

Chapter 3

EVALUATION OF AN EXPERIMENT INVOLVING LARGE COLUMN LEACHING OF LOW GRADE COPPER SULFIDE WASTE: A CRITICAL TEST OF A MODEL OF THE WASTE LEACHING PROCESS

L. M. Cathles

Department of Geosciences
The Pennsylvania State University
University Park, Pennsylvania 16802

L. E. Murr

Department of Metallurgical and Materials Engineering
New Mexico Institute of Mining and Technology
Socorro, New Mexico 87801

ABSTRACT

Results of two years of leaching of 160 metric tons of low grade industrial copper sulfide waste in a large (40' high 10' diameter) thermally insulated tank at the New Mexico Institute of Mining and Technology are analyzed in the light of a previously developed model of the waste leaching process. It is shown that the model is verified in all major aspects and that the parameters in the model that characterize the leaching of a particular sulfide waste are usefully constrained by the results of the tank leaching experiment. The similarity between waste leaching parameters determined from the tank experiment and from interpretation of the leach behavior of test dumps constructed of similar waste encourages optimism it may be possible to predict the leach behavior of field dumps from suitably interpreted column experiments using the computer model developed.

INTRODUCTION

For many years it has been industrial practice to leach the copper out of the low grade copper sulfide (or oxide) "waste" piles that are the by-products of porphyry copper open pit mining by deliberately applying water to the waste. A very substantial amount of copper is produced in this fashion (e.g. Kennecott has traditionally produced ~100,000 tons of Cu/year by this method). Because the dollar value of copper produced by dump leaching is high, it is desirable that the dump leaching process be understood as thoroughly as possible and that the efficiency of the process be maximized.

Toward this end a model of the dump leaching process was developed. An early version of this model was reported by Cathles and Apps (1). The model was tested as thoroughly as possible against available leach data. In early 1974 individuals at Kennecott involved in the development of the leach model approached the New Mexico Institute of Mining and Technology with the idea of running a controlled leach experiment in the large 40' high 10' diameter thermally insulated stainless steel tanks set up at the Institute in what is now called the John D. Sullivan Center for In Situ Mining Research. The New Mexico columns are big enough that a reasonable representative waste sample can be tested under controlled conditions. The resulting collaboration between Kennecott and the Metallurgy Department of the New Mexico Institute of Mining and Technology resulted in the experiment described in this paper.

The leaching model (1) was used to design the New Mexico tank experiment and to predict its results. The experiment has been described in several publications (2,3) and was evaluated at the end of one year in light of model predictions (4). At that time it appeared the column had behaved generally as expected, although the waste leaching characteristics were not precisely those expected. The column had heated up to 55-60°C in ~8 months as anticipated but non-sulfide copper was leached much more rapidly than expected and the sulfide copper less rapidly.

A second year of leaching has now been completed, doubling the data available for interpretation. The experiment is now terminated. Just before shutdown tracer experiments were performed in the column and rhodamine-B dye was added to the influent solution until the dye appeared in the effluent to stain the waste in the column and reveal the extent of solution/rock contact. The column was systematically unloaded, the amount of dye staining recorded, the waste samples analyzed for contained copper and examined petrographically. The purpose of this paper is to evaluate the model of the dump leaching process in light of our now considerably extended knowledge of the New Mexico large scale column leaching experiment and bring the evaluation made at the end of one year of leaching (4) up to date. To do this we will first briefly describe the important aspects of the dump leaching model we seek to evaluate and previous efforts to calibrate or test it. We will then describe the

results of the New Mexico experiment and interpret them using the model. New data on the New Mexico experiment suggests the initial predictions of how the column would leach were more accurate than they appeared to be after one year of leaching.

THE MODEL

The model has been described in detail in a paper by Cathles and Apps (1), updated to include bacterial catalysis in a later paper (5), and extended to include two dimensional (horizontal and vertical) air flow (6). The reader is referred to these publications for mathematical details. Briefly, sulfide copper is considered to leach only where oxygen is present in the air filled portions of the inter-rock pore space in the tank (or dump). Oxygen, supplied by air convection, dissolves locally in the liquid coating each waste fragment (see Figure 1). Bacteria catalyze the conversion of ferrous to ferric iron. Ferric iron is assumed to be buffered at some constant concentration (~1 gpl). Ferric iron diffuses into the rock fragments to react with copper and iron sulfide minerals to generate heat and put copper and Fe^{++} into solution. In natural dumps the heat generated helps drive the air convection that brings more oxygen to the sites of reaction.

The rate of copper sulfide leaching is thus controlled by the slowest of three processes:

- (1) The rate of air convection.
- (2) The rate of bacterial conversion of Fe^{++} to Fe^{+++} .
- (3) The kinetics of sulfide oxidation by Fe^{+++} .

In slightly more detail the oxidation kinetics are described by a standard shrinking core model which has two parameters, τ_{CS} and τ_{DS} ; τ_{CS} is the time required to leach all the sulfide copper from a typical waste fragment at 20°C if the oxidation kinetics are controlled entirely by the rate of reaction of Fe^{+++} with the sulfide grains and diffusion of Fe^{+++} to the sites of oxidation is fast. τ_{D} is the time required to completely leach sulfide copper from a typical waste fragment at 20°C if sulfide oxidation is fast and the leach rate is controlled by the rate at which Fe^{+++} can diffuse to the sites of reaction through the liquid filled porosity of the rock. τ_{CS} and τ_{DS} together describe kinetics where diffusion or chemical reaction rate can control the rate of oxidation at different stages of leaching or different temperatures. τ_{CS} and τ_{DS} are given a temperature dependence by assigning each an activation energy, E^* . [$\tau(T) = \tau(T_0) \exp(E^*/RT_0 - E^*/RT)$; $T_0 = 20^\circ\text{C}$.]

Bacterial control is introduced by assuming there is a temperature, T_{sick} , above which bacterial conversion of ferrous to ferric iron begins to be impeded, and a final temperature, T_{kill} , at which bacterial conversion ceases entirely. The model assumes the sulfide oxidation kinetics lose all temperature dependence at T_{sick} and extrapolates the leach rate linearly from its value at T_{sick} to zero at T_{kill} . In this way the death of bacteria can stop sulfide

oxidation in the model. Since sulfide oxidation reactions generate the heat that warms the columns or dump, model dumps (or columns) will never reach temperatures greater than T_{kill} .

Finally the rate of air convection is controlled by design in the case of the New Mexico column or by bouyant forces and permeability in the case of natural dumps. Temperature and oxygen profiles in the dump or column are computed numerically using finite difference techniques (1). The procedures used are well known and standard. The cooling effects of evaporation as incoming air is saturated with water and the effects of temperature dependent vapor saturation on the pseudo-heat capacity of air are taken into account in the model. Account is also taken of the seasonal temperature variation of the ambient air.

A kinetic model was used for the leaching of non-sulfide copper similar to that described above for the sulfide copper. In this case leaching was assumed to take place regardless of presence or absence of bacteria or oxygen. The leach rate is controlled entirely by T_{CNS} , T_{DNS} , and the activation energies E^*_{CNS} , E^*_{DNS} .

The model as described above is certainly far from perfect. Particular weak spots are the assumption that Fe^{+++} is buffered at some constant value within the column, the lack of dependence of non-sulfide leaching on sulfide leaching (acid generation), and possibly that bacteria do not catalyze the leaching of sulfides themselves (as well as the $Fe^{++} \rightarrow Fe^{+++}$ conversion). The model is quite flexible, however. The kinetic expression allows for variation in leach rate (as T_C and T_D are varied) over a broad enough range to handle most situations encountered in industrial practice. The temperature dependence is of a standard and reasonable form. Changes in ferric iron solubility and perhaps some sulfide bacterial effects can be logically included in the "chemical" activation energies. The method of incorporating bacterial control is crude, but appears surprisingly adequate for our present purposes. The New Mexico tank experiment was designed as a stringent and controlled test of the model.

PREVIOUS EFFORTS TO CALIBRATE OR TEST THE MODEL

The model was first applied to five well studied Kennecott test dumps in an effort to "calibrate" it. The case of the Utah Copper Division's Midas test dump for which a great deal of data is available was reported previously (1). The New Mexico column was loaded with Chino Mines Division type I waste (chalocite, low iron mostly as pyrite). Data from two test dumps constructed of Chino type I waste was available. Although the data on these dumps is not as complete as in the Midas test dump case, Figure 2 shows it was possible to obtain good agreement between model and observed leach rate and cumulative copper recovery in the first year of leaching was about 14.5% of the copper contained in the dump. Table 4 (column 1) shows the model parameters required to obtain the match of Figure 2.

The Chino waste leached considerably more rapidly than did the Utah Midas test dump waste, primarily it was thought, because the Chino waste tended to spall or depreciate as it leached whereas the Utah Midas test dump waste did not. The dominate copper sulfide mineral in the Chino waste was chalcocite; chalcopyrite was the dominate copper sulfide mineral in the Midas test dump waste.

The model made a number of predictions and efforts were made to verify these (5). Briefly the model predicted rims leached of copper sulfides should develop around waste fragments that do not decrepitate. The leached rims had not previously been observed but when deliberately looked for were found in abundance. Modeling made clear the permeability of most dumps must be very high (~ 1000 Darcies). Recent air injection tests indicate this is indeed the case. Modeling indicated that bacteria must be important to the leaching process and at least catalyze the oxidation of Fe^{++} to Fe^{+++} . (Fe^{+++} then does the sulfide leaching.) There is no evident inorganic reason leach rate should show a strong temperature dependence to $\sim 55^\circ C$ and then stop. If bacterial catalysis were not inhibited around $55^\circ C$ the model clearly indicates dumps should heat up till the water in them boils. Dumps only rarely are observed to have temperatures greater than $55-60^\circ C$. The prediction that the New Mexico column would heat up to $55-60^\circ C$ and then stop heating was confirmed by the first year leaching results and demonstrates the importance of bacterial catalysis to the leaching process.

Finally the model indicated that the amount of makeup acid traditionally added to the leach solutions or the amount of iron added to leach solutions during copper recovery by iron precipitation is in most cases small compared to the amount of acid and iron generated by leaching within the dump. Thus the model predicted that acid addition should affect only the very near surface portion of a dump and substitution of solvent extraction for iron precipitation should have no impact on the leaching process. These predictions appear confirmed by experience.

The model has thus sustained a number of tests to this point. The most important point for our present purposes is that prior to running the New Mexico column experiment we had some knowledge of how we thought the Chino type I waste would leach. The main issue for present consideration is how good that estimate was, or conversely whether the results of the New Mexico column experiment could be used to successfully predict the leaching of waste dumps built at an operating property. It is precisely in this area that recent results from the New Mexico column experiment are most encouraging, since they indicate the waste parameters determined for the column are much closer than formerly thought to those previously inferred for the Chino test dumps.

NEW MEXICO COLUMN LEACHING RESULTS

Figure 3 shows the geometry of the New Mexico tank. Details as to tank construction and operation are given elsewhere (2,3). Table 1 gives

some of the important physical and chemical parameters of the tank and its contained waste. The tank is a converted liquid oxygen storage dewar measuring approximately 40 ft (12.3 m) high and 10 ft (3.1 m) in inside diameter. The walls of the tank are made of 304 stainless steel and 1 ft of perlite insulation separates an inner and outer wall around the entire tank. Ports were cut into the tank as shown in Figure 3. These ports allowed sampling of solution (via porous cup lysimeters), measurement of temperature, and sampling of air to measure oxygen content.

The first three feet of the tank were filled with +2" quartzite overlying an air distribution system (see Figure 3). The column was then loaded with 160 metric tons of Chino type I waste to a height of 34.5 feet above the base of the tank. The weight of the ore was obtained by weighing rail cars empty and full but nevertheless should be considered somewhat uncertain. The remaining space housed a rotating sprinkler rod that distributed water uniformly to the top of the column during flushes.

The 6000 l of non-gravitational retained water in the tank (see Table 1) was estimated in two ways: The tracer experiments performed at the close of leaching showed a slug of NaCl was recovered after ~ 9000 l of solution passed through the tank (3). Secondly the copper concentration in effluent solutions generally fell to < 0.4 times its initial value after 7700 l of flush solution were applied and recovered. The flush volume typically used (7700 l) was designed to recover most of the copper solubilized over the period since the previous flush assuming that non-gravitational water would occupy ~ 10% of the tank volume, a supposition born out by the observed tank performance. It should be noted that the tank contained about 336 kg of sulfide copper and 240 kg of non-sulfide copper and that 330 kg or 57% of the total copper was recovered over the 2 years of leaching. The mass of ore in the tank is more likely less than 160 tonnes than more so the percentage copper removal is likely greater than 57%.

Figure 4 summarizes the observed leach performance of the column. The second chart gives the schedule of air flow through the tank and when solutions were applied to the column to flush out solubilized copper. Most of the flushes were of 48 hour duration with application rates of about 0.5 gal/ft²-hr (2.5 l/min into tank) over the top of the waste column. Flushes 6, 14, and 17 were longer, flushes 14 and 17 being of 96 hour duration and flush 6 of 5 week duration at about half the normal flush rate. The top graph gives the temperature at the various ports as a function of time and also shows ambient temperature. The third graph shows the oxygen consumption rate from the air passed through the column. The last chart shows the manner in which copper was recovered from the column.

Several important features of the leaching are apparent from Figure 4. First of all, a substantial amount of copper, about 75 kg or 13% of the copper contained in the column, was recovered before the first flush when the column was

inundated with water and then drained as preparation for the start of leaching. The water used for the inundation was taken from Kennecott dumps at Chino and so was somewhat acidic. Examination of data from the early flushes (#1-5) indicates copper could have been removed more rapidly in the early stages if more solution had been applied. This situation was remedied by flush 6 which represented an effort to flush as much already solubilized or initially acid soluble copper as possible from the tank.

The top graph shows that the leach column generally tracked average ambient temperature till about the 150th day of leaching when the column started to heat up dramatically. The strong upward curvature of the temperature lines indicates a strong temperature dependence of the rate of leaching. At about 45°C the curves sharply bend over although they continue to creep up to ~ 60°C. This indicates the cessation of effective bacterial catalysis of the leaching process and may reflect the gradual development of thermophilic bacteria. The effect of solution application is dramatically revealed as sharp drops in the temperature at all the ports and a sharp rise in the temperature at the base of the column. The base is cooled by incoming air and rewarmed by solutions passed through the column during flushes. The warm ore is cooled by solution flushes. The major application of flush solutions during flush 6 is seen to cause the temperature at all the ports to become nearly identical and equal to ambient temperature as one might expect.

The rate of oxygen consumption (curve 3) is particularly interesting since it directly reflects the rate of sulfide (copper and iron) oxidation. The strong temperature dependence of leaching is again indicated by the large difference between the rate of oxygen uptake at the 95th and 195th days of leaching. The air flow through the tank was the same in these two periods but the rate of oxygen uptake was much greater at the second time when the column temperature was warmer. It should also be noted that the rate of oxygen consumption steps upward from the 130th to 190th day of leaching in a fashion parallel to the stepping up of air flow through the column. This indicates the rate of oxidation was controlled in this period by the rate of air flow into the tank. The oxidation rate was only briefly controlled by air flow rate after the 190th day. The leach rate soon became controlled by bacterial inhibition or chemical kinetics and the oxygen consumption rate dropped slightly. No increase in oxidation rate was observed between day 300 and 330 when the air flow rate was increased.

Figure 5 gives some data bearing on the chemistry operative within the column. Copper concentration in effluent solutions generally was initially 3.5 g/l (sometimes as high as 5 g/l) and then fell to 0.5 to 1.5 g/l. After the solution application stopped the copper concentration climbed back up to close to its initial value. The drop is interpreted as reflecting dilution by applied water short circuiting through major channels in the column. Lysimeter

data (Figure 5) shows copper concentration generally in the same range as the copper concentration in solutions recovered. Port 1 (the center of the column) consistently had copper concentrations greater than those in the recovered solutions, however. In one period the copper concentration in the port 1 area was extremely high - ~ 16 g/l. Figure 5c and d shows the ferric iron concentrations in solutions entering and leaving the column were also high. Lysimeter data show ferric iron concentrations within the column of 10-30 g/l with values of 40-50 g/l and higher occurring in the central portions of the tank.

As previously mentioned, at the end of the leach test the waste in the column was stained with rhodamine-B dye in a final solution flush. As the column was unloaded the zones where flush solutions contacted the waste were revealed by red staining. Figure 6 shows a model of the stained areas at various levels in the tank and also gives the total copper assays at various locations. On average about 50% of the waste in the tank was contacted by leach solutions. The copper content of the waste was generally very low - much less than the starting grade of 0.36 wt% total copper.

In unloading the column an interesting hard layer was encountered between ports 1 and 2 in the middle section of the column. The waste was cemented with gypsum (probably actually bassanite) crystals. The copper grade was high (0.29%), there was much evidence of jarosite staining and a sulfide with composition approximately FeS was abundantly observed. It is speculated that the FeS may be an intermediate leach product of pyrite - a speculation supported by the observation of traces of elemental sulfur. Bassanite probably precipitates due to very high SO_4^{2-} concentrations in this very actively leaching portion of the column.

MODELING OF THE COLUMN LEACHING

Two new pieces of data were added by the second year of leaching and the post mortem analysis that strongly affect previous interpretations of the first year's data. The column was leached over another full year's temperature cycle. It clearly cooled down and tracked the ambient temperature cycle to a considerable extent in this period. When evaluated through modeling this cooling requires heat losses from the sides of the column. The heat losses required are of reasonable magnitude and could have been anticipated but were not included in the modeling of the first year of leaching.

More importantly the post mortem showed all the waste in the column is not accessed - at least not at any one time. The "channels" of solution flow shift around so more of the column is in fact accessed than the instantaneous staining picture suggests. This must be the case since $> 57\%$ of the total copper in the column was recovered yet only $\sim 50\%$ of the column was dye stained. Also copper has been almost completely leached from unstained locations. More

than 50% of the column must therefore have been accessed. How much more is unknown at the present time but can potentially be constrained once more of the column waste is chemically analyzed.

As a result of this new information the model was modified to take into account heat losses through the sides of the column. This was done by inserting a volumetric heat loss ($\text{cal}/\text{cm}^3 \text{ waste}/\text{sec}$) equal to the heat loss that would occur through the sides of the column. At any point along the column this heat loss term may be expressed:

$$A = - \frac{2K_T}{rb} (T_{\text{col}} - T_{\text{amb}}) \quad (1)$$

K_T is the thermal conductivity of the 1 ft of perlite insulation and supporting trellis (which holds the two walls apart). The conductivity of glass wool is $2.2 \times 10^{-5} \text{ cal}/\text{cm}^2\text{-sec}$. The conductivity might be doubled by the supporting trellis and substantially increased by the modifications made to insert the sample ports which involved cutting holes through the tank and short circuiting the perlite insulation with plates of steel. The ports themselves were insulated but the short-circuiting plates remain. b is the thickness of the perlite insulation which is 1 foot, and $2/r$ is the ratio of the circumference to cross sectional area of the tank. r is 5 feet. Using a value for K_T , twice that of rock wool to account for the trellis, and the appropriate values of r and b , the value of K_{col} (defined equal to $2K_T/rb$) obtained is $\sim 2 \times 10^{-8} \text{ cal}/\text{cm}^3\text{-}^\circ\text{C}$. This is a minimum value since the effects of altering the column by adding ports have not been included.

To account for probable fractional access of the waste by leach solution (and probably also air) the three cases shown in Table 2 were modeled. Case 1 assumes 100% of the waste is contacted by air and leach solution. Case 2 assumes that 100% of the non-sulfide copper is contacted but only 70% of the sulfide copper. This case is considered likely because the initial inundation flush in which the column was completely filled with water allowed access to all non-sulfide or previously solubilized copper. Non-sulfide copper presumably would not be accessed any better than sulfide copper after this inundation flush but a substantial portion probably had already been recovered. Case 3 assumes 70% of the non-sulfide and 70% of the sulfide copper are accessed. The access is accounted for simply by changing the grade of the sulfide and non-sulfide copper appropriately - i.e. by reducing them by a factor of 0.7. Thus we deal with "effective" or accessed copper grades, not total copper grade.

The model itself involves a large number of parameters but many of them are fairly well constrained. We know, for example, the non-sulfide and sulfide grade of the waste quite well so the main unknown is the fraction of waste accessed. We know the mineralogical ratio of moles of pyrite to moles of sulfide copper which places an upper bound on FPY. We also know that pyrite

leaches less rapidly than sulfide copper since pyrite blebs have been observed to remain behind in rims leached completely of sulfide copper minerals. We can make fair estimates of the density and heat capacity of the waste although, as we will see, this parameter is also constrained by modeling. The average ambient temperature cycle is well known in the area and was measured over the period of the test. The approximate temperatures at which the bacteria become sick and die are immediately apparent from the results of the first year of leaching. The precise values of these temperatures are not particularly significant. The permeability of the waste, although important to dump leaching, is not important for the column test since air is forced through the column at a prescribed rate regardless of permeability. We know a great deal of the non-sulfide (or previously solubilized) copper was recovered on the first inundation flush and on subsequent flushes up to the major flush #6. It is thus fair to assume the recovery of non-sulfide copper is rapid (i.e. τ_{CS} and τ_{DNS} are small). The importance of non-sulfide copper leaching becomes negligible after the first half year or year of leaching. E_{DNS}^* and E_{CS}^* are therefore not of great significance. We know the diffusional activation energy E_{DS}^* must be ~ 5 kcal/mole since this is a value typical for diffusion of all ions in water. The schedules of air and water application are known and heat losses by these mechanisms can be calculated directly.

We are thus left with five principle variables whose values must be evaluated by modeling: τ_{CS} , E_{CS}^* , τ_{DS} , FPY , and K_{col} . Additionally we have the fraction of waste accessed by air and flush solutions. The principal column observations are: the history of copper recovery from the column, the history of oxygen consumption rate, and the thermal history of each of the four observation ports and the base of the column. We also have some background observations or intuitions previously mentioned that help constrain some of the parameters. We will now show that the parameters describing leaching are fairly well constrained for any particular fraction of sulfide and non-sulfide copper accessed.

The general methodology of analysis is shown in Table 3. For a given fraction of sulfide and non-sulfide copper accessed the rate of leaching of sulfide copper is governed by τ_{CS} , E_{CS}^* and τ_{DS} . The oxygen consumption depends on these parameters plus FPY (i.e. the amount of iron sulfide leached along with the copper sulfides). The temperature depends on the oxygen consumption and the heat losses through the sides of the column. Thus given a combination of τ_{CS} , E_{CS}^* , and τ_{DS} , comparison of copper leaching and oxygen consumption and temperature will determine appropriate values of FPY and K_{col} .

A large number (62) of models were run to constrain the five principal variables listed above and to elucidate possible tradeoffs between these variables for each of the three cases indicated in Table 2. Figure 7 gives summary diagrams showing the temperature history at the ports, copper solubilized, and oxygen consumption for

the best fitting models for each of the three access cases of Table 2. The parameter values for these cases are given in Table 4. The fits are all quite good and so quite similar.

Figure 8 compares the model temperature, oxygen consumption, and copper leaching curves (dashed lines) for the best fitting model of Case 2 (see Table 4) to the observed curves (solid lines). Although the model fit is not perfect it is quite good. The model base heats up each time flush solutions are applied and heats up the same amount observed. The observed base temperature was a little cooler during the first winter (note dashed ambient temperature curve) than the model base suggesting the model should have communicated thermally a little better with the outside than it did.

The Port 1 observed temperature is again a little cooler in winter than the model again suggesting thermal communication between the column and its environment at the port 1 level should have been a little greater than assumed in the model. The model and observed changes in temperature during solution flushes are again of very similar magnitude and direction. Note the flushes cool down port 1 but warm up the base of the column.

The observed and model temperatures at ports 2 and 4 are quite close to those observed. The decrease in model temperature at Port 2 is a bit greater than observed which may suggest solutions are not flowing near the thermocouple as fast as if flow were completely uniform.

Model and observed oxygen and copper recovery curves are quite similar. The model copper curve indicates model leaching may be slightly too fast at later times. The Case 2 match was not perfected to the extent the Case 1 match was. Case 1 copper recovery is nearly coincident with that observed. Note that the rate of oxygen consumption for the model is very close to that observed. Note low consumption in the zero to 100 day period when the column was cool and the much higher consumption that follows the same step-like pattern from 130-195 days. In fact it can be seen that the field airflow rate was overestimated by about 40% (the steps are lower than the model indicates they should be)! We can conclude that overall the match between model column behavior and the behavior of the actual column is excellent. An equally good match was obtained for Cases 1 and 3 as shown by the similarity of the curves in Figure 7.

The next question is how unique the parameters in the models are. A large number of models were run to address this question by calculating the impact of changes in important model parameters relative to the best fitting cases.

It was found that if parameters that allow heat generation are decreased below certain limits the model column becomes too cool. The constraints on τ_{DS} and K_{col} are particularly tight. Both affect the temperature of the column strongly in the later stages of leaching. The constraints

on τ_{CS} are less strong. The effect of increasing τ_{CS} from 250 to 350 months can be observed in fit deterioration but the effects become dramatic only when τ_{CS} is increased to 500 months or so. The column tests do not place a tight upper bound on τ_{CS} .

It was found that a tight lower limit is placed on τ_{DS} by the leaching results. As τ_{DS} is decreased in magnitude leaching becomes too fast at the later stages of the leaching test and model copper recovery and oxygen consumption are too great. Similarly it can be seen that the initial (0-100 day) oxygen consumption rate requires τ_C be greater than at least 150 months. If τ_C were this low the initial rate of oxygen consumption in the model would be twice that observed.

E_{CS}^* is constrained within loose bounds by the direct observation of the rate at which various ports heated up at various temperatures (4) (i.e. the strong upward curvature of the port temperature curves below $\sim 45^\circ\text{C}$, the temperature at which bacterial catalysis begins to be inhibited). Direct estimation from the port temperature curves yields a value of E_{CS}^* between 20 and 25 kcal/mole. Within this range there is a tradeoff between values chosen for E_{CS}^* and FPY. It was found, for example, that a model with E_{CS}^* decreased to 20 kcal/mole and FPY increased from 13 to 16 provides almost as good a match to the observed column behavior as the base Case 2 model. The model is not quite as good - initial oxygen consumption is a bit too high and the oxygen consumption match is not as good in the period from 600-720 days. More importantly an FPY of 16 is probably too close to the mineralogical ratio of 17.8 to be compatible with the observed significantly slower leaching of pyrite compared to chalcopyrite or chalcocite.

Finally the column behavior constrains some of the other model parameters. The heat capacity of the waste per unit volume strongly controls the magnitude of temperature swings during flushes. If $\rho_T C_T$ is reduced below the value used the magnitude of temperature fluctuations is strongly increased.

We can conclude that the parameters of the model are all fairly tightly constrained by the observed column leaching behavior given the fraction of waste in the column accessed by leach solutions. Table 4 shows how the model parameters change as the fraction of waste accessed is decreased. The change is entirely as might have been anticipated. Access of a smaller fraction of waste in the column requires that the fraction accessed be leached faster and, to preserve heat balance together with the observed amount of oxygen consumed, requires lower values of FPY. The direction of shift is such as to bring the column parameters much closer to the values that were anticipated from analysis of the leaching of test dumps constructed of Chino Type I waste. The only real difference between the model parameters that describe the column leaching and those that describe the dump leaching are the lower values for τ_{CNS} and τ_{DNS} for the column that were required by the observed rapid initial flushing of

copper from the column.

The values of parameters determined are also reasonable. The value of τ_{CS} is lower than had been calculated in the early stages of model development (1), and the value of E_{CS}^* is higher than might be anticipated from activation energies published in the literature (4). But both these "discrepancies" can be explained by the observed concentrations of Fe^{+++} in the New Mexico column. The Fe^{+++} concentrations were both much higher than the 1 gpl value assumed in the model (explaining the lower value of τ_{CS}) and also increased as temperature increased (explaining the higher value of E_{CS}^*).

The fact that the parameters determined independently for large scale column leaching and test dump operation are similar is encouraging. It provides hope that column experiments and computer dump models may ultimately be used to predict how dumps will leach in the field.

CONCLUSIONS

From the previous discussion it can be concluded:

- (1) The model of the dump leaching process previously developed has been confirmed in all major aspects by the two year large column experiment carried out at the New Mexico Institute of Mining and Technology.
- (2) The parameters of the model that describe the leaching of a particular waste are fairly well constrained by the results of the New Mexico column leach test. All factors considered there is little tradeoff possible between model parameters if the fraction of waste contacted and leached is specified (see Table 4).
- (3) The similarity between model parameters describing sulfide copper leaching determined from the results of the New Mexico column experiment and those determined prior to the column experiment from the leach behavior of test dumps constructed of similar waste at the Chino Mines Division of Kennecott Copper Corporation suggest it may be possible in the future to predict the leaching of field dumps from suitably interpreted column leach experiments. The previous paper (6) emphasizes the importance a proper model of the field dump leaching process will play in this predictive process.

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ACKNOWLEDGMENTS

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GLOSSARY OF SYMBOLS

C_T	Heat capacity of dump (cal/g-°C)
FPY	Moles pyrite leached per mole of sulfide Cu
T	Temperature (°C)
T_{sick}	Temperature at which bacteria became sick
T_{kill}	Temperature at which bacteria became inactive (°C)
τ_{CS}	Time required to leach a typical waste particle of all its sulfide copper at 20°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°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)
k_{col}	Parameter describing heat loss from column (see equation 1)

E_{CNS}^*	Chemical activation energy for nonsulfide leaching (cal/mole)
E_{DNS}^*	Diffusional activation energy for nonsulfide leaching (cal/mole)
X_S	Fraction of sulfide copper left at dump location at any time
X_{NS}	Same as above but for nonsulfide acid soluble copper
ρ_T	Density of dump (g/cm ³)

TABLE 1. Physical and chemical parameters of the New Mexico large column (Kennecott) experiment

WASTE CHARACTERISTICS

MASS	1.6 ± 0.2 x 10 ⁵ kg
DENSITY	2.28 ± .28 g/cc
COPPER GRADE	0.36 wt% 576 ± 72 kg
SULFIDE	0.21 wt% 336 ± 42 kg
NON-SULFIDE	0.15 wt% 240 ± 30 kg
PYRITE CONTENT	6.55 wt%
FPY	17.8
ESTIMATED RETAINED WATER	6000 liters
PERMEABILITY	0.4-1.2 Darcies

OPERATION SUMMARY

FLUSH VOLUME	7700 liters (0.5 gal/ft ² -hr for 48 hours)
RECOVERED COPPER	330 kg (57% TOTAL)
INSTANTANEOUS SOLN/ROCK CONTACT	50%

TABLE 2. Three cases considered by modeling. Also shown are the percentages of accessed sulfide and non-sulfide copper that must be leached to account for the 330 kg of copper actually recovered. The copper remaining in the accessed zones is given for comparison to values measured in Figure 6.

	CASES		
	1	2	3
CONTACT SULFIDE Cu	100%	70%	70%
CONTACT NON-SULFIDE Cu	100%	100%	70%
COPPER LEACHED FROM ZONES CONTACTED			
TOTAL	57%	69%	82%
SULFIDE	27%	38%	69%
NON-SULFIDE	100%	100%	100%
COPPER REMAINING	0.15%	0.11%	0.06%

TABLE 3. Methodology of analysis using model.

METHODOLOGY		
COPPER	O ₂ CONSUMPTION	TEMPERATURE
τ_C	τ_C	τ_C
E_C^*	E_C^*	E_C^*
τ_D	τ_D	τ_D
	FPY	FPY
		K_{col}

τ_D - late leach rate

FPY - copper/O₂ consumption

K_{col} - O₂ consumption/temperature

FPY < 17.8 (mineralogical ratio)

E_C^* - Temperature response, 20-25 kcal/mole

$\tau_C >$ Value fixed by initial O₂ consumption rate

$\tau_C < ?$

TABLE 4. Model parameters that best describe the leaching of test dumps constructed of Chino Type I waste (first column) compared to model parameters that best describe the leaching of Chino Type I waste in the New Mexico column experiment for various assumptions of the amount of waste effectively contacted and leached (see Table 2).

MODELING RESULTS					
		New Mexico Column			
	CHINO DUMPS (TYPE I WASTE)	FIRST YEAR	CASE1	CASE2	CASE3
ACCESS S	-	100%	100%	70%	70%
NS	-	100%	100%	100%	70%
τ_{CS}	250-300	850	600	250	150
τ_{DS}	150	150	300	75	30
FPY	12	15.4	17.8	13	9
E_C^*	15k	25k	25k	25k	25k
K_{col}	-	0.0	8×10^{-8}	6×10^{-8}	7×10^{-8}
ρ_{TC}	.6	.6	.6	.6	.6
τ_{CNS}	250-300	6	6	5	5
τ_{DNS}	150	6	6	5	5
T_{sick}	55	50	45	45	45
T_{kill}	65	55	55	55	55
k'	1000	.3		.2-1.2	

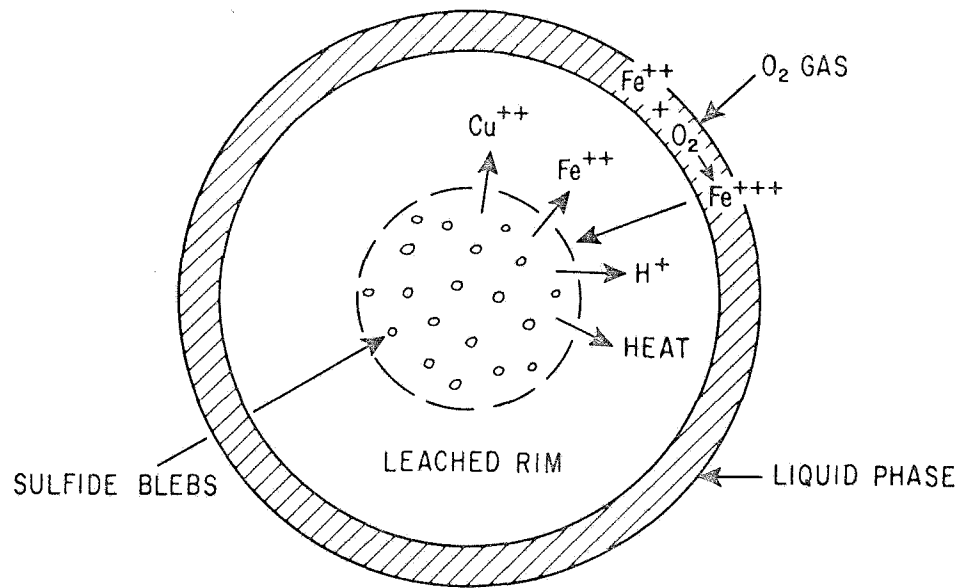


Figure 1. Schematic diagram showing steps involved in the leaching of copper sulfides from a typical, non-spalling, waste fragment.

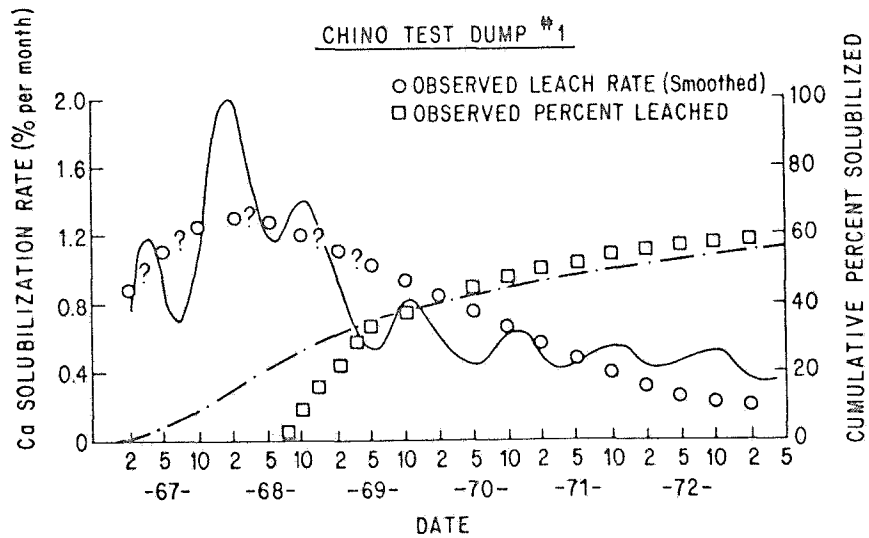


Figure 2. Observed and model leaching of a 47' high test dump built of Chino Type I waste.

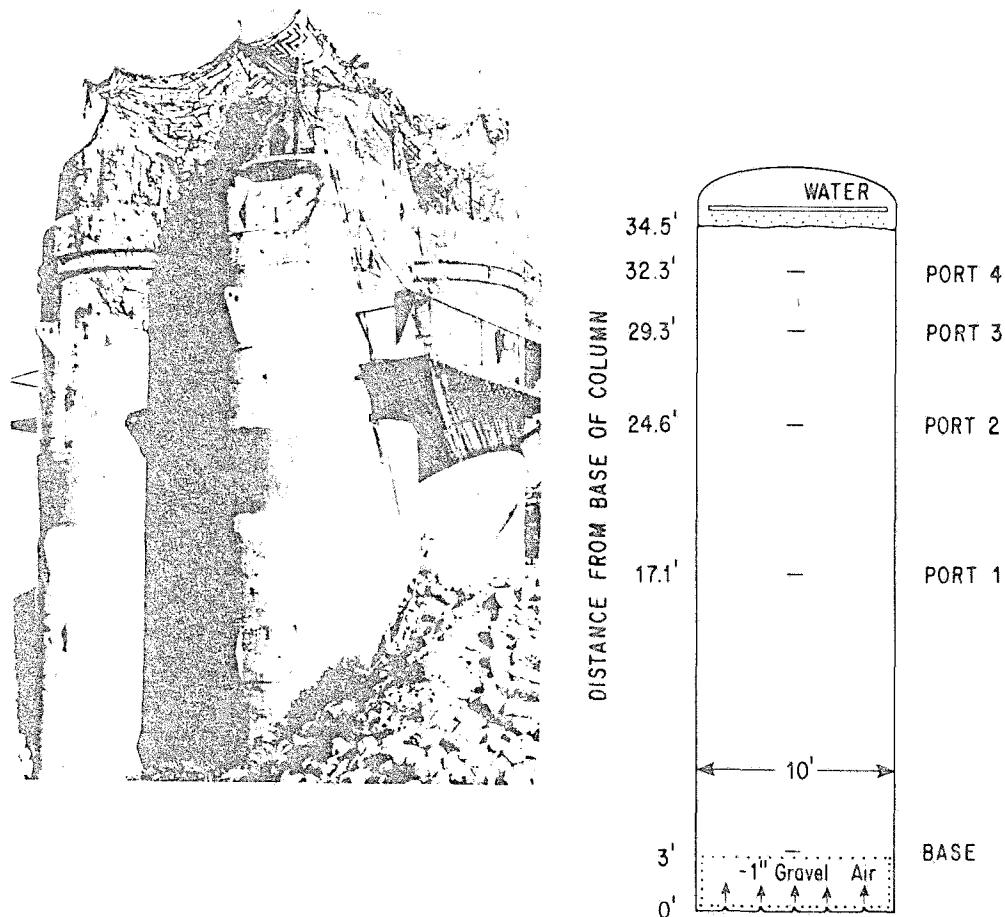


Figure 3. The columns in which large scale tank leach experiments were carried out at New Mexico Institute of Mining and Technology, Socorro, New Mexico.

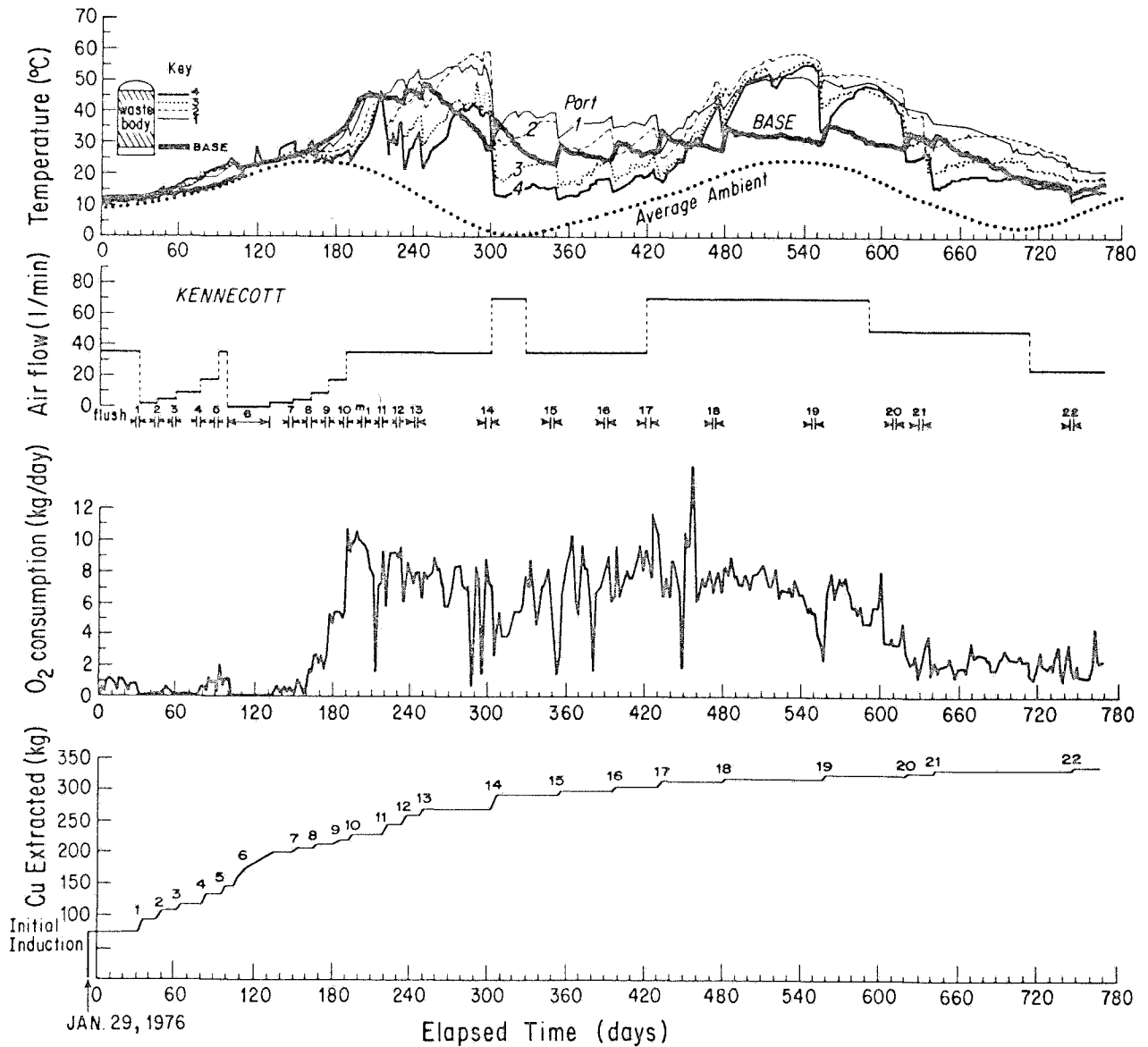


Figure 4. Leach behavior of New Mexico tank.

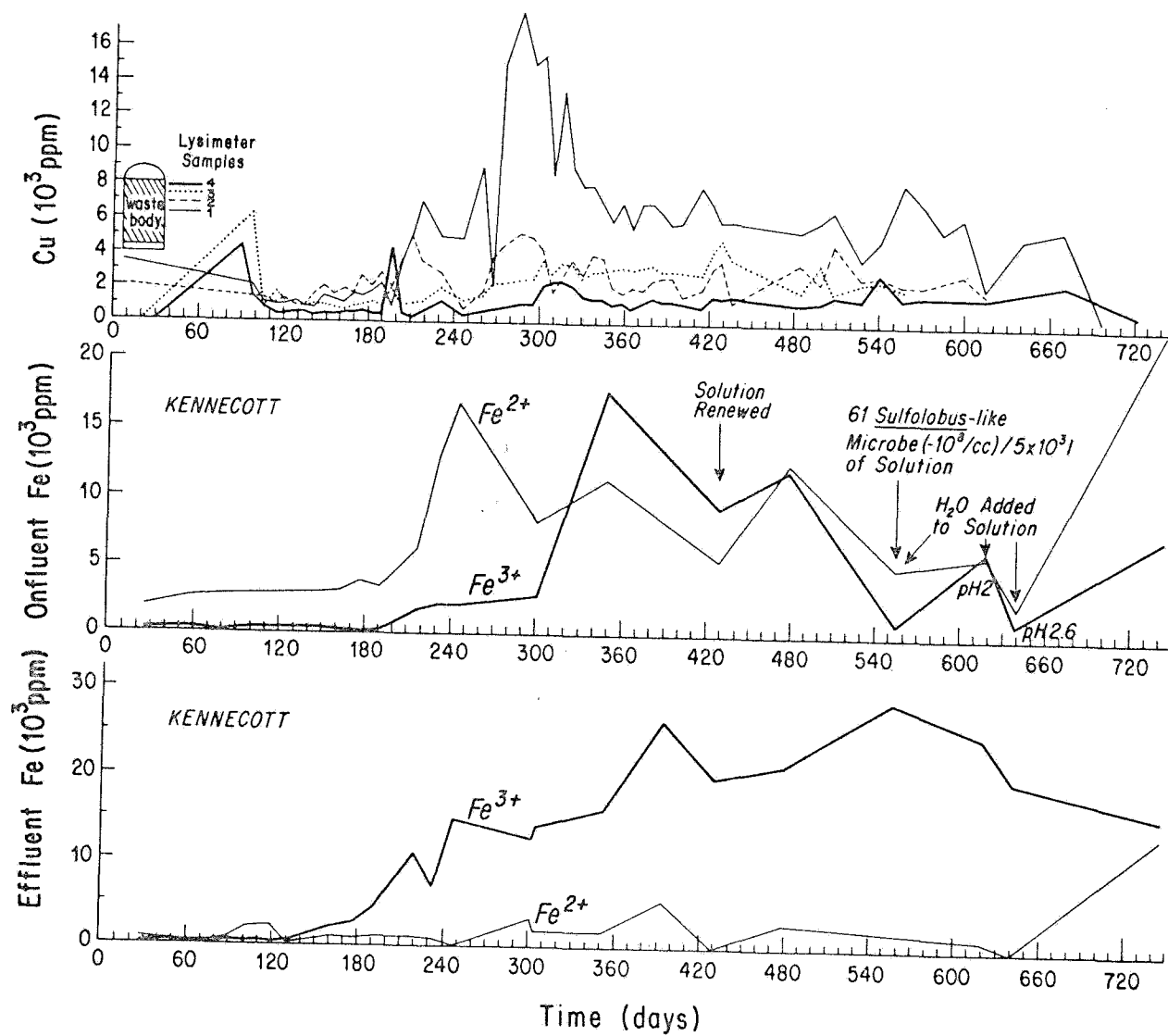
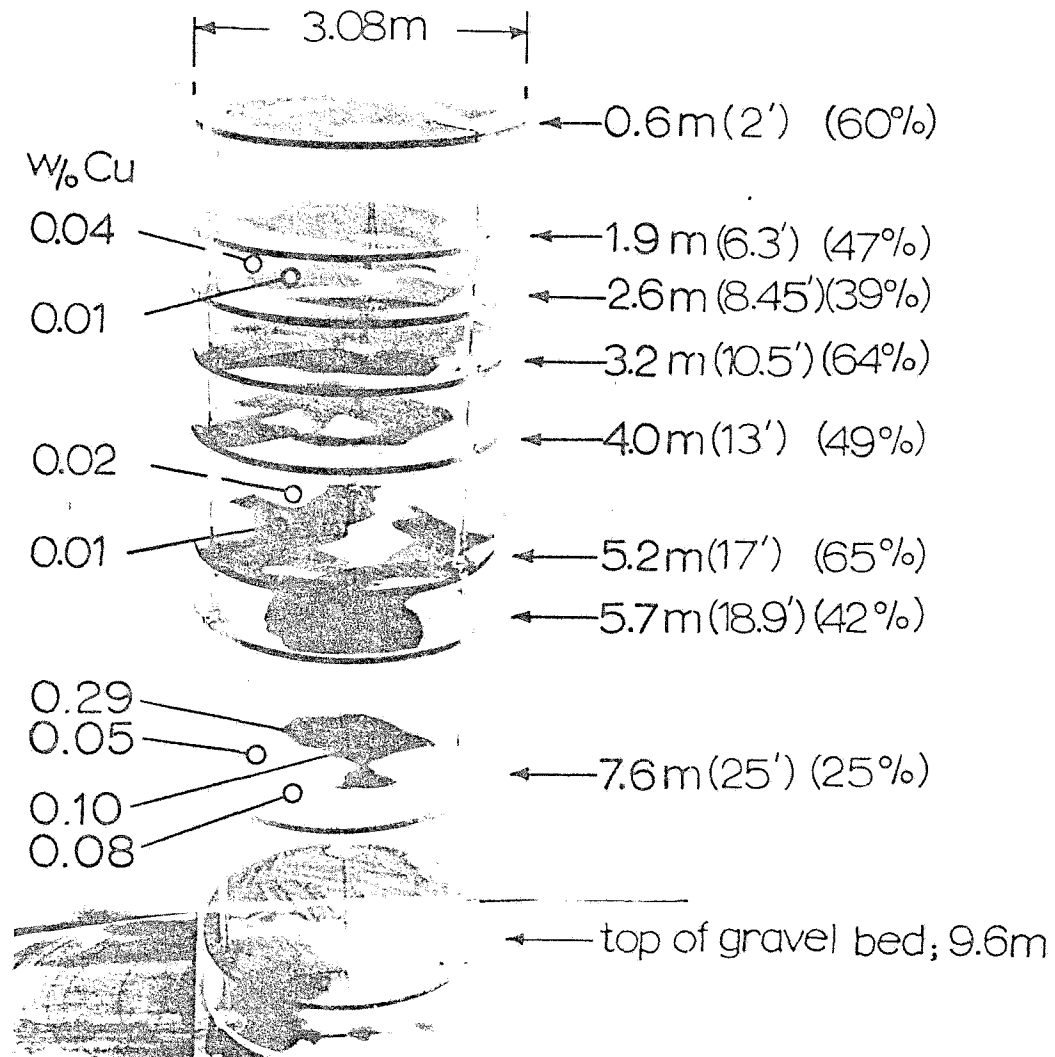


Figure 5. Nature of solutions during leaching.



Kennecott

Figure 6. Stained areas contacted by leach solution at end of test and copper assays of particular locations in the column.

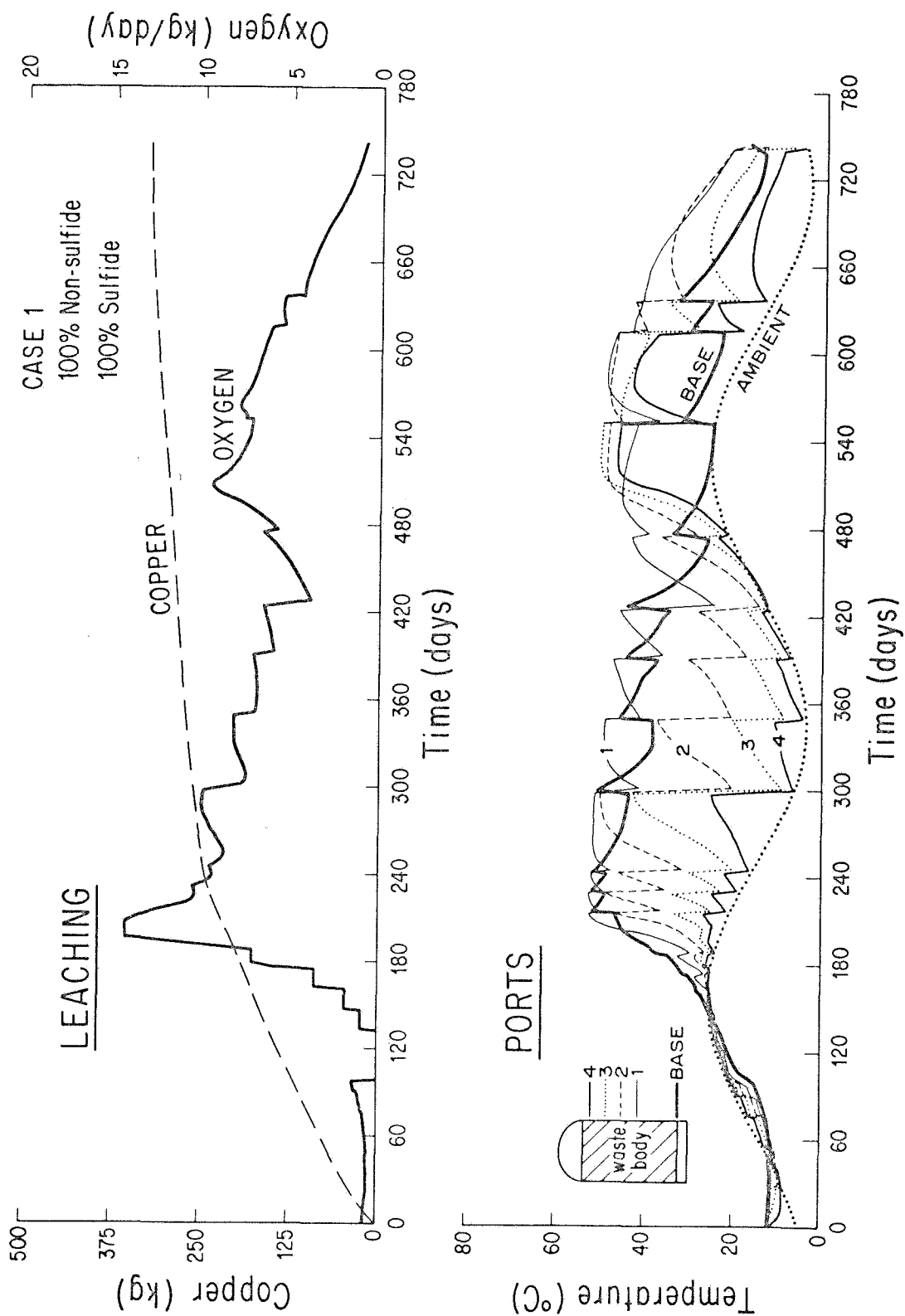


Figure 7. Model leach column behavior for three best fitting cases of Table 4.

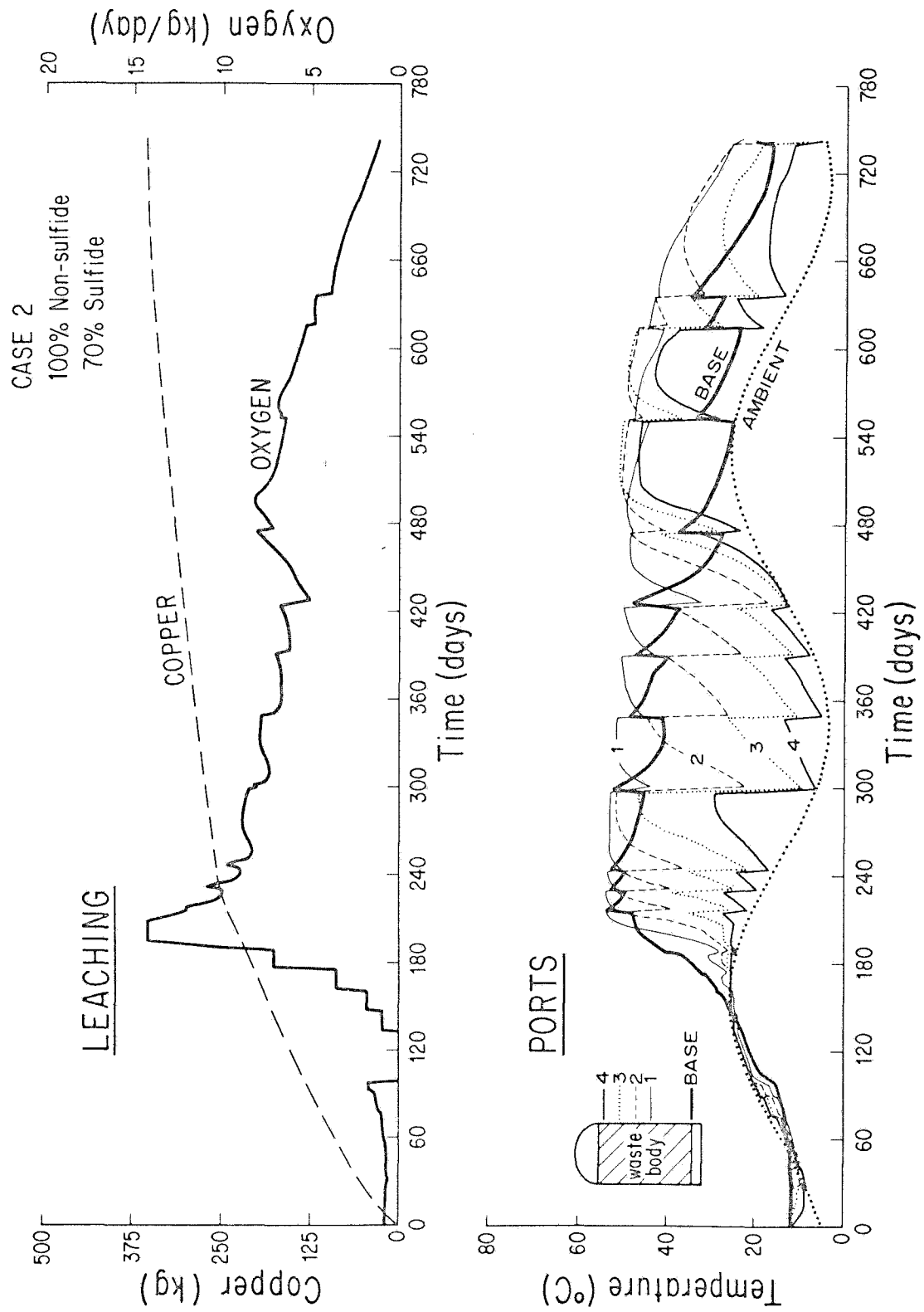


Figure 7 continued.

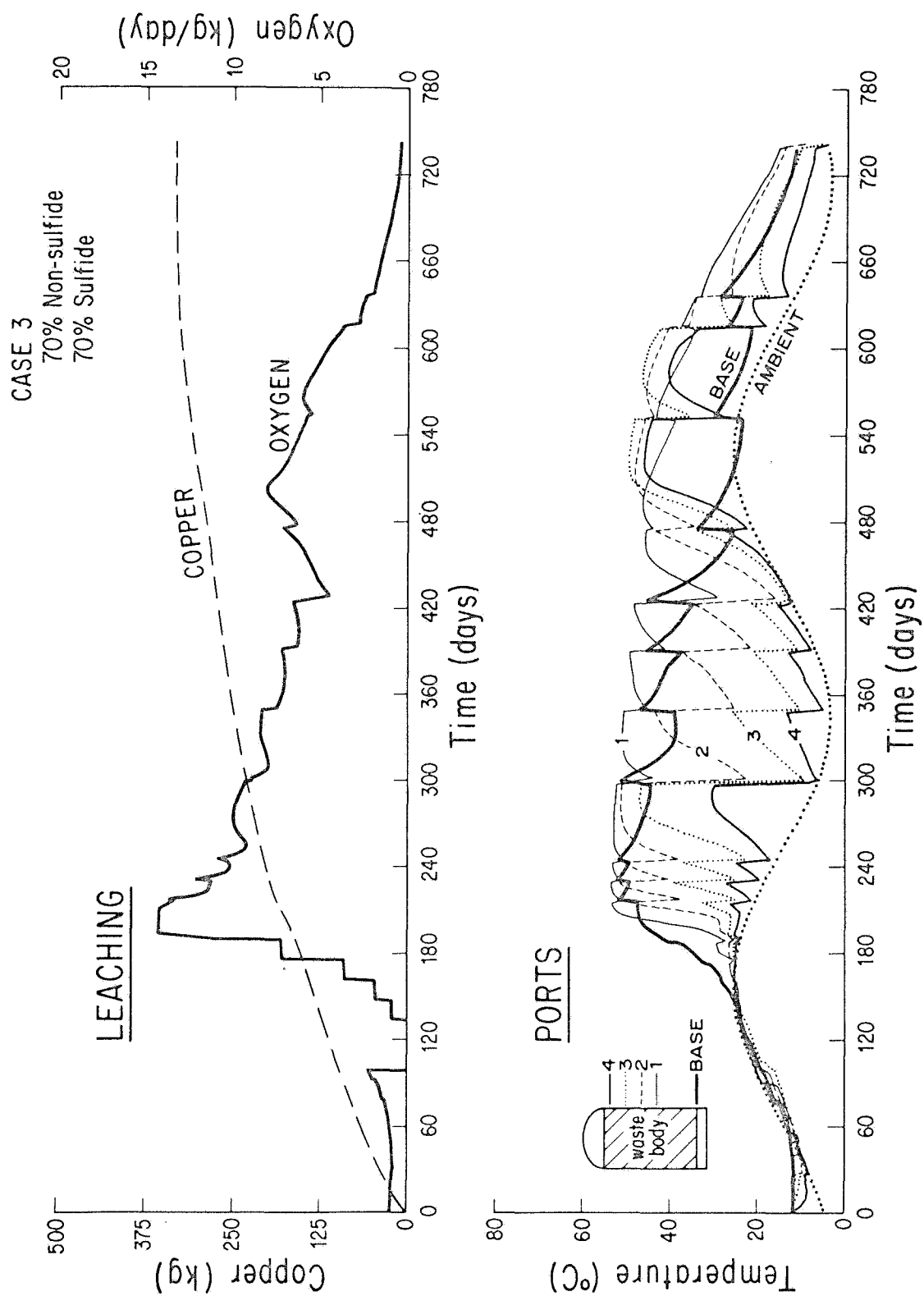


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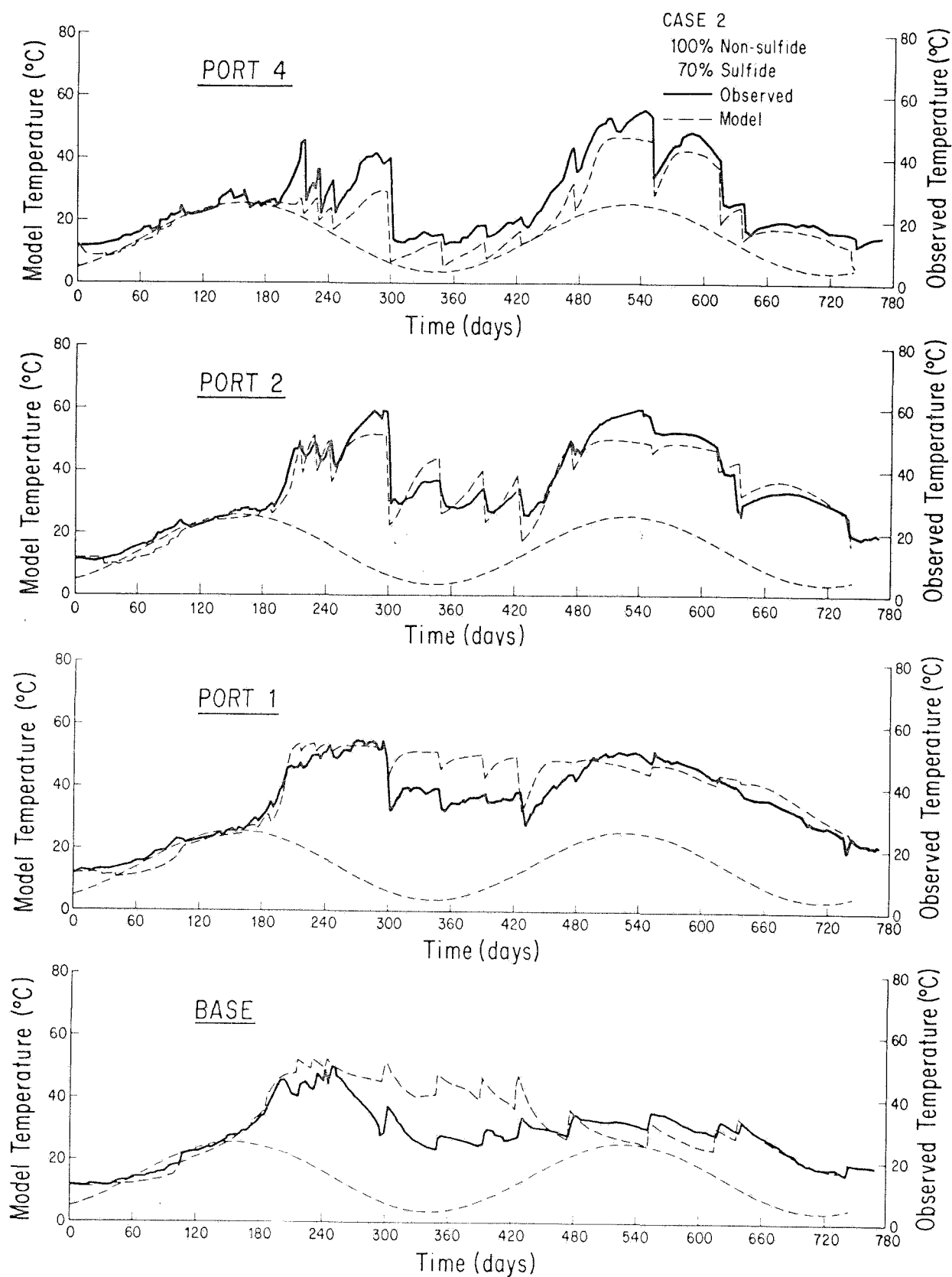


Figure 8. continued

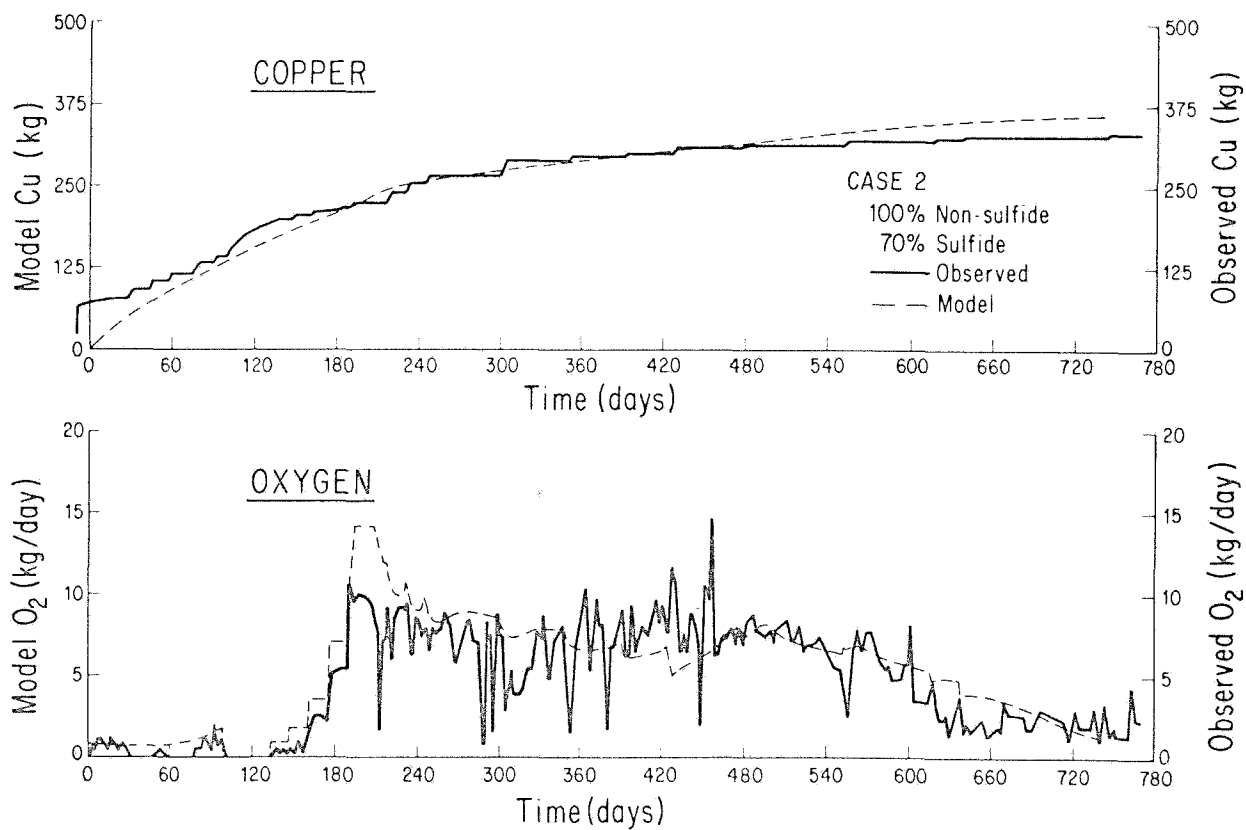


Figure 8. Comparison of model case 2 (dashed curves) to observed column behavior (solid lines). Model ambient temperature (dashed sinusoidal curve) is also given as a reference.