad (10)$$

$$R_{O_2} = \rho_m G_s H([O_2^g]) \frac{\partial X_S}{\partial t} OXCU \quad (11)$$

$$A = \rho_m G_s H([O_2^g]) \frac{\partial X_S}{\partial t} ACU \quad (12)$$

$H([O_2^g])$ is the heavyside step function and has a value of unity for $[O_2^g] > 0$, and zero if $[O_2^g] = 0$, reflecting the fact that sulfide mineral in the dump will be oxidized only if oxygen is present in the gas-filled pores of the dump.

The rate of leaching of sulfide or non-sulfide copper is described by a shrinking core model.

$$\frac{dX}{dt} = \frac{-3X^{2/3} B(T)}{6\tau_D X^{1/3} (1-X)^{1/3} + \tau_c} \quad (13)$$

X , τ_D and τ_c may refer to sulfide or non-sulfide copper. Both τ_c and τ_D for both kinds of copper are given temperature dependence:

$$\tau(T) = \tau(T_0) \exp(E^*/R_0 T_0 - E^*/RT). \quad (14)$$

$B(T)$ is a factor which accounts for the fact bacterial catalysis of the sulfide leaching process becomes ineffective and leaching is inhibited between the temperature at which the bacteria become "sick", T_{sick} , and the temperature at which they become inactive or dormant, T_{kill} . $B(T)$ is defined as follows:

$$B(T) = 1.0 \quad T < T_{\text{sick}}$$

$$B(T) = \frac{T_{\text{kill}} - T}{T_{\text{kill}} - T_{\text{sick}}} \quad T_{\text{sick}} < T < T_{\text{kill}} \quad (15)$$

$$B(T) = 0.0 \quad T_{\text{kill}} < T$$

Between T_{sick} and T_{kill} the temperature in equation (14) is considered to remain at T_{sick} .

Finally the air in the dump is considered to be always water saturated. The air outside the dump is considered dry and the heat required to vaporize sufficient water to saturate the air is accounted for as the air circulates into the dump. Inside the dump the density of the water vapor saturated air (compared to the dry air outside) is a function of temperature and oxygen concentration in the air. The enthalpy of water saturated air is a function of temperature. The following expressions were used to describe these two parameters over the range of conditions pertinent to dump leaching:

$$\mathcal{H} = .24T + \frac{514620}{\rho} \exp(-5220.9/(T + 273)) \quad (16)$$

$$\frac{\rho}{\rho_0} = 1 - (3.66 \times 10^{-3}(T - 20)) + 2.83 \times 10^{-2}(1 - [O_2^g]) + 4.7093 \times 10^5 \exp(-5220.9/(T + 273)) \quad (17)$$

The equations ((4), (5), (7)) that represent the model are solved numerically using finite difference techniques and a computer. Equation (4) and (5) are elliptic equations and are solved sequentially using the alternating direction implicit method (5). Equation (7) is solved by following air flow into the dump. At each grid point in the dump the streamline passing through that point is followed backward till it exits the dump and the oxygen concentration computed according to (7). It is assumed that the dump rests on insulating impermeable ground. The central axis of the dump is insulating by symmetry considerations. The top and right side of the dump are assumed to allow free air flow in or out and be at a constant (no seasonal variation) ambient temperature.

Discussion of Results

Figure 2 shows the results of one particular calculation. The figure represents a cross-section through half a dump. The dump is assumed to be much longer in the direction in and out of the page than it is wide. The center of the dump is at the left; a free face into which air can convect to the right. Air circulation is shown by streamlines with arrows on them, temperature contours are shown by solid lines without arrows, and contours showing the fraction of normal oxygen in air in the dump are given as dotted lines. The particular cross-section is for a dump 100 ft high and 200 ft wide and is for a time 2 years after the dump was constructed. It can be seen that the dump has heated up substantially and is sustaining air convection vigorous enough to maintain oxygenated air throughout the dump. Also the dump has nowhere heated up to over T_{sick}

(40°C), so bacteria are active everywhere and the rate of leaching is controlled by chemical leach kinetics (i.e. by the values of τ_c , τ_D , E_c^* , E_D^* , and X as shown in equation (13). In this figure (and in all following ones unless otherwise indicated) the values of leach parameters are as shown in Table 1. These are probably not the best parameters we could have chosen (4). Our purpose in this paper is to elucidate the important systematics of a two dimensional air convection model of dump leaching, so the precise value of the parameters used is not important. Also all calculations were made using a 10 x 10 computational grid. It has been verified that this grid size is adequate. No significant changes resulted from increasing it to 20 x 20.

Leaching histories were computed for a large number of model dumps of different sizes, different permeabilities, different rates of average yearly solution application, different pyrite contents and various waste characteristics. In each case the amount of copper solubilized was computed. The remaining figures in this paper discuss the factors that the model indicates affect the rate of copper solubilization in an important way. The term solubilize is used to indicate copper oxidized without the prejudice that it is actually flushed by leach solutions and recovered.

One of the most important conclusions is indicated in Figure 3, which plots the percent sulfide copper solubilized in two years versus dump dimensions for various irrigation (i.e. average yearly water application) rates. It can be seen that smaller dumps leach substantially better than larger ones and irrigation tends to decrease leaching rates in smaller dumps by depressing dump temperature and thus slowing leaching kinetics. Larger dumps leach substantially better if the irrigation rate is higher, however.

Figure 4 shows the temperature, oxygen, and air convection configurations in some of the dumps plotted in Figure 3 and explains the difference in behavior between low and high dumps. If irrigation rates are low, high dumps will tend to heat up to 50°C over broad regions. At this temperature the leach rate is zero because the bacteria in the model have been killed (e.g. the temperature is too hot, see Table 1 and equations (13) and (15)). Application of water at increased rates to the high dumps cools them to temperatures where the bacteria become active again and efficient leaching can take place.

Figure 5 illustrates the same phenomena for 100 foot high dumps. Dumps with low irrigation rates in the figure initially enjoy advantage because they heat up quickly. They soon become too hot for their bacteria, however, and the dump with irrigation rate of 0.5 gal/ft²-hr leaches at a faster rate at these later times because it is cool enough to enjoy effective bacterial catalysis.

Figure 6 shows what happens over a longer period of time. For larger dumps there is an initial transient where the oxygen starved portion of the dump is gradually reduced in size by the migration of the leaching front. This front, as shown in Figure 4 for 200' sized dumps, is also coincident with a thermal front, as one might expect.

For 100' high dumps as shown by Figure 6 the time required to eliminate the oxygen starved cool region depends on the irrigation rate but is generally ~2 years. After this transient the leach rate generally drops either because the dump remains at temperatures too hot for the bacteria (~50°C) or because the leach rate decreases because substantial amounts of copper have been recovered from the dumps.

Figure 7 shows temperature, oxygen, and air flow configurations for the base case curve of Figure 3. This figure shows clearly how the oxygen starved, cool, non-leaching portion of the dump increases as dump size increases. Only the edges of large dumps leach at all (at first), and even these edges do not leach well because of bacterial control at $T \geq 50^\circ\text{C}$. Eventually the hot portion of the dump would presumably (we have not calculated this effect) expand at the expense of the oxygen starved portion. This expansion is quite slow, however. Temperatures in test holes into numerous Kennecott dumps at Bingham Canyon, Utah suggest that most leaching in large dumps takes place fairly close to the face of the dump (Table 2) as suggested by the model (Figure 7).

Figure 7 also illustrates the difference between the one and two dimensional models. In the one dimensional model air would be obliged to convect upward uniformly from the entire base of the dump. The configuration of the oxygen starved region would be very different than in the two dimensional case, and some of the operational implications are also different.

Figure 7 suggests an operation strategy. There is little value in applying extra leach water to the cool central portions of the dump. These portions, which leach slowly by air convection into the top surface of the dump need to be nurtured, not extinguished with water. Application might be beneficially focused on the hot, bacterial controlled edges, however.

Figures 8 and 9 show that large dumps will leach substantially better if they are more permeable. It is much more important to preserve as high a permeability as possible (perhaps by rail dumping) in high dumps than it is in small dumps.

Figures 10, 11, and 12 show the effects of waste characteristics on leaching. Faster leach kinetics are beneficial for dumps less than ~100 ft high but bad for dumps higher than this. The reason is that faster kinetics make the size of the near-face leach zone smaller (see Figure 12). Similarly, if FPY is smaller and the kinetics of leaching the same (i.e. the waste generates less heat per fraction copper leached but the rate of leaching is the same), small dumps leach less well and larger dumps better (Figure 11). The reason is that small dumps benefit from the extra heat, but large dumps, being bacterially limited, are hurt. Large dumps leach better if they are built of low pyrite waste and/or are irrigated more intensively.

Conclusions

The practical conclusions that can be drawn from the above discussion are:

- (1) Optimum dump height is 50-100 ft (Figure 3).

(2) If dumps higher than 100 ft must be built:

- (a) They should be built so as to preserve as great a permeability as possible (Figure 8).
- (b) They should be built of waste with low pyrite content (low FPY, Figure 11); slow leach kinetics of the waste may be beneficial (Figure 10).
- (c) They should be irrigated more intensively than lower dumps (Figure 3), and perhaps selectively or especially on hot portions of the dump near the face (Figure 7 and discussion in text)

The recommendations with regard to increased irrigation for large dumps is different from the recommendation that would be made on the basis of one dimensional modeling, and illustrates the need to consider two dimensional air convection.

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Table 1. Base case parameters. For definition of symbols see Glossary.

G_s	.2 wt.% Cu
τ_{cs}	500 mo
τ_{DS}	500 mo
E_C^*	12,000 cal
E_D^*	5,000 cal
G_{NS}	.07 wt% Cu
τ_{CNS}	250 mo
τ_{DNS}	250 mo
E_{CNS}^*	12,000 cal
E_{DNS}^*	5,000 cal
T_{sick}	40°C
T_{kill}	50°C
T_{start}	20°C
T_{amb}	20°C
FPY	20

Table 2. Drill hole temperatures in holes in Utah Copper Division, Kennecott Copper Corporation dumps at Bingham Canyon

Hole	Average Temperature	Comments
WH 1	40.4°C	90 ft from Face Blue Water II, 5960 level
WH 3	27.8°C	65 ft from Face Blue Water II, 6910 level
WH 5A	32.3°C	70 ft from Face Blue Water II, F level
WH 6	31.2°C	100 ft from Face Blue Water II G level
WH 7	46.5°C	300 ft from Face Blue Water II Code 51
WH 9	60.5°C	100 ft from Face Midas, 6190 level (no leaching on adjacent pond)
WH 10	38.3°C	300 ft from Face Midas, 6290 level
WH 11A	49.5°C	650 ft from Face Midas, 6290 level
WH 15	21.3°C	10 ft from Face, Tiewakee, G level
WH 18	56.61°C	400 ft from Face, Keystone, 6800 level (no leaching 350' radius)
WH 23	25.3°C	30 ft from Face, Copper Notch, 7000 level
WH 24A	20.3°C	350 ft from Face, Dry Fork, A level
WH 26	28.4°C	800 ft from Face, Dry Fork, D level
WH 28A	25.6°C	400 ft from Face, Dry Fork, H level
WH 29	28.9°C	70 ft from Face, Verona, H level
WH 30A	22.9°C	370 ft from Face, Freeman, H level

Glossary of Symbols

A	Heat sources or sinks (cal/cm ³ -sec)
ACU	Calories produced in leaching one gram of sulfide copper (cal/g _{Cu})
C_1	Heat capacity of water (cal/g-°C)
C_m	Heat capacity of dump (cal/g-°C)
FPY	Moles pyrite leached/mole sulfide Cu.
g_o	Gravitational acceleration (cm/sec ²)
G_s	Copper grade of dump (g _{sulfide Cu} /g _{waste})
H	Dump height (ft)
\mathcal{H}	Enthalpy of air (cal/g)
k'	Permeability of dump (cm ² (1Darcy=10 ⁻⁸ cm ²))
K_m	Thermal conductivity of dump (cal/cm°Csec)
$[O_2]$	Concentration of O ₂ in air in dump (g _{O2} /cm ³ air)

$[O_2]_{STP}$	Concentration of O_2 in air under standard conditions ($20^\circ C$, 1 atm) (g_{O_2}/cm^3 air)	ρ	Density of air (g/cm^3)
OXCU	Grams O_2 required to leach a gram of sulfide copper.	ρ_o	Density of air at standard T and p ($20^\circ C$ and 1 atm) (g/cm^3)
p	Air pressure ($dynes/cm^2$)	ρ_m	Density of dump (g/cm^3)
q	Mass flux of air (g/cm^2 -sec)	ν	Kinematic viscosity of air (cm^2/sec)
q_1	Mass flux of water through dump (g/cm^2 -sec)		
R_{O_2}	Rate of O_2 uptake in dump (g_{O_2}/cm^3 dump-sec)		
R_{Cu}	Rate of sulfide copper leaching at a particular dump location (g_{Cu}/cm^3 sec)		
ds	Distance along streamline		
t	Time (sec)		
T	Temperature ($^\circ C$)		
T_{sick}	Temperature at which bacteria became sick		
T_{kill}	Temperature at which bacteria became inactive		
τ_{CS}	Time required to leach a typical waste particle of all its sulfide copper at $20^\circ C$ assuming diffusion is infinitely fast and chemical rates control the speed of leaching (sec)		
τ_{DS}	Time required to leach a typical waste particle of all its sulfide copper at $20^\circ C$ assuming chemical reaction rates are infinitely fast (sec)		
E_{CS}^*	Activation energy for sulfide leaching (cal/mole)		
E_{DS}^*	Activation energy for Fe^{3+} diffusion in water (cal/mole)		
τ_{CNS}	Same as above but for nonsulfide copper (sec)		
τ_{DNS}	Same as above but for nonsulfide copper (sec)		
E_{CNS}^*	Activation energy for nonsulfide leaching (cal/mole)		
E_{DNS}^*	Diffusional activation energy for non-sulfide leaching (cal/mole)		
X_S	Fraction of sulfide copper left at dump location at any time.		
X_{NS}	Same as above but for non-sulfide acid soluble copper.		
γ	Pseudo heat capacity of air including effects of water vapor saturation ($cal/g^\circ C = K/T$)		

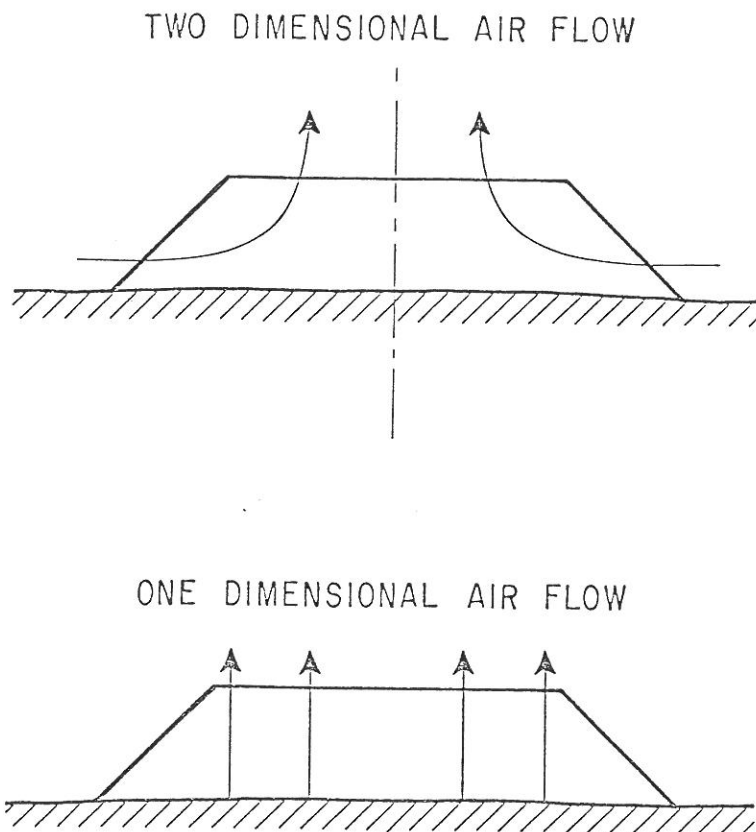


Figure 1. One dimensional (vertical only) air flow is not generally realistic for air convection in waste dumps.

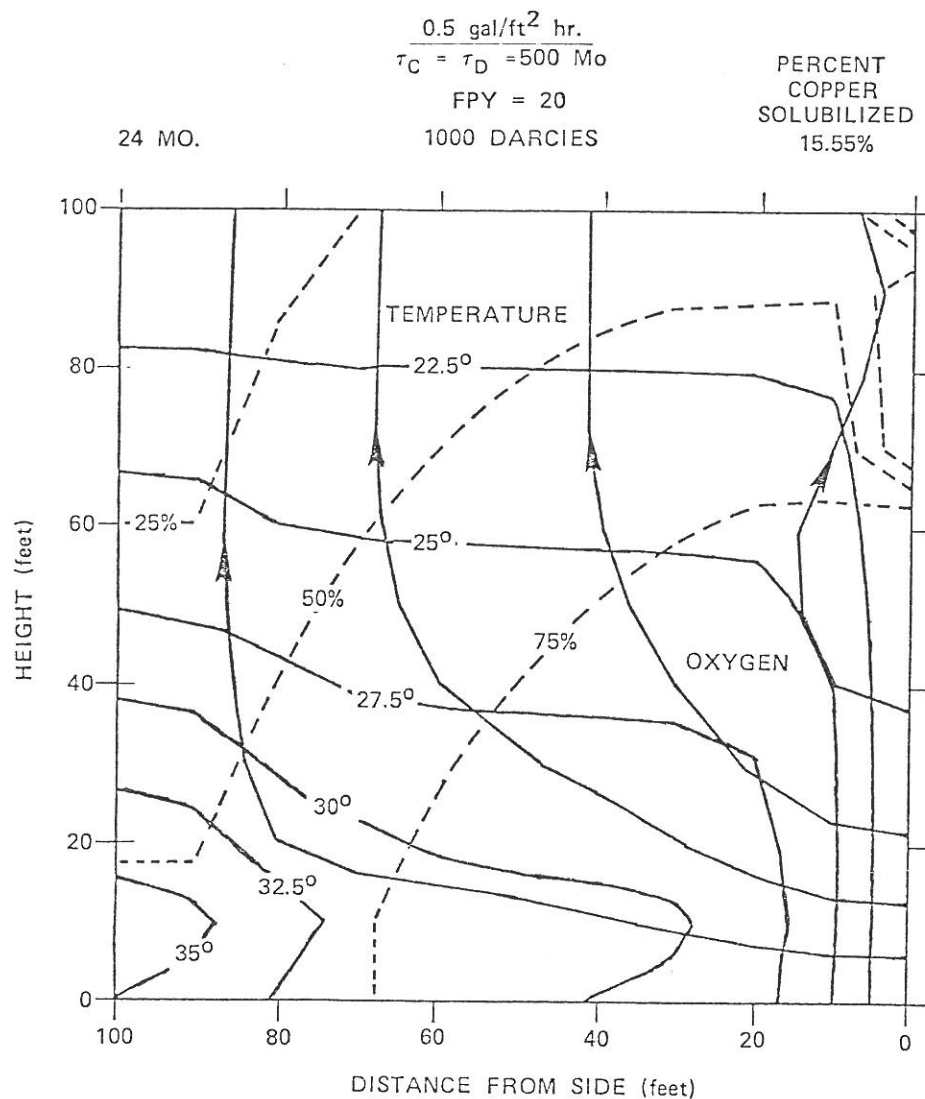


Figure 2. This figure illustrates the results of a cross section through a model dump. Only half the dump is shown. The left boundary is the center of the dump; the right and top surfaces are exposed to air. Air convects into the dump along streamlines (lines with arrows). The closer the streamlines are together (in any one diagram) the faster the air flow. The temperature of the dump is indicated by solid temperature contours. The oxygen content of the air in the dump (as a fraction of normal) is shown by dotted contours. It can be seen that this 100 ft x 200 ft dump has heated up to about 35°C in its central portion in the 2 years it has been under leach and that air convection is vigorous enough to maintain oxygenated conditions throughout the dump.

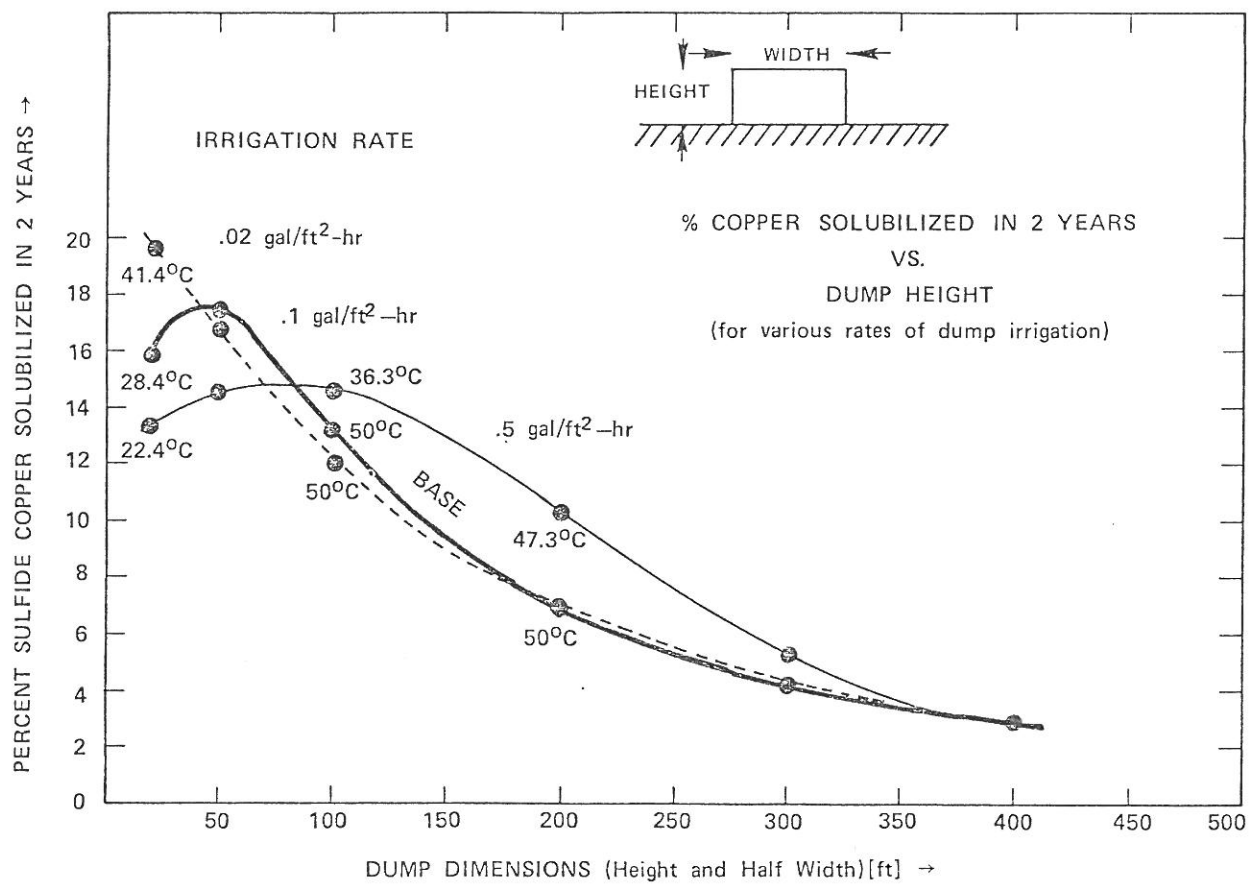


Figure 3. Leach rate as a function of dump depth for various irrigation rates. Optimum dump height is 40 to 70 ft for conditions at most operating properties. Higher irrigation rates, although detrimental for leaching of small dumps, can be beneficial for dumps over ~75 ft high.

EFFECT OF IRRIGATION RATE ON DUMPS OF VARIOUS SIZES

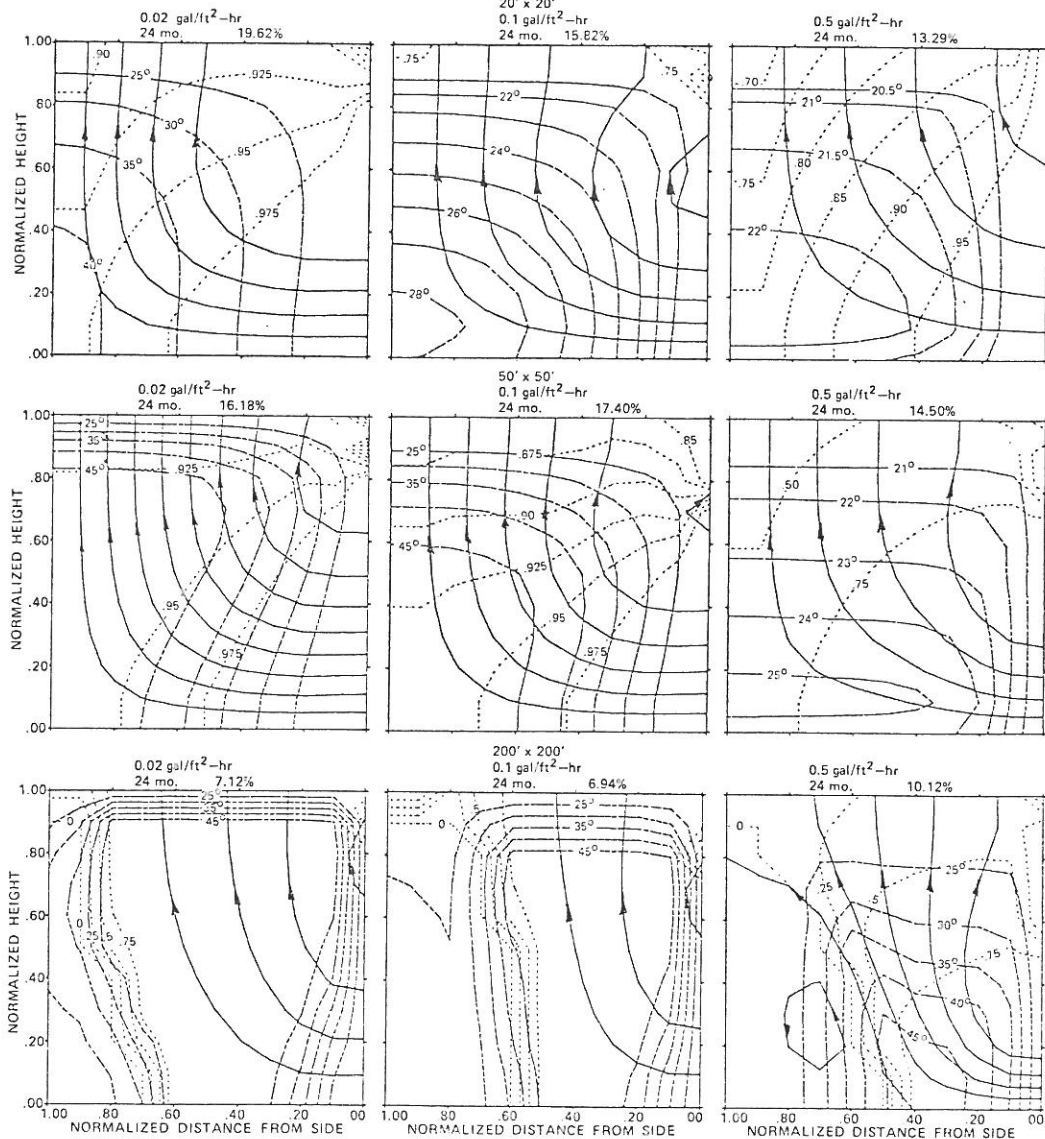


Figure 4. The effect of irrigation rate on dumps 20, 50 and 200 ft high. Conventions are the same as in Figure 2. The percentage of copper solubilized in 24 months (the time of the cross section) is shown on the top of each cross section. The figure shows small (20 ft) dumps leach less well at higher irrigation rates because the dump is cooled and the kinetics of leaching are slowed. On the other hand higher dumps (200 ft) leach better at higher irrigation rates because the application of more water prevents the dumps from heating up to temperatures sufficient to kill or impair bacterial catalysis (40-50°C in the model).

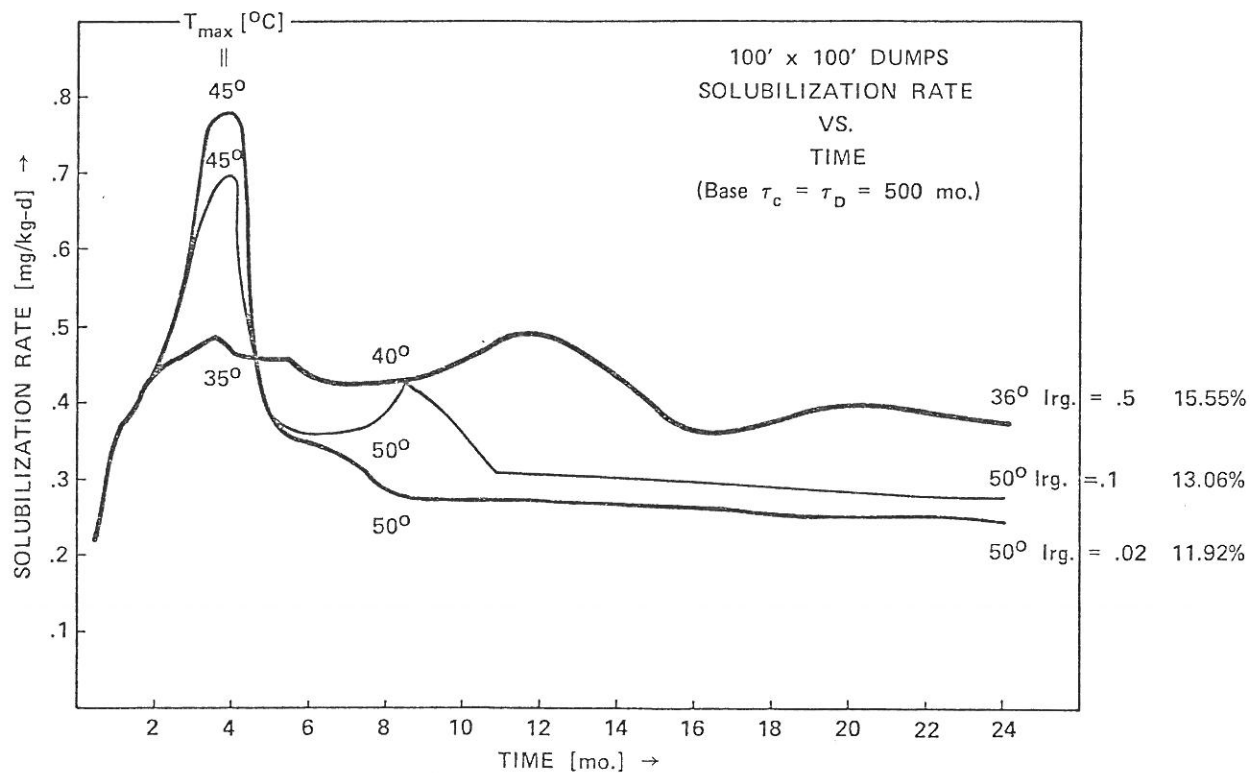


Figure 5. Solubilization rate of 100 ft high dumps as a function of time for various irrigation rates. Maximum temperatures in the dump are shown along the curves. The initial peak in leach rate is a transient associated with the initial warming of the dump. The figure shows, as does Figure 4, that higher leach rates at higher irrigation rates are achieved by keeping temperatures lower and bacterial catalysis active.

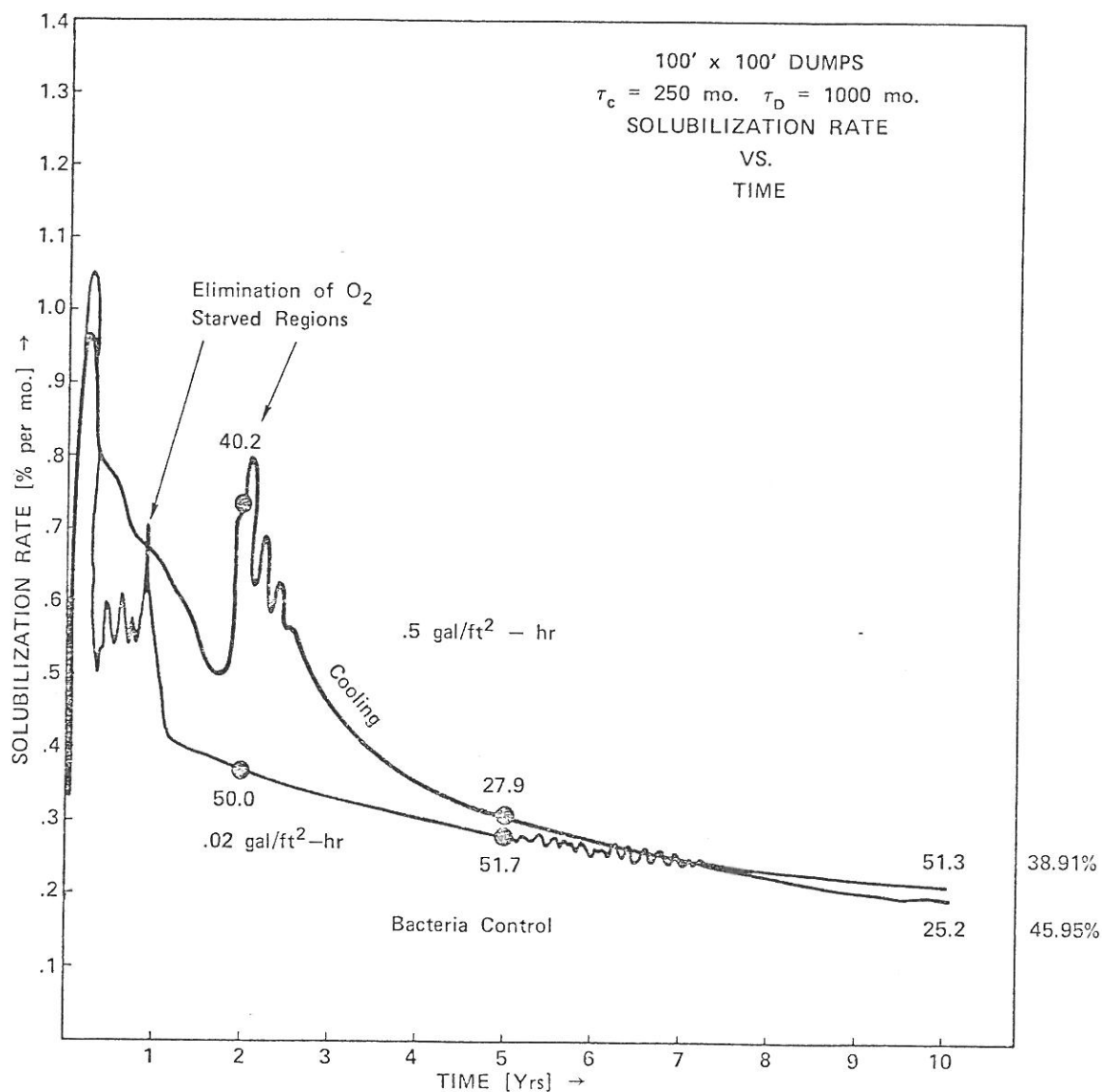


Figure 6. Solubilization rate is plotted for a longer period of time for 100 ft dumps with different leach kinetics than those in Figure 5. Again maximum temperature of the dumps is shown at various points along the curve and two rates of irrigation are considered. An initial peak associated with the migration of the leaching front into areas of the dump still oxygen starved is noted. Because of effective bacterial catalysis the dump with higher irrigation rates leach substantially better than the one with a lower irrigation rate.

LEACHING AND RECOVERING COPPER

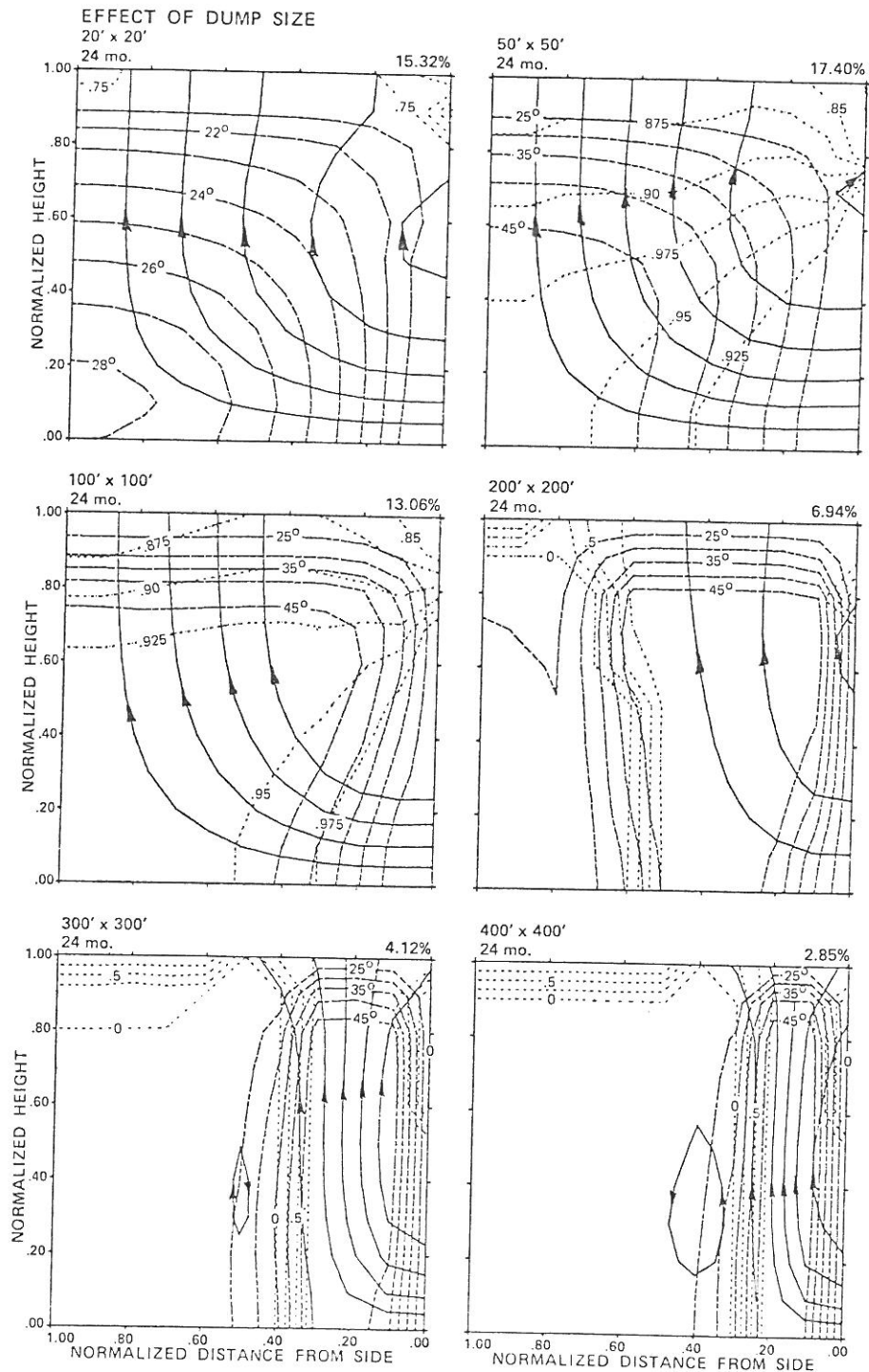


Figure 7. The conventions are the same as in Figure 2. It can be seen that for high dumps leaching is effectively restricted to those areas near the dump face at least in the first years of leaching. Some convection into the back portions of the dump occurs but this is comparatively slow and is ineffective in oxygenating and leaching more than the upper 50 ft or so of the dump.

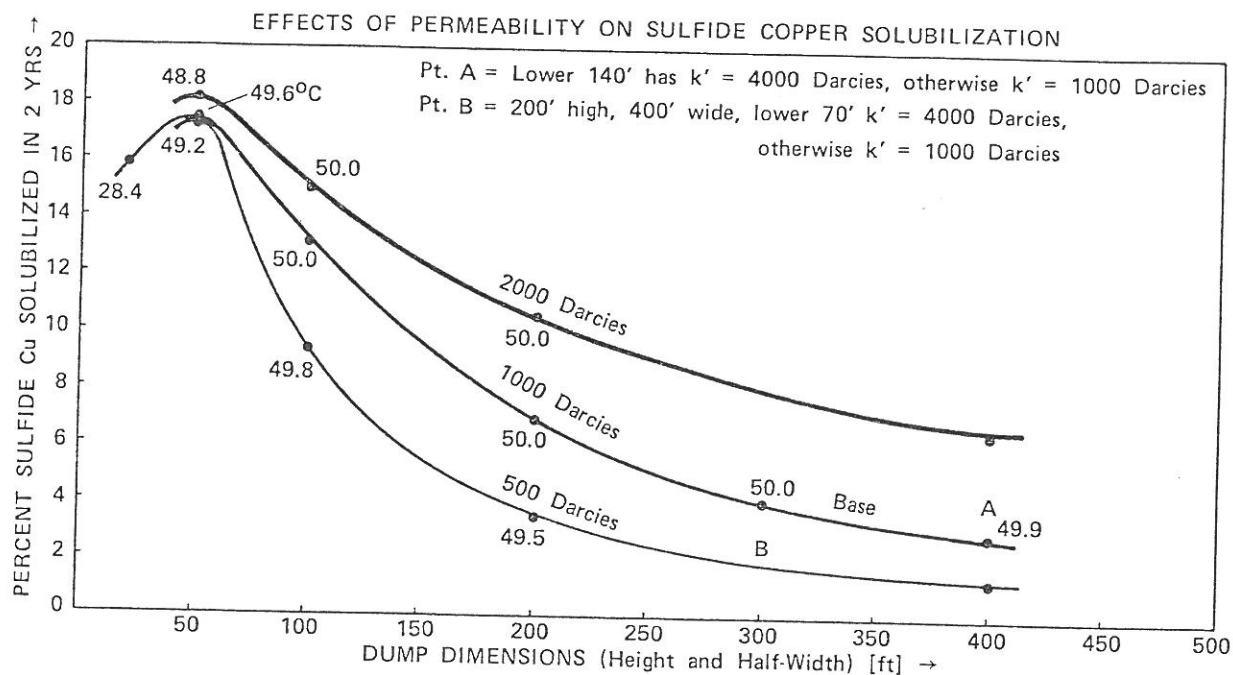


Figure 8. The amount of copper solubilized in two years plotted versus the dump height for various dump permeabilities. Higher permeability dumps leach better than low permeability ones. Dumps should be constructed so as to have as high a permeability as possible.

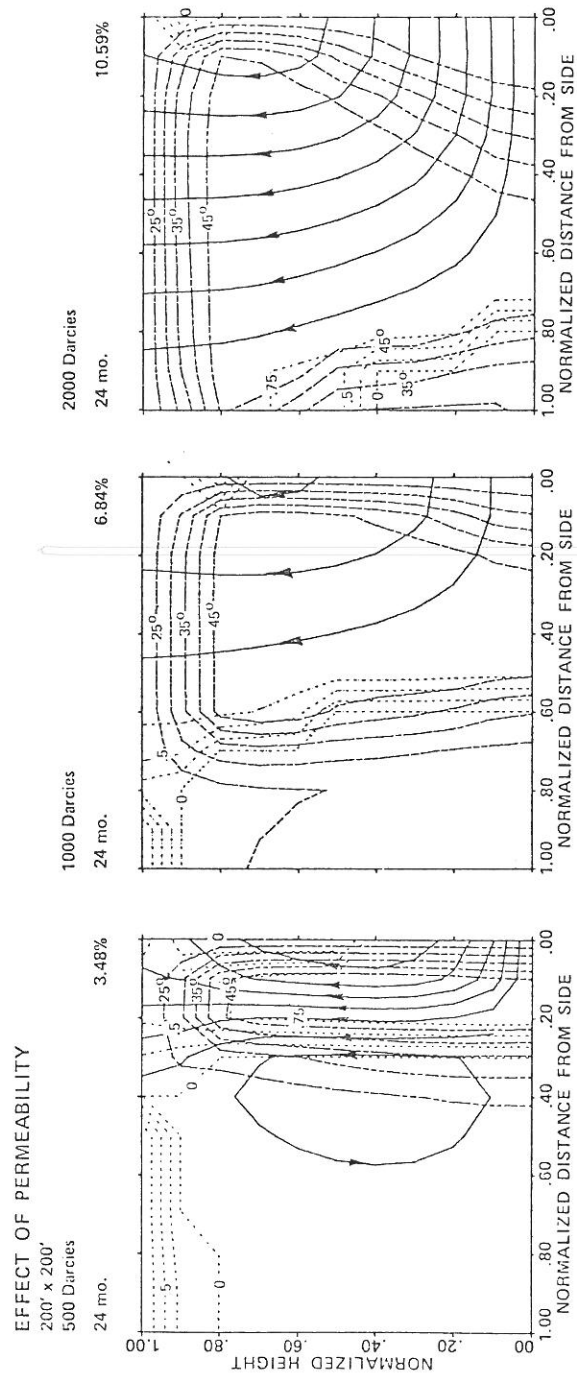


Figure 9. Conventions are the same as in Figure 2. Figure shows high permeability dumps leach better because a greater fraction of the dump can be oxygenated by air convection.

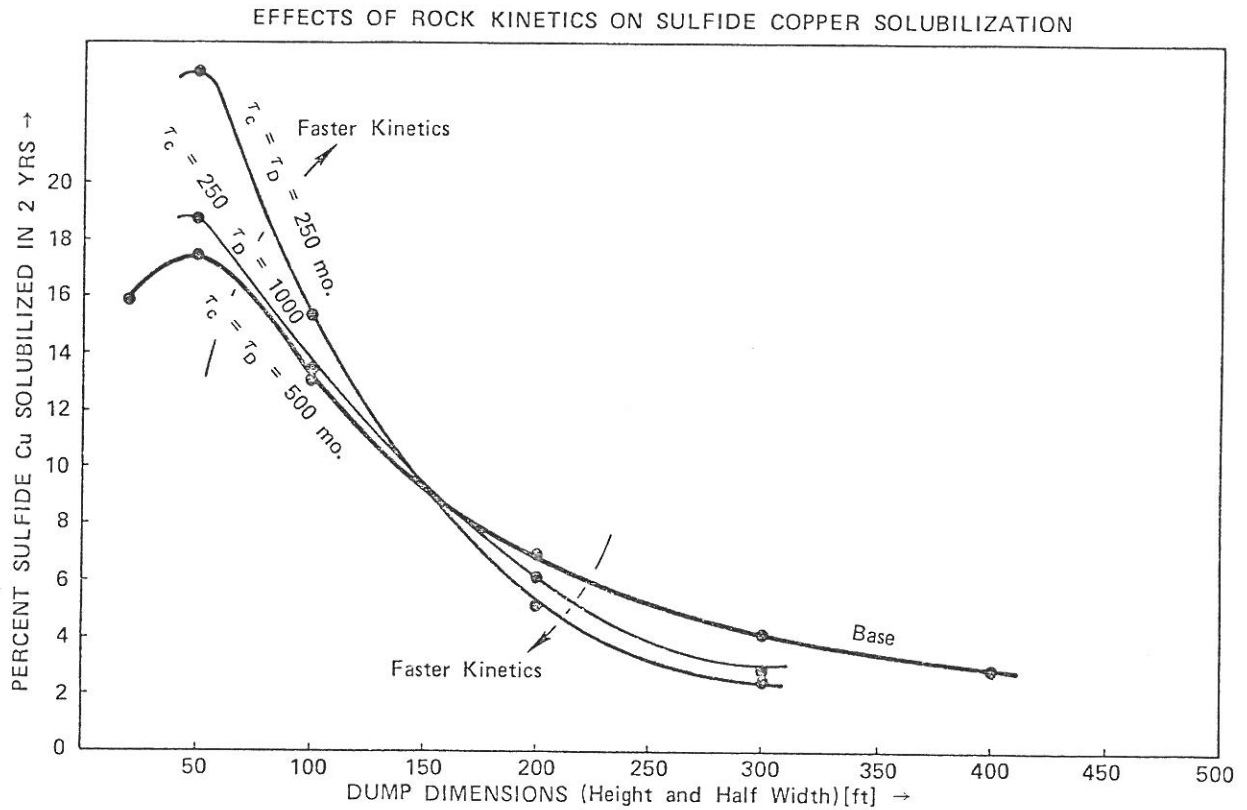


Figure 10. The percent copper solubilized in two years versus dump height for various waste fragment leach kinetics. Although small dumps leach faster if the leach kinetics of their constituent rock fragments are faster, higher dumps leach less well if the leach kinetics are faster because leaching is more restricted by the greater rate of oxygen consumption.

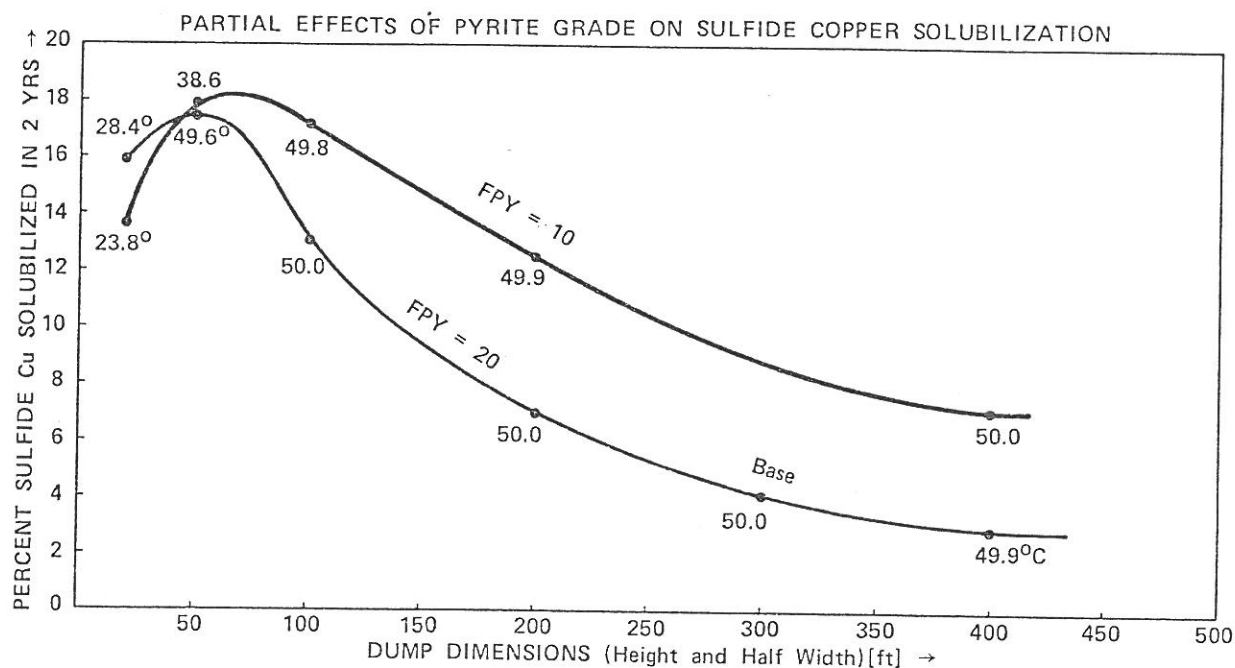


Figure 11. For the same leach kinetics more oxygen is consumed with $FPY = 20$ than for $FPY = 10$. Faster oxygen consumption leads to larger areas of the dump being oxygen starved. Note that irrigation rate (Figure 3), leach kinetics (Figure 10) and pyrite content all produce similar curves. The difference between small and large dumps in all these cases relates to their relative ability to get rid of heat by conduction to the environment and to the geometry of the hot cell near the edge of the dump (see Figure 12).

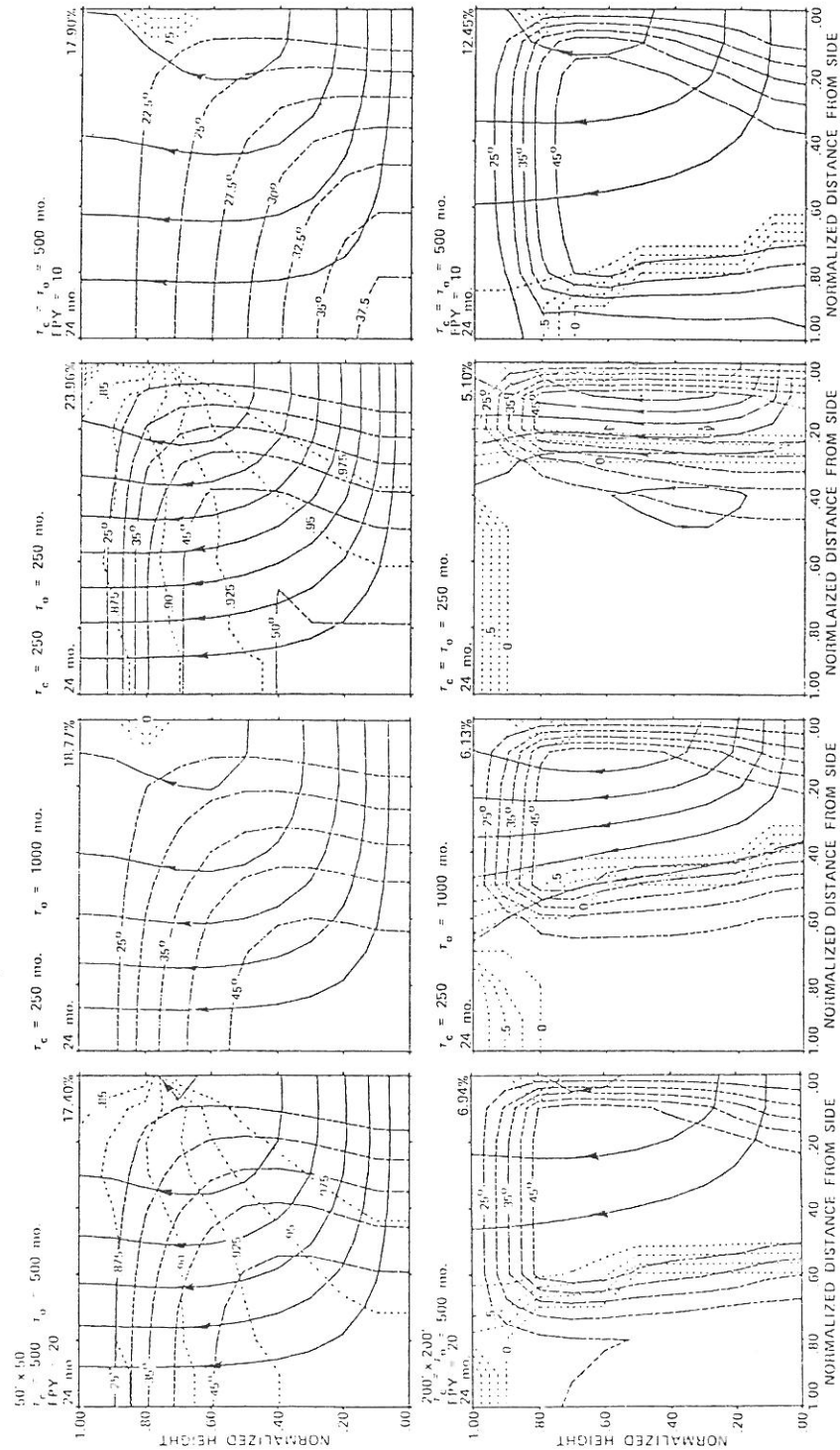


Figure 12. Conventions are the same as in Figure 2. The effects of changes in leach kinetics for FPY on the size of the hot cell near the face of the dump. It is suggested in the text hot cells (Table 2) should be "extinguished" by application of extra water.