NUREG/CR-4061
PNL-5318

Leachate Plume Migration Downgradient from Uranium Tailings Disposal in Mine Stopes

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Pacific Northwest Laboratory
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NUREG/CR-4061
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Manuscript Completed: January 1985
Date Published: February 1985

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Washington, D.C. 20555
NRC FIN B2370

ABSTRACT

A method previously developed at Pacific Northwest Laboratory has been simplified and extended to better evaluate the environmental consequences of below-water-table disposal of uranium mill tailings in mine stopes. The method described uses analytical expressions for the velocity potential and examines numerically the convective transport of tailings liquor and leachate through the aquifer and into a water supply well located downgradient from the mine stope. The overall dependence of the leachate plume size and shape on the hydrologic parameters and the tailings disposal geometry are presented in graphical form for use in preliminary assessments. The graphical results are also used to set up worst-case scenarios for return of the leachate constituents to the biosphere via the pumped water supply well. The interactive computer models developed to evaluate such worst-case conditions are presented, discussed, and used to evaluate four typical situations.

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ACKNOWLEDGMENTS

This study was sponsored and supported by the Waste Management Branch, Division of Radiation Programs and Earth Sciences, Office of Nuclear Regulatory Research of the U.S. Nuclear Regulatory Commission under FIN B2370, Task 5: Evaluation of Seepage and Leachate Transport from Tailings Disposal Facilities. The authors gratefully acknowledge the interest, suggestions, and continued encouragement of Mr. Frank Swanberg, NRC Research Project Manager. His untiring efforts to maintain a balance between providing useful practical results and yet encouraging and enabling important research results have enabled significant progress. The authors also express their appreciation for Dr. M. G. Foley's capable local management of the project; to Dr. Glendon Gee for his careful review of this report; to Ms. Janelle Downs-Berg, for the technical editing of the document; and to the Sigma V word processing group who capably handled typing of the text and the many equations.

EXECUTIVE SUMMARY

The environmental consequences resulting from the seepage of water and contaminant through uranium mill tailings into the surrounding groundwater is a primary concern associated with the disposal of uranium mill tailings. Various methods currently used and suggested for disposing of these tailings include depositing the tailings in pits excavated during surface mining operations; depositing the tailings in specially constructed pits with liners, sump drains, and covers; and placing the tailings in deep mine stopes where the ore was mined.

When tailings are placed in deep abandoned mines stopes, the primary environmental concerns are the movement of concentrated tailings liquor into the groundwater and the leaching of contaminants as the uncontaminated groundwater seeps through the tailings. To better evaluate the environmental consequence of below-water-table disposal of uranium mill tailings in mine stopes, Pacific Northwest Laboratory (PNL), under contract to the U.S. Nuclear Regulatory Commission (NRC), has modified and extended methods previously developed at PNL (McKeon and Nelson 1984). Under the previous study, a mathematical model was developed to characterize the amounts, rates, travel times, and flow paths. This method, which was simplified and extended for this study, is easy to use and is appropriate when a limited amount of data is available. The model's analytical equations for velocity potentials and the convective transport of tailings liquor and leachate through the aquifer were changed little, but the expressions for flow into the downgradient water supply well were significantly simplified. The extension of the model involved providing an analytical stream function for the downgradient well and using a more complete model to provide improved and more detailed descriptions of the shape of the tailings leachate plume downgradient from the tailings-filled stope.

The overall dependence of the configuration of the leachate plume on the hydrologic parameters and disposal system geometry is provided in a graphical form. The graphs, which delineate plume shape and size, can be used for preliminary leachate plume assessments and in planning more detailed assessments. Specifically, the effects of hydrologic and geometric variables on maximum leachate plume depth, maximum plume width, and the representative leachate plume length can be estimated from these graphs. This allows us to estimate the appropriate position of the water supply well and set the long-term pumping rates that will give worst-case situations for use in the detailed assessment.

The leachate plume shape depends strongly on the hydraulic conductivity contrast as measured by the ratio of tailings to aquifer hydraulic conductivity. The orientation of the stope in the groundwater gradient in the regional aquifer is also important. The stope geometry, represented by the length to diameter ratio of the stope, influences the plume shape less than either the hydraulic conductivity contrast or stope orientation. Other factors influencing the plume size and shape, listed in order of diminishing importance, include the porosity ratio of the tailings to aquifer materials, the magnitude of the regional groundwater gradient, and the actual magnitude of the aquifer material hydraulic conductivity.

The more detailed assessment considers the potential concentrations of uranium tailings leachate that under worst-case conditions may be returned to the biosphere by pumping from a water supply well located downgradient from the tailings disposal stope. Unique interactive computer codes were developed by PNL for this purpose. Specifically, these evaluation tools enable estimating the variation and changes in concentration of leachate constituents in the plume, both in space and time. The interactive capability allows us to rapidly determine the expected concentration of the leachate constituents that will occur in the water pumped from the downgradient water supply well.

In this study, only one of the geochemical interactions was incorporated into the analysis. The geochemistry of tailings leached by groundwater is incorporated from laboratory leaching column studies. The laboratory column results were directly scaled up based on column volume and equivalent residence time concepts. The second group of geochemical interactions, those between the contaminated leachate and the aquifer porous media, are not currently incorporated in the analysis.

The results of the more complete analysis for the concentration at the well as a function of time indicate that the original concentration of contaminant (sulfate in the test case reported here) in the tailings slurry is reduced by 66% (from 9,300 to 3,200 mg/L) from dilution caused by different travel distances and times through the flow system. The results also indicate that the amount of dilution changes with the orientation of the mine stope with respect to the regional gradient. The minimum reduction of 66% in the peak sulfate concentration occurred when the stope orientation was perpendicular or at an angle of 90° to the regional gradient. As the orientation angle diminished from 90° to 45°, to 20°, and then to 0°, the reduction in peak sulfate concentrations were 66%, 70%, 79%, and 78%, respectively.

The predicted concentration of contaminant at the water supply well is environmentally unacceptable; however, this peak concentration could be lowered significantly by incorporating the geochemical interactions between the contaminated fluid and the porous media (i.e., neutralization, sorption, ion exchange, precipitation). These results indicate the need to continue research and to develop technology that can be used to analyze geochemical interactions and contaminant transport.

INTRODUCTION

The disposal of uranium mill tailings has warranted considerable study in recent years. Among the primary concerns in this effort are the environmental consequences resulting from the leaching of tailings by groundwater and the subsequent leachate migration away from the tailings disposal site. A variety of methods are used to dispose of tailings, but our study focused on assessing the consequences of disposal of uranium mill tailings in abandoned deep mine tunnels and stopes below the water table.

Pacific Northwest Laboratory (PNL) under contract to the U.S. Nuclear Regulatory Commission (NRC) developed an idealized model, which is described in McKeon and Nelson (1984) ("Evaluation Methods for the Consequences of Below Water Table Mine Disposal of Uranium Mill Tailings)". The model was designed to enable better understanding of interactions in the tailings groundwater flow system and to provide an aid in evaluating the environmental consequences of stope disposal of tailings below the water table. The idealized model was purposely selected because often only limited aquifer data are available. If data are limited, the use of the more elaborate groundwater models capable of considering spatially varying hydraulic conductivity is usually unrealistic and is often more costly. Because the idealized models can be used more easily, more simulations can be run to establish the overall dependence on the hydrologic factors and their effect on leachate plume shape, rates of migration, and concentration distributions. The model for three-dimensional fluid flow used in the previous work (NUREG/CR-3560, McKeon and Nelson 1984) was simplified and extended for application to this study. The tailings-filled mine stope idealized as a prolate spheroid has a uniform hydraulic conductivity that is different than the regional deep aquifer in which the disposed tailings are embedded. The large regional aquifer has a constant hydraulic conductivity throughout its extent. A wide range of contrasting conductivities between the tailings and the aquifer is considered.

The basic flow model was simplified because we found that the doublet-like terms originally used for the well potential were very small and had a negligible effect on the pathlines generated. The extensions to the model involved deriving an analytical stream function for the flow into the downgradient pumping well and some other related extensions that enabled better description of the leachate plume shape downgradient from the stope. Appendix A provides a complete definition of terms in this report and the changes and extensions to the model equations are presented in Appendix B.

Through this work we provide results that can easily be used to describe the leachate plume configuration downgradient from the tailings-filled stope. The overall plume depth, width, and representative plume length are illustrated in graphs for a wide range of stope dimensions and hydrologic conditions. These overall plume dimensions may be directly used for preliminary plume assessment. They are also helpful in determining which comprehensive computer evaluations provide detailed plume information. Both plume shape and the concentration distributions within the plume at various times can then be obtained for worst-case assessment.

The leachate plume concentrations were generated by using experimentally measured tailings leaching curves appropriately extended using the residence time-scaling methods described by McKeon and Nelson (1984). Unfortunately, the geochemical interactions of the leachate with the aquifer (buffering capacity, etc.) are not included in the analysis in this report. The methods for incorporating such results into the plume analysis were worked out, but the geochemical/transport analysis from laboratory column data developed on a companion project at PNL was not completed in time to be included in this analysis. The following analysis therefore represents a very conservative method to estimate the environmental consequences of below-water-table disposal of uranium mill tailings in mine stopes.

LEACHATE PLUME SHAPE

The leachate plume shape found downgradient from a tailings-filled mine stope is conveniently described in terms of the maximum plume depth, the maximum attained plume width, and a representative plume length. Actually, the plume varies in depth, width, and length in space and with time, but the overall plume dimensions are convenient in describing the effects of changing hydrologic parameters on the overall plume shape. These same plume-size parameters are also useful in selecting the particular well locations and pumping rates required to produce the worst-case environmental consequences.

The water quality was assessed in terms of the plume shape, concentration distributions of leachate constituents within the plume at various times, and the subsequent concentration of the leachate constituents pumped from the water supply well by using the extended interactive computer models. These interactive models have been designed so that the user may obtain the complete analysis with relative ease. Before describing the interactive models and discussing the examples of their use, the overall plume description is discussed and the graphical summaries showing the significance of particular hydrologic parameters affecting the plume shape are considered.

MAXIMUM LEACHATE PLUME DEPTH

Among those factors influencing the overall plume shape, and particularly the plume depth, are the ratio of the tailings hydraulic conductivity to the aquifer hydraulic conductivity, K'/K, the angular orientation of the mine stope major axis with the regional groundwater gradient, θ, and the relative stope size, a/b. These three dimensionless parameters determine the maximum downgradient plume depth expressed as a ratio to the stope radius (i.e., the L/b ratio shown in Figures 1 and 2).

In Figure 1 the leachate plume depth is shown as a function of the permeability contrast, K'/K, for various stope orientation angles, θ, and stope dimension ratios, a/b. When there is no permeability contrast, or $K'/K = 1$, the leachate plume depth is the same as the stope depth, 2b, or more specifically $L/b = 2$. This is as expected because with equal hydraulic conductivities, groundwater is neither diverted into nor away from the stope and the downgradient depth of the leachate plume is simply the stope diameter; therefore, $L/b = 2$ as shown in Figure 1 when $K'/K = 1$. As the tailings to aquifer hydraulic conductivity ratio, K'/K, becomes progressively smaller than unity, the tailings embedded in the aquifer are less and less permeable and the upstream groundwater increasingly tends to be diverted around the stope rather than pass through the tailings. Therefore, the downgradient leachate plume depth is reduced. In contrast, as the tailings hydraulic conductivity becomes progressively larger than that of the regional aquifer (i.e., $K'/K > 1.0$), more and more of the upstream groundwater tends to flow into and through the tailings in the stope, so the leachate plume depth becomes considerably larger than the stope depth. Hence, L/b may be considerably greater than 2, as shown in

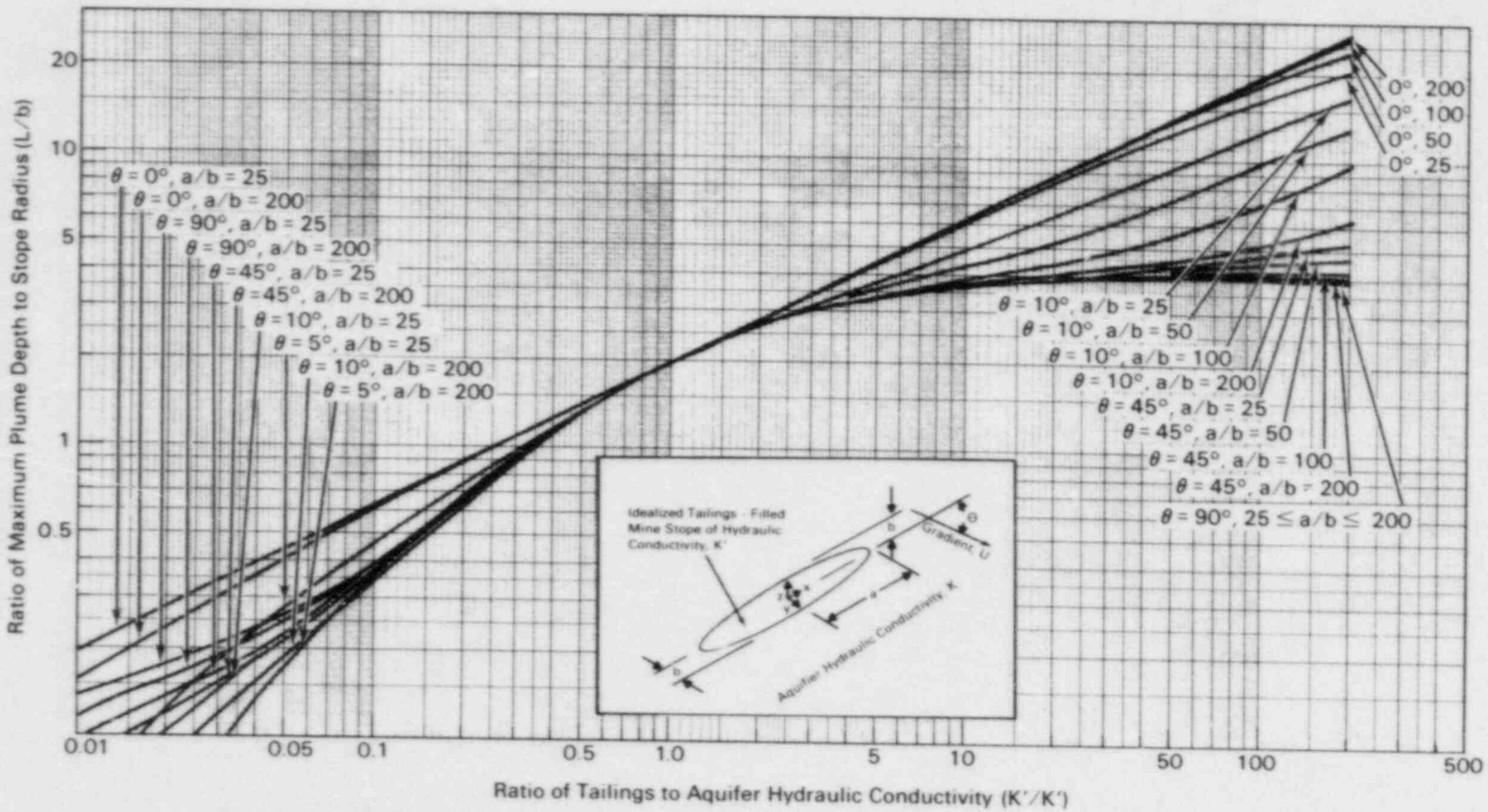

FIGURE 1. The Dependence of Maximum Leachate Plume Depth on the Ratio of Tailings to Aquifer Hydraulic Conductivity Ratio, K'/K, Stope Orientation Angle, θ, and the Stope Half-Length to Radius Ratio

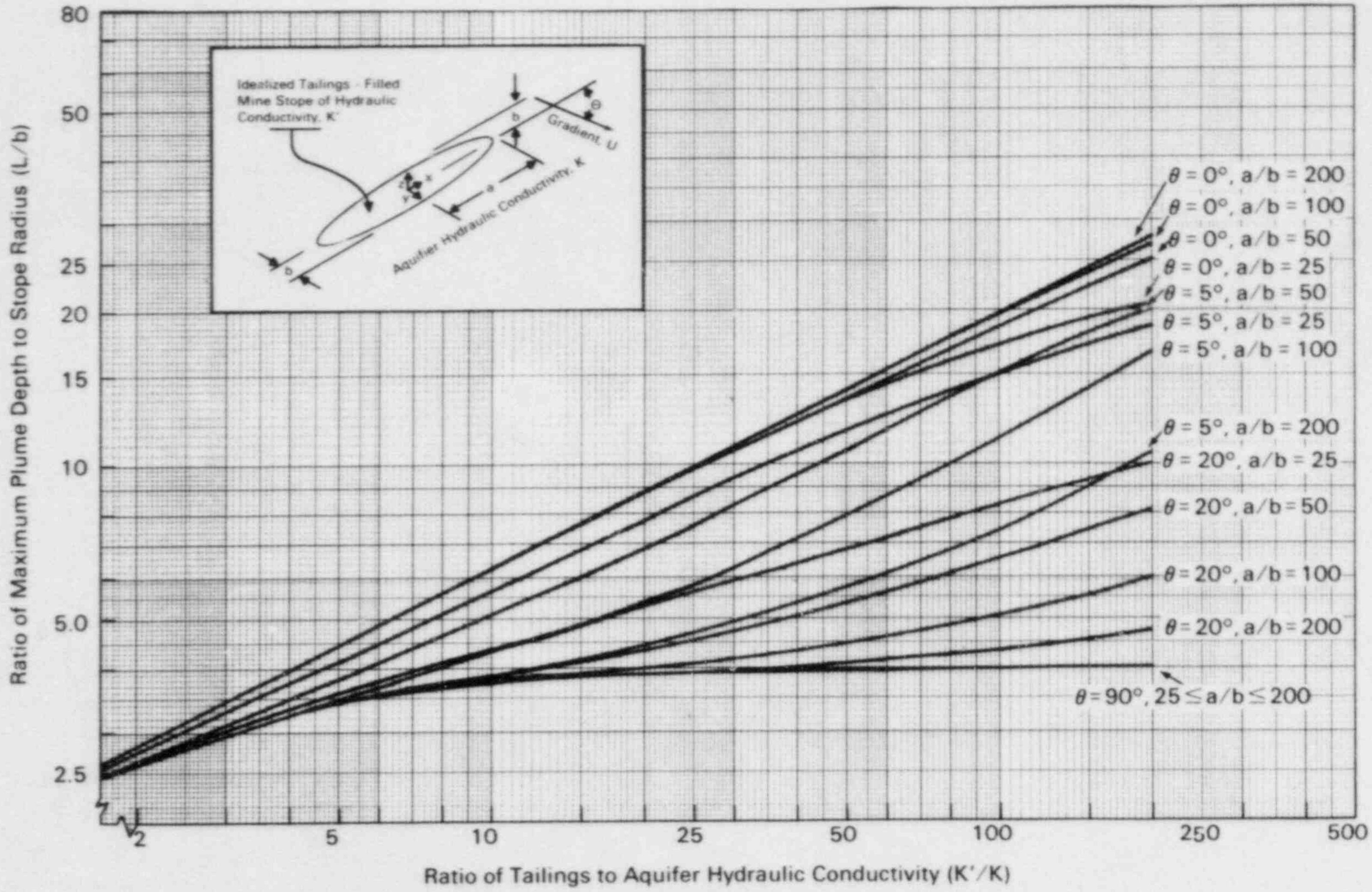

FIGURE 2. The Dependence of Maximum Leachate Plume Depth on the Ratio of Tailings to Aquifer Hydraulic Conductivity Ratio, K'/K, Stope Orientation Angle, θ, and the Stope Half-Length to Radius Ratio

Figures 1 and 2. The contrast or ratio of the hydraulic conductivity of the tailings to that of the regional aquifer has the most important effect on the downgradient plume depth.

In Figure 2, the orientation of the stope major- or x-axis with respect to the regional groundwater gradient as measured by the angle θ is the variable that next affects the leachate plume depth. The greatest leachate plume depth occurs for $\theta = 0°$ when the longest axis of the stope is aligned parallel with the regional aquifer gradient, U. In this case, the stope and regional gradient are parallel; the ratio of stope length to diameter, a/b, is seen to have a small effect on the plume depth and then only at the higher values of permeability contrast, K'/K.

At the other extreme orientation angle of $\theta = 90°$, the regional gradient is perpendicular to the major axis of the stope, and a considerably shallower plume depth occurs as seen in Figure 2. When the gradient, hence groundwater flow, is perpendicular to the length of the stope, the plume depth becomes essentially independent of the ratio of stope length to diameter, a/b. Furthermore, the plume depth to stope radius ratio approaches the limit, L/b--a constant value of 4. In other words, when the flow is normal to the stope, the maximum downstream plume depth is never more than twice the stope diameter, which is significantly shallower than that occurring at the other orientation angles that are less than 90°. Figure 2 also shows that the ratio of stope length to diameter, a/b, is most significant at the intermediate angles of stope orientation rather than at either extreme. The greatest effect of the a/b ratio occurs at stope orientation angles between 10° and 20° as illustrated in Figures 1 and 2.

The plume maximum depth ratio, L/b, was found to depend slightly on the regional gradient, U, at orientation angles between $\theta = 10°$ and 20° and at the highest values of a/b = 200. At the regional gradient value of U = 0.0005, however, L/b changed less than 0.4% from the value at U = 0.001. No differences were found otherwise, so the results shown in Figures 1 and 2 are appropriate for all gradients in the range $0.0005 \leq U \leq 0.005$. Only small errors occur outside this range, but it would probably be more appropriate to use the interactive computer code to provide results for gradients outside the above range.

Example of Finding the Maximum Plume Depth

The results in Figures 1 and 2 can be used to easily and quickly estimate the maximum downgradient leachate plume depth. Suppose the particular case of interest were as follows

Aquifer Hydraulic Conductivity	K = 100 m/yr	
Uranium Tailings Hydraulic Conductivity	K' = 5000 m/yr	
Aquifer Effective Porosity	P = 0.2	
Uranium Tailings Effective Porosity	P' = 0.3	(1)
Aquifer Uniform Gradient	U = 0.001	
Stope Orientation with Aquifer Gradient	$\theta = 20°$	

Stope Half Length	a = 300 m
Stope Radius	b = 6 m

The useful ratios for figuring the plume depth are

$$\frac{K'}{K} = \frac{5000}{100} = 50$$

$$\frac{a}{b} = \frac{300}{6} = 50 \qquad (2)$$

From Figure 2, using $\theta = 20°$ and the ratios in Equation (2) yields $L/b = 5.35$ or

$$L = 5.35 \times b = 5.35 \times 6 = 32.1 \text{ m} \qquad (3)$$

The maximum plume depth is 32.1 m.

MAXIMUM LEACHATE PLUME WIDTH

The maximum plume width downgradient from the tailings disposal stope depends on essentially the same three dimensionless parameters that the plume depth depends on. Specifically, the contrast in hydraulic conductivity, the orientation of the stope in the uniform aquifer gradient, and the length to diameter ratio of the stope are the important parameters in defining the maximum plume width.

The maximum plume width expressed as the ratio to the stope radius (i.e., W/b), is plotted in Figure 3 for stope orientation angles of 0° and 5° for the usual range of stope length to diameter ratios ($25 \leq a/b \geq 200$). When $\theta = 0°$, the longest axis of the stope is aligned parallel to the hydraulic gradient in the regional aquifer, and the maximum plume width is primarily dependent on the permeability contrast ratio, K'/K. Only for large stope length to diameter ratios is the maximum width affected. Even at the lower values of a/b, the $\theta = 0°$ linear curve is only moderately reduced. However, as the stope orientation angle increases to as little as $\theta = 5°$, significant changes in the dependence of plume width on K'/K are seen. Figure 3 shows that the ratio is less significant than the stope length to diameter ratio, a/b, particularly in the left-hand part of the figure.

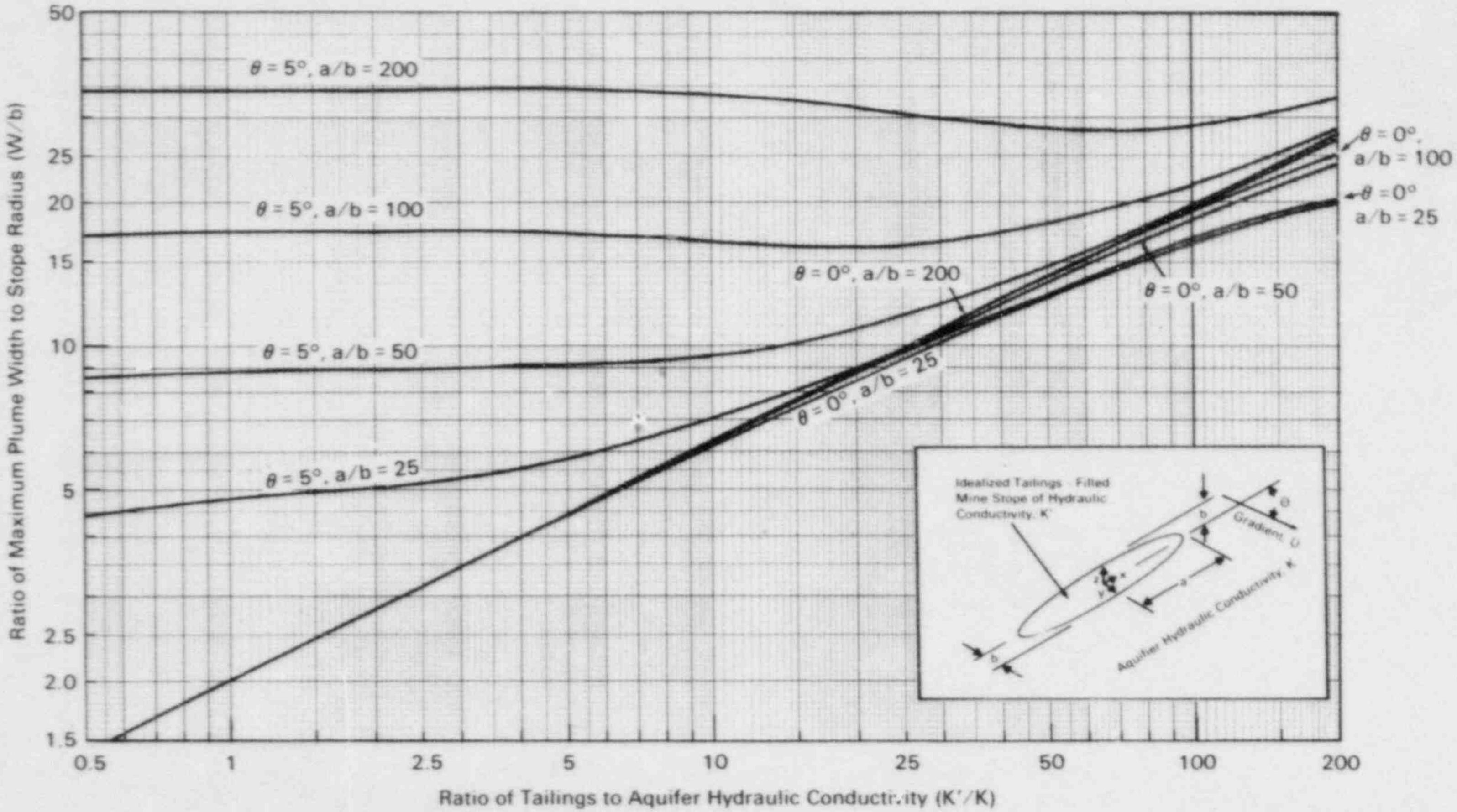

FIGURE 3. The Dependence of Maximum Leachate Plume Width on the Tailings to Aquifer Hydraulic Conductivity Ratio, K'/K, and Stope Length to Diameter Ratios for 0° and 5° Stope Orientation Angles

The shift to increased dependence on a/b with increasing orientation angles is more evident in Figure 4, where the horizontal coordinate has been changed to the a/b ratio. The importance of the permeability contrast ratio, K'/K, gradually diminishes with increasing orientation angles, θ. As the orientation, θ, increases from 45° to 90°, the plume width dependence on permeability gradually vanishes until finally at $\theta = 90°$, it depends only on the stope length.

This gradual transition in dependence of the plume width is very natural. At values of θ near zero, the length of the stope is essentially aligned with the gradient, and the plume width to stope radius ratio is controlled almost exclusively by the extent that upstream groundwater moves into or detours around the stope as controlled by the permeability contrast ratio. Under such conditions, the projected stope length normal to hydraulic gradient is very small (essentially zero), so the ratio a/b is of minor significance. However, as θ increases, the projected stope length normal to the hydraulic gradient rather quickly begins dominating the plume width. At the larger angles for θ, the permeability contrast, K'/K, affects the plume width very little. Any changes in the amount of upstream groundwater entering the stope cause only a small local effect near the ends of the stope. Finally, if $\theta = 90°$, the entire stope length is normal to the regional groundwater flow direction, and it is the stope length ratio, a/b, that effectively determines the leachate plume width.

The leachate plume width depends slightly on the magnitude of the regional gradient, U, at extreme values of the various hydrologic ratios. This minor dependence is seen in Figure 5, where the maximum plume width ratio, W/b, is plotted against the magnitude of the regional aquifer gradient. Over most of the range of the gradient, U, where

$$0.0005 \leq U \leq 0.005 \qquad (4)$$

little dependence is noted. A small dependence is evidenced in the upper left-hand part of Figure 5 for high a/b and K'/K ratios. Minor dependence is also shown in the lower right-hand part of the figure at fractional values of hydraulic conductivity contrast, K'/K, and a low value of a/b. Except at these extreme values, the plume width does not depend on the magnitude of the regional gradient. Accordingly, the results in Figures 3 and 4 can be used in the range of gradients in Equation (4).

Example of Finding the Maximum Plume Width

The maximum plume width may be estimated from Figures 3 and 4 for the condition of the example case in Equation (1). The ratios needed for use in Figures 3 and 4 are

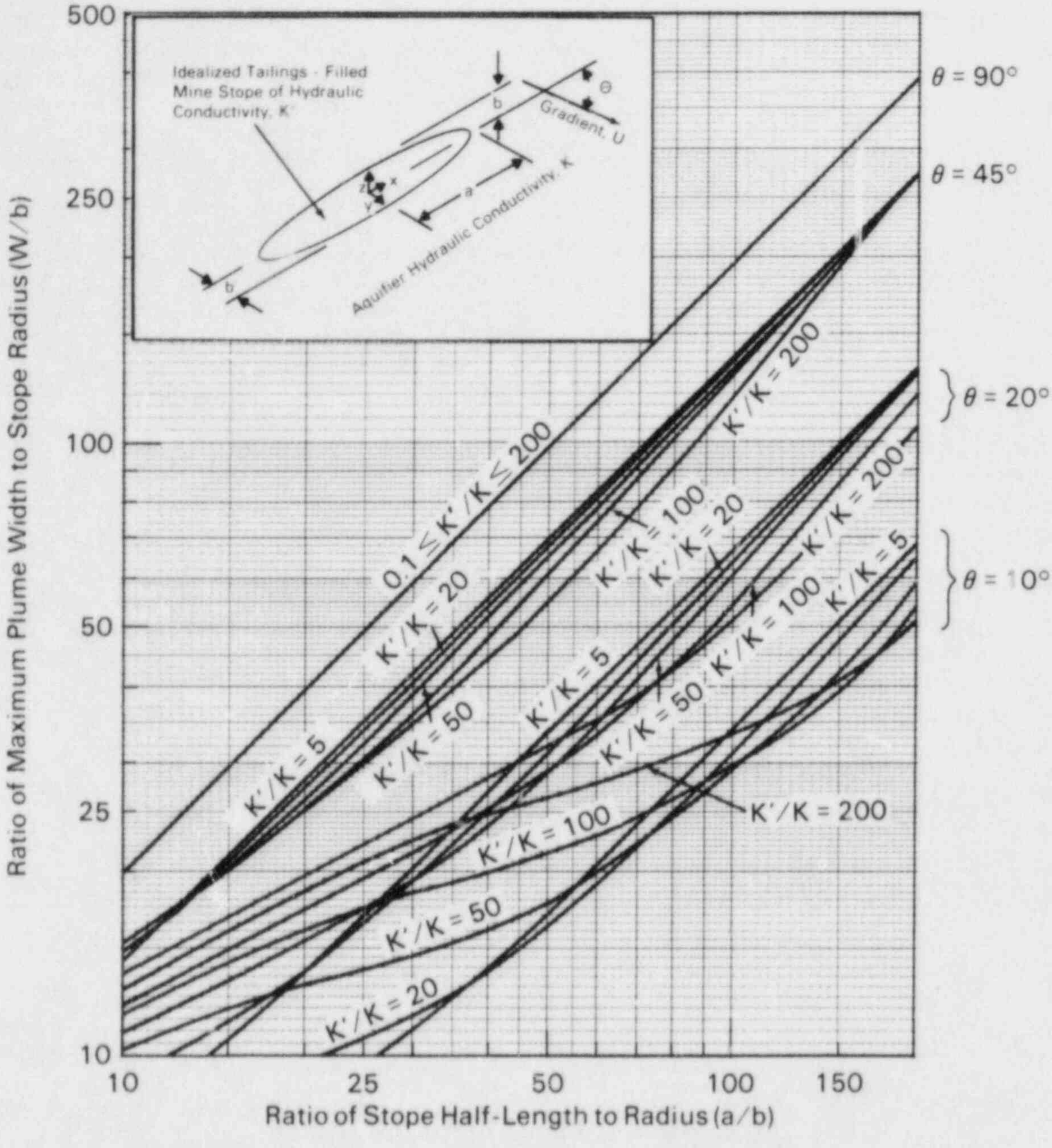

FIGURE 4. The Dependence of Maximum Leachate Plume Width on the Stope Half-Length to Radius Ratio, the Permeability Contrast Ratio, K'/K, and the Stope Orientation, θ

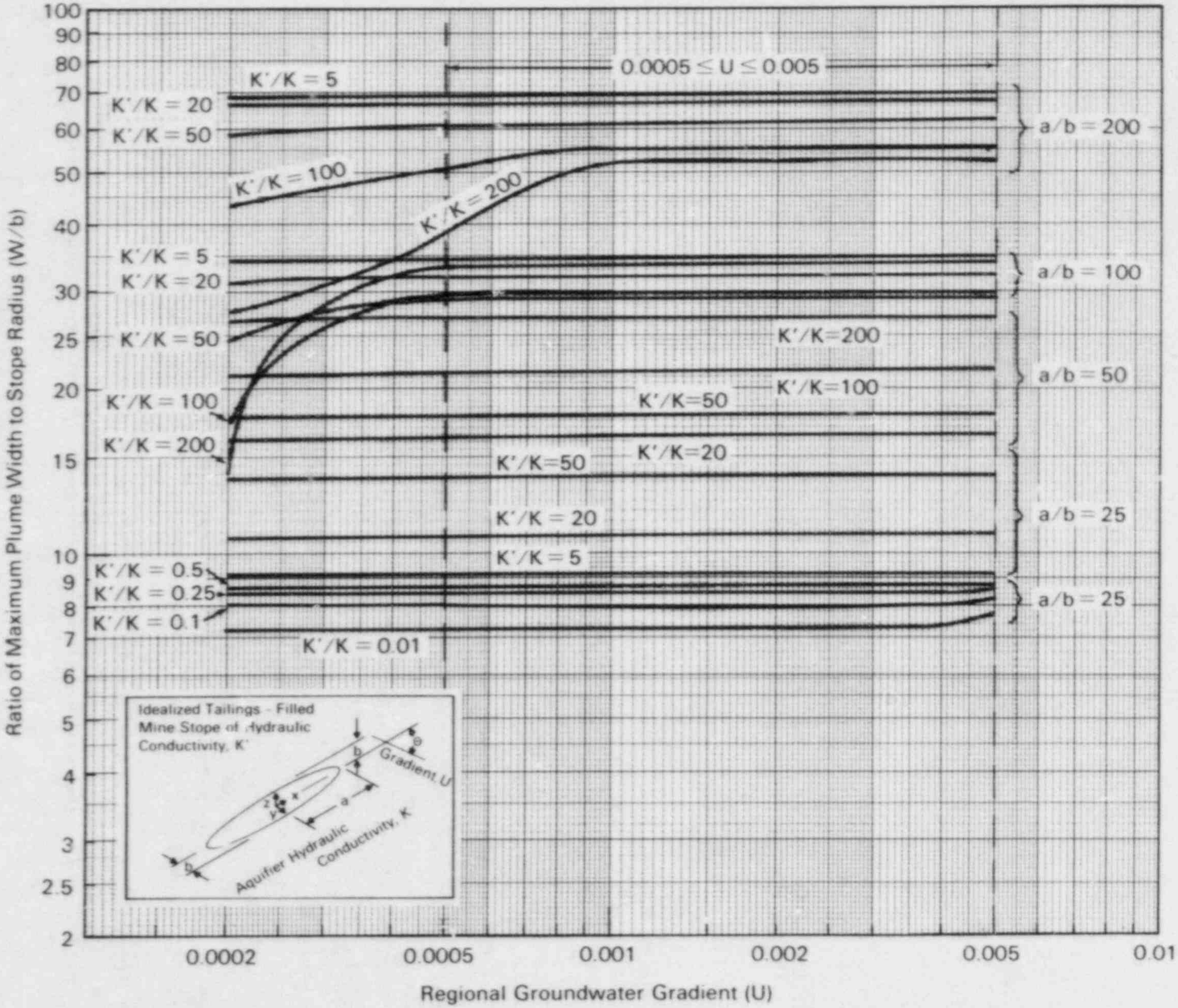

FIGURE 5. Minor Dependence of the Dimensionless Plume Width, W/b, Upon the Magnitude of the Regional Aquifer Gradient, U

$$\frac{a}{b} = \frac{300}{6} = 50 \qquad (5)$$

$$\frac{K'}{K} = \frac{5000}{100} = 50 \qquad (6)$$

and we observe that the aquifer gradient is within the range of Equation (4), so both Figures 3 and 4 are appropriate for use in this example. In Figure 4, using a/b = 50 and K'/K = 50, one obtains a value of W/b = 17.75 or

$$W = 17.75 \times b = 17.75 \times 6 = 106.5 \text{ m} \qquad (7)$$

which is the maximum leachate plume width expected downgradient from the tailings-filled stope for the example case.

REPRESENTATIVE PLUME LENGTH

The leachate plume length, unlike the plume depth and width, is rather cumbersome to represent as a maximum value. To provide maximum plume length would require arbitrary choices involving both the representative chemical constituent selected and the concentration cutoff value chosen for that constituent. Such arbitrary choices are required because there are so many chemical constituents and each one usually leaches from the tailings at a different rate; therefore, no unique concentration cutoff value adequately represents all of the chemical species.

A more useful and representative plume length may be defined in terms of the leachate pore volume occurring along the longest groundwater flow path through the tailings-filled mine stope. This particular pathline is not only the longest, but also always passes directly through the center of the stope. Downgradient from the stope, this special pathline becomes the major longitudinal axis for the advancing leachate plume. Accordingly, by using a representative plume length defined by the first pore volume that passes along the longest leachate pathline through the tailings, it is possible to determine the total path lengths for any of the other constituents. That same representative plume length is easily extended to any desired cutoff concentration for any particular constituent by using the experimental tailings leaching curves.

The representative plume length expressed as a dimensionless ratio, $\Gamma P/bP'$, is shown in Figures 6 and 7 as a function of the hydraulic conductivity contrast ratio, K'/K, the stope orientation angle, θ, and the stope length to

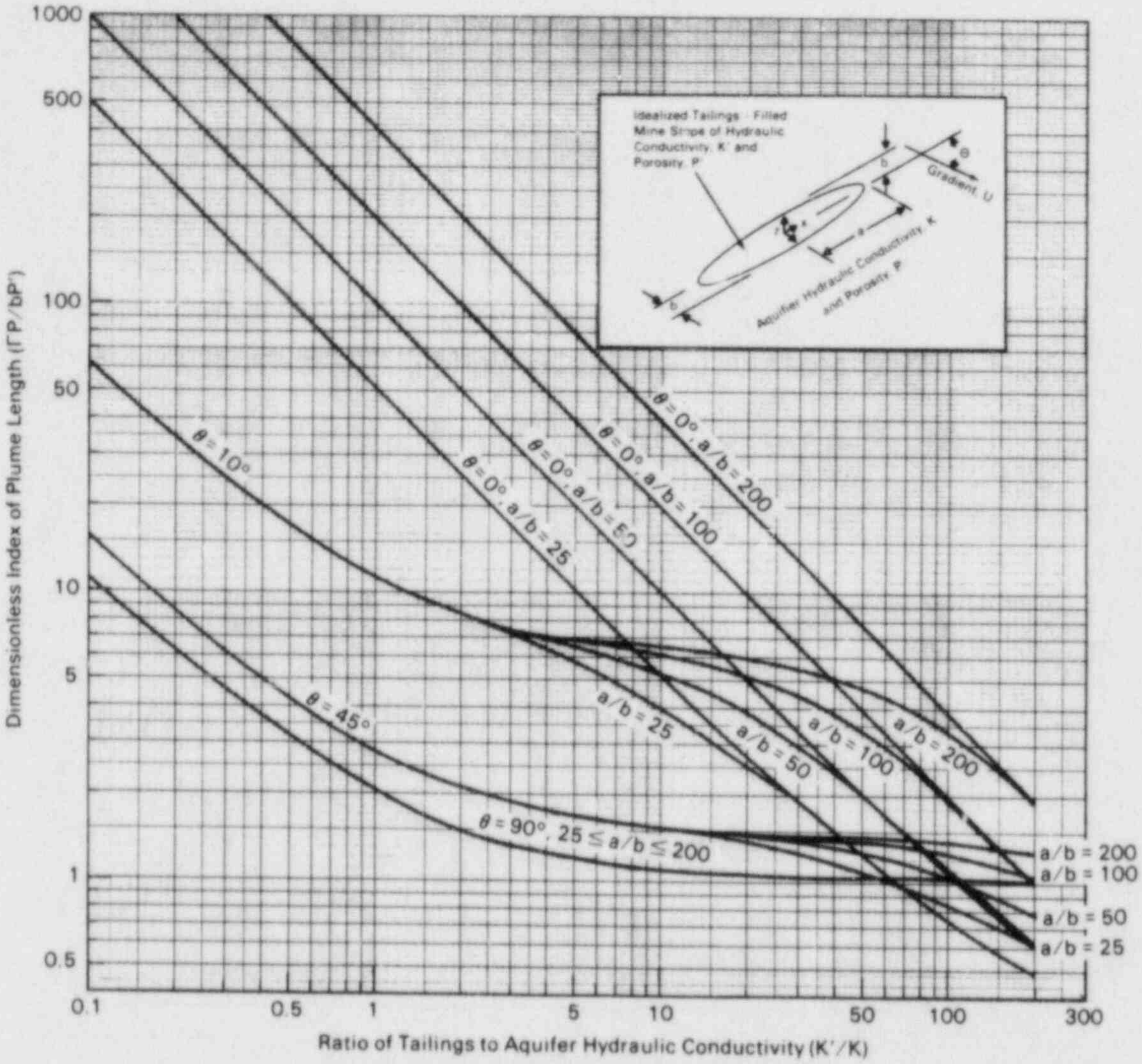

FIGURE 6. The Dependence of the Representative Plume Length on the the Hydraulic Conductivity Ratio and Stope Half-Length to Radius Ratio for Various Stope Orientation Angles

diameter ratio, a/b. The dimensionless representative plume length ratio is

$$\frac{\Gamma P}{bP'} \tag{8}$$

where

Γ	is the representative plume length	L
P	is the effective porosity of the aquifer	None
b	is the stope radius	L
P'	is the effective porosity of the tailings in the stope.	None

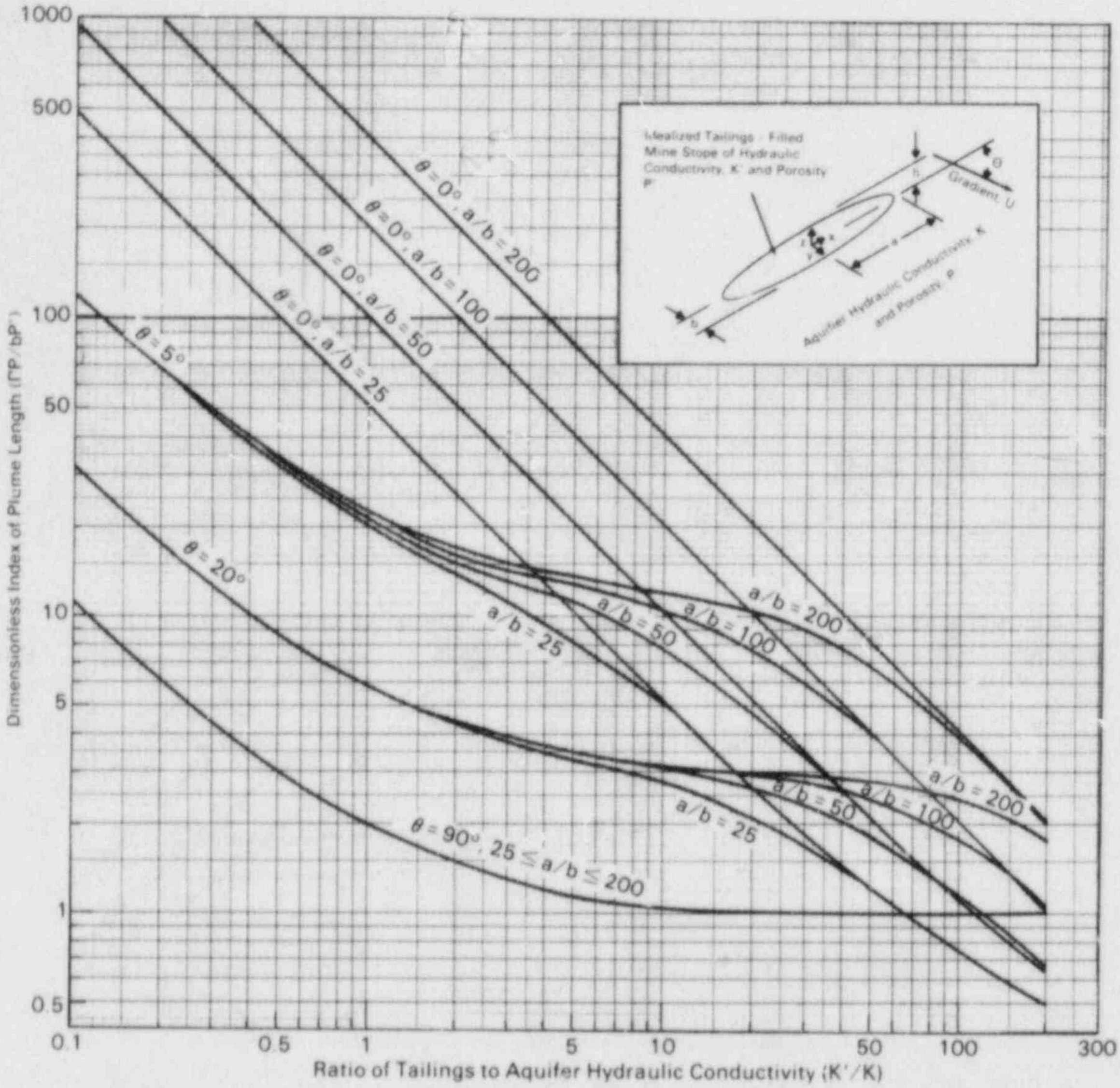

FIGURE 7. The Dependence of the Representative Index of Plume Length on the Hydraulic Conductivity Ratio and Stope Half-Length to Radius Ratio for Various Stope Orientation Angles

In Figures 6 and 7 the general trend of decreasing representative plume length with increasing contrast in hydraulic conductivity is a consistent trend related to the relative amounts of groundwater that are diverted into and through the stope because of the conductivity contrast. In general, the larger the amount of groundwater passing through the stope, the shorter the representative plume length. Conversely, the less groundwater passing through the stope at the lower ratios of K'/K, the longer the representative plume length. We also note that the representative plume length does not depend on the ratio of stope length to diameter, a/b, at a stope orientation angle of $\theta = 90°$. The dependence on a/b gradually increases, first in the higher K'/K ranges with decreasing orientation angles, until at $\theta = 0°$ a very regular dependence occurs. At conditions of $\theta = 0°$, the plume length dimensionless parameter essentially doubles each time that the a/b ratio doubles. This is consistent with the longest pathline through the stope always being 2a (i.e., the total stope length). At $\theta = 0°$, the distinct decreasing logrithmic linearity of the plume length with the hydraulic conductivity contrast K'/K is observed except for very slight curvature at very high K'/K values. This strong diminishing trend is again evidence of the strong dependence of the plume length on the amount of groundwater passing through the tailings, which is controlled by the conductivity contrast.

Example of Using the Representative Plume Length Ratio

The representative plume length may be estimated from Figures 6 and 7 and applied quite easily for a range of leachate constituents. It is convenient to use the same example situation as previously summarized in Equation (1) and with the specific ratios in Equation (6),

$$\theta = 20° \qquad \frac{K'}{K} = 50 \qquad \frac{a}{b} = 50 \tag{9}$$

Using the parameter values in Figure 7 yields the plume length ratio

$$\frac{\Gamma P}{bP'} = 1.8 \tag{10}$$

Solving for the representative plume length, Γ, in Equation (10) and using the appropriate effective porosity and stope radius values from Equation (1) gives

$$\Gamma = \frac{1.8\ bP'}{P} = 1.8 \times 6 \times \frac{0.3}{0.2} = 16.2\ \text{m} \tag{11}$$

So for the example case, the representative plume length is 16.2 m. Such a representative plume length is conveniently used with the laboratory-measured tailings leaching curves to obtain the overall plume lengths for various leachate constituent concentrations.

Figure 8 shows the effluent concentrations[a] for Mg, Na, and SO_4 measured in the laboratory when groundwater was used to leach duplicate columns of uranium tailings. The concentrations are plotted against the dimensionless number of column volumes of effluent that have passed through the experimental columns. In the figure, we note that the concentration is constant for the first column volume of leachate (i.e., for the initial volume of liquor in the tailings). The concentration then falls off rapidly as the first few column volumes of groundwater pass through, and then gradually flattens as the effluent concentration approaches the initial background concentration of the groundwater.

The leaching curve may be used with the calculated representative plume length to determine the overall plume length between the front of the plume and whatever constituent concentration is of interest. The representative plume length is the length of the pathline that is created by the first column volume of leachate passing along the longest pathline through the stope. In Figure 8, the first column volume of leachate is the short, horizontal initial part of each curve. The plume length from the plume front to the location of a particular concentration can be found by measuring the number of column volumes from the ordinate to the selected concentration on the leaching curve and multiplying this by the representative plume length. For example, if we select a sulfate concentration of 3450 mg/L from Figure 8, then the number of column volumes is 2. Multiplying by the example representative plume length of 16.2 m from Equation (11) gives an effective plume length of 32.4 m from the 3450 mg/L concentration contour to the front of the plume. Similarly, the plume length for the leachate to return to the original groundwater concentration of 300 mg/L gives 17 x 16.2 or a total sulfate plume length of 275.4 m. One observes, however, the maximum total plume length for sodium is only 2.5 x 16.2 or 40.5 m. In a similar manner, the representative plume length from Figures 6 and 7 can be used with the leaching curve for the particular constituent of concern to obtain the plume length for any particular constituent and for the specific leachate concentration of interest.

USE OF OVERALL PLUME SHAPE IN MORE DETAILED EVALUATIONS

Although the overall plume shape provided by the graphical results is usually useful in preliminary evaluations, more detailed results are often needed. Those more detailed evaluations can be provided through use of the interactive computer codes developed in this project and presented in this report. However, the graphical results for overall plume depth and width are very helpful in setting up the worst-case problems of use in more detailed assessments.

(a) Data taken from Martin, W. E., B. Opitz and J. Serne. 1984. "The Effects of Column Dimensions on Uranium Mill Tailings Leach Curves." PNL-SA-1251, Pacific Northwest Laboratory, Richland, Washington. Submitted for publication in Uranium.

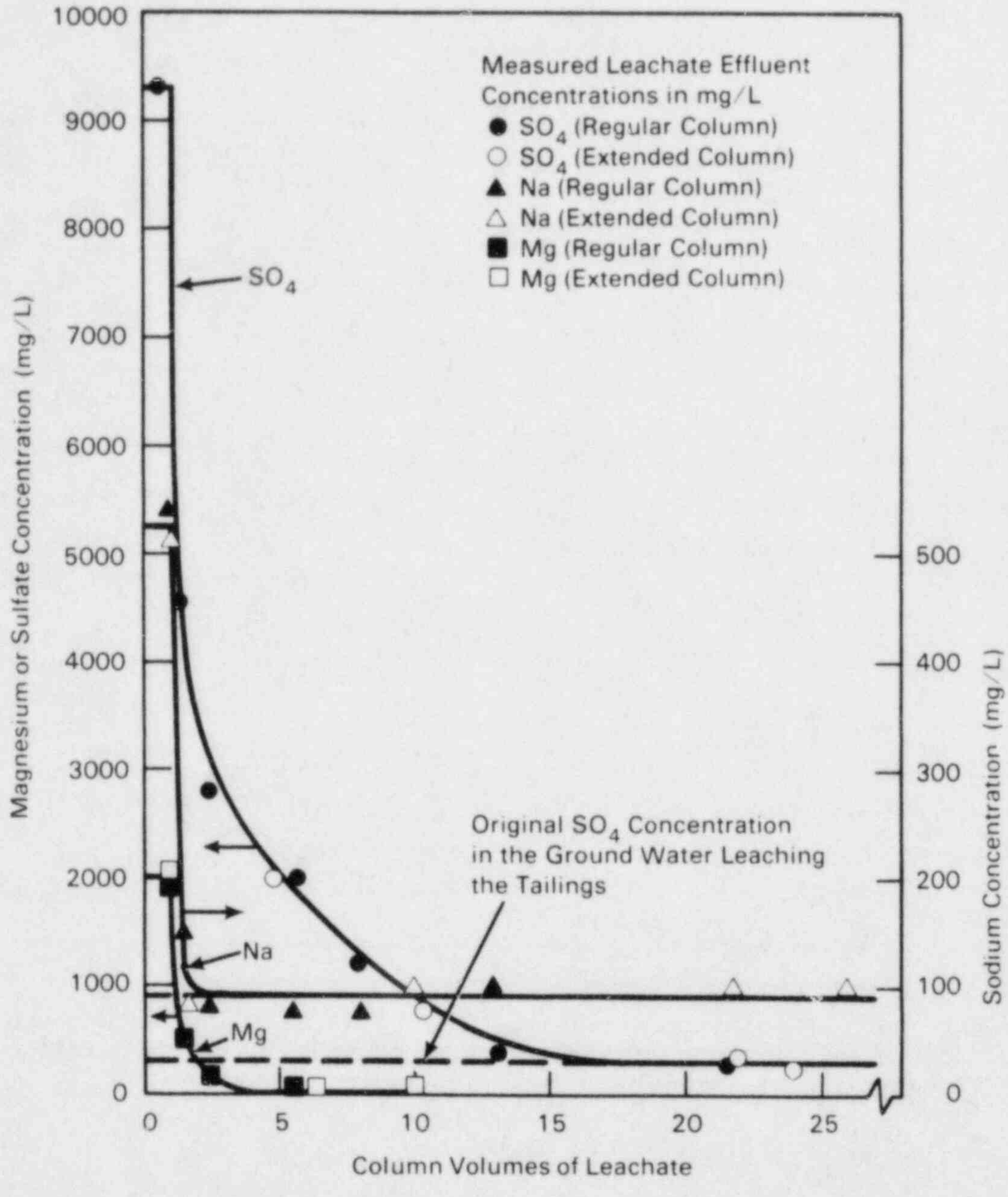

FIGURE 8. Typical Laboratory-Measured Groundwater Effluent Leaching Curves for Mg, Na, and SO_4 from Uranium Tailings

Typically the worst-case type scenario by which tailings leachate may reach the biosphere is through a water supply well intercepting the leachate plume downgradient from the mine stope in which the tailings were disposed. Various quantities of water supply needs may be involved depending on demand for water. Table 1 summarizes some water supply quantities necessary for typical uses in the vicinity of deep underground uranium mining operations. The data in Table 1 may be used to estimate an initial water withdrawal rate for use as the pumping rate for a domestic water supply well located

TABLE 1. Typical Water Use Requirements for Rural Areas (from Armco 1949 and Todd 1970)

Conditions of Water Use	Water Use, gal/day/unit	Water Use, L/day/unit
One Person		
When water pumped and carried by hand	6 to 8	22.71 to 30.28
One pump at kitchen sink	8 to 10	30.28 to 37.85
Complete plumbing and modern appliances	20 to 40	75.70 to 151.4
Schools	15 to 17	56.78 to 64.35
Camps (running water, kitchen, laundry, showers, baths and flush toilets)	40 to 45	151.4 to 170.3
Camps with flush toilets	20 to 25	75.70 to 94.63
Camps without running water or flush toilets	5 to 7	18.93 to 26.50
Animals		
For each horse, mule, or head of cattle	8 to 10	30.28 to 37.85
For each heavy producing dairy cow	10 to 22	37.85 to 83.27
For eacn hog	3 to 6	11.36 to 22.71
For each sheep	1 1/2 to 3	5.68 to 11.36
For each 100 chickens	2 to 4	7.57 to 15.14
For each 100 turkeys	10 to 17	37.85 to 64.35

downgradient from the tailings disposal stope. This will provide a worst-case scenario for the environmental consequences of the particular deep tailings disposal system being analyzed.

Example Worst-Case Domestic Well Evaluation

Suppose that one wishes to evaluate the worst-case for tailings concentrations pumped from a domestic water supply well located 500 m downgradient from the tailings disposal stope used in the previous examples [i.e., see Equation (1)]. Suppose furthermore, that the downgradient water supply well supplies a farmstead which has eight people who, from Table 1, use 30 gallons per day per person or a total of 240 gallons of water per day. Suppose further, that the livestock and chickens use an additional 158 gallons per day or that the total long-term pumping rate is

$$Q = 398 \text{ gal/day} = 1506 \text{ L/day} = 550 \text{ m}^3/\text{yr} \qquad (12)$$

If the water pumped from the well is not diluted by uncontaminated groundwater flowing above and below the leachate plume, then from the previously calculated plume depth [Equation (3)], the worst-case pumped well cannot be perforated over more than 32.1 m. In other words, the in-flow rate per unit length of perforated well is

$$q = \frac{-550}{32.1} = -17.13 \frac{m^2}{yr} \tag{13}$$

where the minus sign indicates water withdrawn from the well [from Equations (3), (12), and (B.25) in Appendix B]. This unit inflow rate to the well is the input used for the worst-case pumping well strength in the computer simulation (see Appendix C). By using the unit pumping strength of $-17.13\ m^2/yr$ from Equation (13), we are assured that worst-case concentrations will be provided in the water pumped from the well in so far as the well perforations are located only in the aquifer depth traversed by the contaminated leachate plume.

The second consideration when determining the worst-case concentration involves making certain that the well does not intercept groundwater over a distance wider than the leachate plume width. This can be easily examined by using Equation (B.34), which expresses the maximum upstream width of a groundwater plume, W_m, that is intercepted or drawn into the pumping well:

$$W_m = \frac{|q|}{2KU} \tag{14}$$

Or using the values for this example case from Equations (1) and (13) gives

$$W_m = \frac{17.13}{2 \times 100 \times 0.001} = 85.65 \text{ m} \tag{15}$$

which is less than the maximum plume width from Equation (7) of 106.5 m. Accordingly, if the well is centrally positioned in the downgradient leachate plume width, the well will provide the worst-case concentration in the water pumped from the well.

If the maximum well influence width, W_m, had been greater than the plume width, W, then the worst-case unit pumping rate could be calculated using the expression

$$q = -2KUW \tag{16}$$

and the total pumping rate would be

$$Q = -qL \tag{17}$$

Experience usually points toward reducing the pumping rate so a worst-case situation is maintained rather than insisting that Q be maintained. The particular case that is finally used in a specific assessment, however, must be left to the judgment of the person making that assessment.

Location of the Downgradient Well

The last major consideration in assessing a worst-case situation using the downgradient pumping well is positioning the well or selecting its coordinate location centrally in the contaminant plume. The vertical location is easy because the leachate plume is always symmetrical in the z or vertical coordinate direction. Accordingly, the well perforation of length L [see Equation (3)] is always in the range

$$-\frac{L}{2} \leq z \leq \frac{L}{2} \tag{17}$$

Selecting the well coordinates (x_0', y_0') for the vertical centerline of the well involves calculating first the dimensionless radial distance, R', using Equation (B.38) (see Appendix B):

$$R' = \frac{(D' + a')(D' + 1)\sqrt{(D' + 1)^2\cos^2\theta + (D' + a')^2\sin^2\theta}}{(D' + 1)^2\cos^2\theta + (D' + a')^2\sin^2\theta} \tag{18}$$

where

R' is the dimensionless radial distance in the z'=0 plane from the original x' = 0, y' = 0 to the center of the well — None

D' = D/b is the dimensionless distance from the center of the well at x_0', y_0' to the closest point on the stope wall — None

$a' = a/b$ is the dimensionless stope half length to stope radius ratio None

θ is the angle (less than 90°) between the regional gradient and the positive x'-axis degrees/radians

After the radial distance, R', is found from Equation (18), the dimensionless coordinates of the pumped well are

$$x_o' = R' \cos \theta$$
$$y_o' = R' \sin \theta \qquad (19)$$

So the coordinates for the pumping well (i.e., x_o' and y_o') are easily calculated using Equation (19).

Example Well Location Coordinates

The coordinates for the center of the downgradient pumping well are easily obtained from Equations (18) and (19). We recall from the text before Equation (12) that D is 500 m; hence, D' is 83.33 m by the definition following Equation (18). Using the example parameters from Equations (1) and (2) gives from Equations (18) and (B.39) that

$$R' = 122.98; \; R = 737.88 \text{ m} \qquad (20)$$

and by Equations (19) and (B.39) then

$$x_o' = 115.57; \; x_o = 693.42 \text{ m}$$
$$y_o' = 42.06; \; y_o = 252.36 \text{ m} \qquad (21)$$

which in the example case appropriately locates the pumping well centrally in the example leachate plume. This completes the initial analysis and we proceed to consider the more detailed computer analysis in the following sections.

COMPUTER MODEL DESCRIPTIONS

Two mathematical models were developed to analyze the steady pathlines of the flow system through and downgradient from an idealized mine stope. PATHLIN1 evaluates the flow system for a mine stope embedded in a regional aquifer with a constant gradient. PATHLIN2 evaluates the flow system for a mine stope embedded in a regional aquifer and with an added downgradient pumping well. The equations describing the two flow and transport systems were derived from potential flow and nondispersive transport theory, so dispersion is not considered in the solution procedure. The basic equations solved in PATHLIN1 are Equations (A.63), (A.64), and (A.65) from McKeon and Nelson (1984). The PATHLIN2 model solves a more elaborate system of ordinary differential equations made up of those in PATHLIN1, but with Equations (B.13), (B.14), and (B.15) from Appendix B of this report added to Equations (A.63), (A.64), and (A.65), respectively, from McKeon and Nelson (1984).

The results for the PATHLIN1 and PATHLIN2 models are the time and space coordinates along pathlines started upgradient from the mine stope. The time value associated with each spatial coordinate is the travel time from the upgradient or beginning of the pathline to the spatial coordinate. Because the system is steady state, the travel time between any two points remains constant over time.

Two additional mathematical models were developed to analyze contaminated plumes and environmental consequences in detail. FRONTS is a companion to the PATHLIN1 model; the results from FRONTS are spatial data describing time fronts or contaminant concentration fronts. CONSEQ is a companion to the PATHLIN2 model; its results are data describing the concentration of contaminant arriving at the pumping well over time. The output from FRONTS and CONSEQ is designed to be easily displayed graphically. Chemical interaction exterior to the stope is ignored in both the FRONTS and CONSEQ models.

FRONTS and CONSEQ use leaching curves of the type shown in Figure 8 to predict the concentration of contaminant in the leachate leaving the stope. The leaching curve gives the concentration of contaminant in the leachate as it varies with the cumulative quantity of fluid (expressed as the number of column volumes) that has passed through a column of mill tailings. Experimental results indicate that the leaching curve, when expressed in a column volume basis, is independent of both the length and the size of the column (Martin, Opitz and Serne 1985). Therefore, a column volume is a unique expression of the residence time of the fluid in a column of any length. Accordingly, otherwise differing flow lengths of groundwater through the mine stope can be interrelated through the pathline residence time across the stope. The number of column volumes (NCV) of leachate that have arrived at an arbitrary location on pathline i after an elapsed time (TREF) can be determined through the residence time scale up using the following equation:

$$NCV = \frac{TREF - [T(i) - T1(i)]}{T1(i)} \quad (23)$$

where

NCV	= the number of column volumes associated with the desired concentration (from the leaching curve as in Figure 8)	None
TREF	= the elapsed time	T
T(i)	= the travel time from the upgradient edge of the stope to the location on pathline i	T
T1(i)	= the travel time across the stope for pathline i.	T

PATHLIN1 PROGRAM

The basic equations solved in this model are Equations (A.63), (A.64), and (A.65) in Appendix A of McKeon and Nelson (1984). Only those equations related to the ellipsoidal-shaped heterogeneous zone and the regional aquifer are incorporated. The equations related to the pumping well are not superimposed in this model. The model is implemented on a Floating Point Systems[a] array processor coupled with a VAX 11/780 computer. This increases computational speed and, hence, reduces the cost of simulation runs. The model is written in standard FORTRAN-77 with the exception of ten statements involved with the array processor that are easily removed for use on other computers as discussed in Appendix C.

The model starts pathlines within the mine stope on the special vertical plane that contains the z-axis and is penetrated by all the pathlines that pass through the stope. By starting pathlines on this special plane, the entire downgradient plume is easily considered. The flow system is also simpler to analyze because it is symmetric about the z = 0 plane; therefore, pathlines need only be considered or started for analysis in half of the system. Travel time and distance through the stope and the up- and downgradient intersections with the boundary of the stope are evaluated explicitly for each pathline using Equations (A.84) through (A.95) in McKeon and Nelson (1984). From the point where each pathline exits the stope and moves into the aquifer, the pathline characteristic differential equations are numerically integrated forward in time until the maximum time (an input control parameter) is reached. The three simultaneous differential equations are integrated using a fourth-order Runge-Kutta scheme. The three equations represent the x, y, and z components of the steady, spatially dependent pore velocity field.

(a) Floating Point Systems, Inc., Portland, Oregon 97223.

FRONTS PROGRAM

The FRONTS program calculates the concentration of contaminant and the location of contaminant fronts in the leachate plume. The model also creates a file for plotting the location of fronts in various x-y planes. Two options are available in this model. The first option calculates and plots equal travel time fronts. The second option incorporates a leaching curve describing the concentration of a specific contaminant in the leachate from the mine stope as a function of the number of pore volumes that have passed through the stope (see Figure 8). The pathline travel time results from the PATHLIN1 program are used with the leaching curve to calculate contaminant concentration fronts along each pathline.

The location of equal concentration fronts begins by calculating the NCV that must pass along a pathline through the stope to produce the selected leachate concentration. The model interpolates between the input leaching curve data to determine NCV. The model next prompts the user for a time of interest, TREF, which is the time for which the plume concentration is to be provided by the code. Equation (23) is solved for the time along the pathline associated with the particular location sought using

$$T(i) = TREF + (1 - NCV) \times T1(i) \tag{24}$$

where

T(i) =	the travel time from the upgradient edge of the stope to the location on pathline i at which the desired concentration front occurs	T
TREF =	the time of interest for which the plume concentration distribution is desired	T
NCV =	the number of column volumes associated with the desired concentration (from the leaching curve as in Figure 8)	None
T1(i) =	the travel time across the stope for pathline i.	T

After T(i) has been calculated for a pathline, the x, y, and z coordinates for each pathline at that time are calculated from the results of the PATHLIN1 model. Although for each concentration front the number of column volumes passed along each pathline is the same, T(i) is usually different for each pathline because of the different lengths and, hence, different travel times through the stope. The x, y, and z coordinates of each pathline at the appropriate time are calculated by linearly interpolating between the small time steps along the individual pathlines.

Example Problems

Four examples are included to demonstrate the use of the interactive computer analysis and show the variation in plume shape and concentration fronts as the angle of the gradient with respect to the longitudinal axis of the stope is varied. Figures 9 through 12 illustrate these results. Each of the four figures shows the pathlines from the stope in the x-y plane for z = 0 and the location of equal concentration fronts within the contaminant plume. Figure 9 is for an angle between the gradient and the x axis of 0°. Figure 10 is for an orientation angle of 20°. Figure 11 is for an angle equal to 45°, and Figure 12 is for a stope orientation angle equal to 90°. The geometric and hydraulic parameters used in these examples are those used previously:

Regional gradient	U = 0.001
Hydraulic conductivity of the regional aquifer	K = 100 m/yr
Porosity of the aquifer	P = 0.2
Hydraulic conductivity of the tailings filled mine stope	K' = 5000 m/yr
Porosity of the tailings	P' = 0.3
Half-length of the mine stope	a = 300 m
Radius of the mine stope	b = 6 m
Maximum travel time	TMAX = 1000 yr

The leaching curve for sulfate used in these examples is that shown previously in Figure 8.

For the 0° case in Figure 9, the plume is long and narrow, about 335 by 80 m, which is much wider than the stope because of the contrast in permeability of tailings within the stope and the aquifer. In situations where the permeability contrast is less, the plume would become much longer and narrower, like a thin pencil-shaped plume. The plume in the 20° case in Figure 10 is rather long, as is the 0° case, but becomes wider similar to the 90° case. The plume in 45° case is a little narrower than the 90° case, but somewhat longer, similar to the 0° case. The plume in the 90° case is essentially as wide as the mine stope is long, but is comparatively shorter in length because the travel paths through the mine stope are short. The pathlines passing through the mine stope follow a nearly straight line (i.e., the pathlines crossing the permeability boundary at this angle show little refraction) because the angle of incidence is nearly perpendicular. For the other examples shown, much more refraction of the pathlines at the permeability boundary occurs; therefore, travel paths through the mine stope are longer.

PATHLIN2 PROGRAM

The additional part of the basic equations for the well used in this model are described in Appendix B [see Equations (B.13) and (B.14)]. These equations for the pumping well are superimposed or added to the equations for the ellipsoidal tailings-filled stope embedded in a large regional aquifer that are

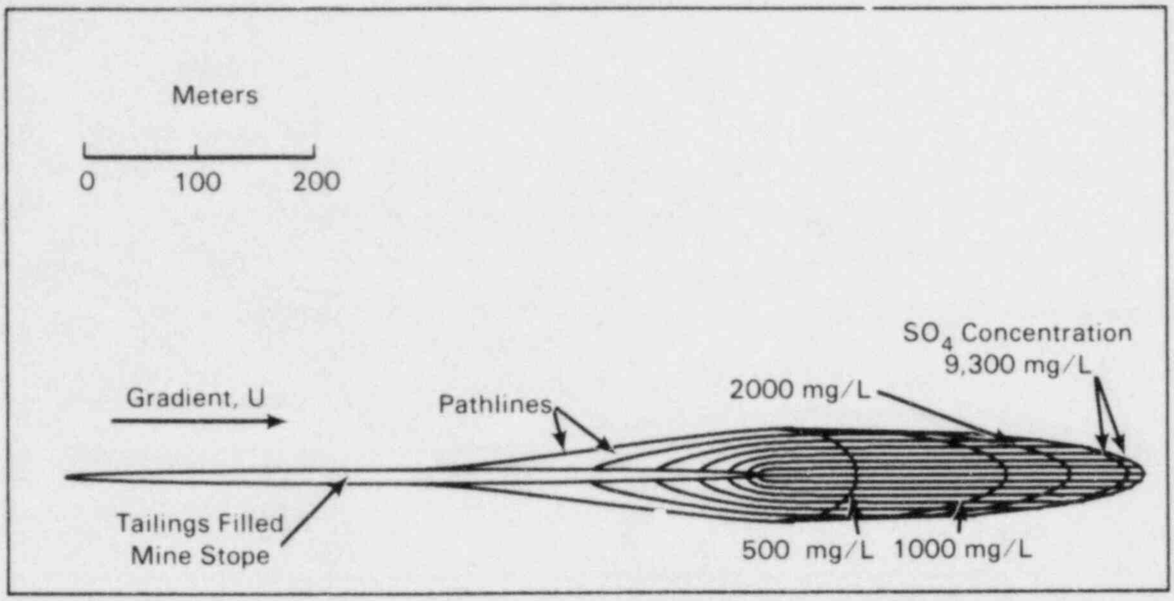

FIGURE 9. Sulfate Plume Shape and Concentrations in the z = 0 Plane, Downgradient from Disposed Uranium Tailings at Time = 1000 Years for a Stope Orientation Angle of 0°

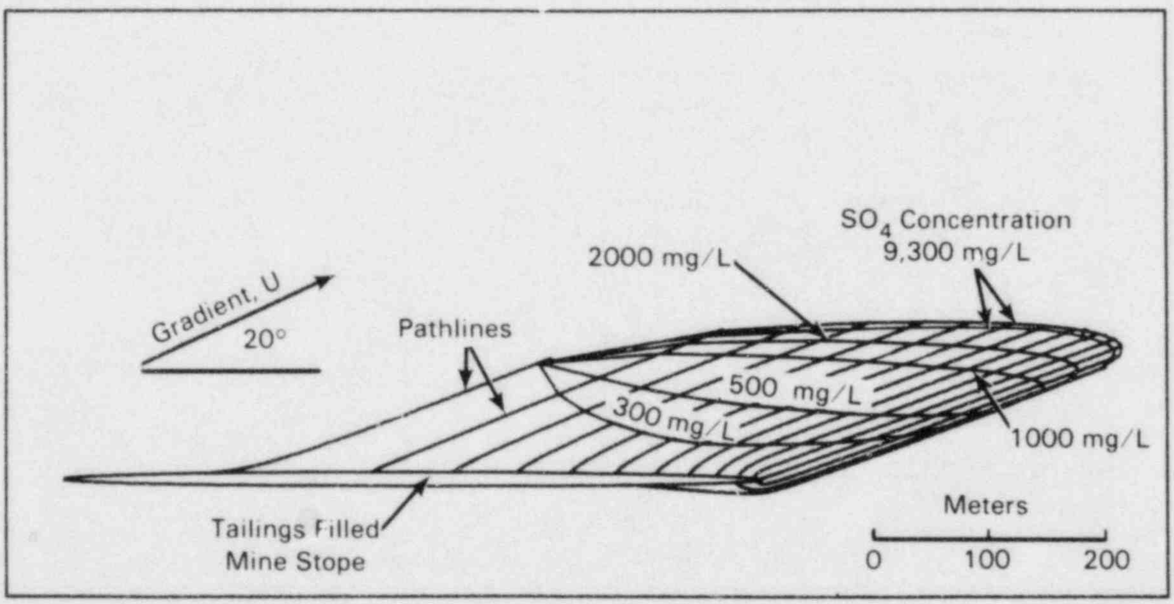

FIGURE 10. Sulfate Plume Shape and Concentrations in the z = 0 Plane, Downgradient from Disposed Uranium Tailings at Time = 1000 Years for a Stope Orientation Angle of 20°

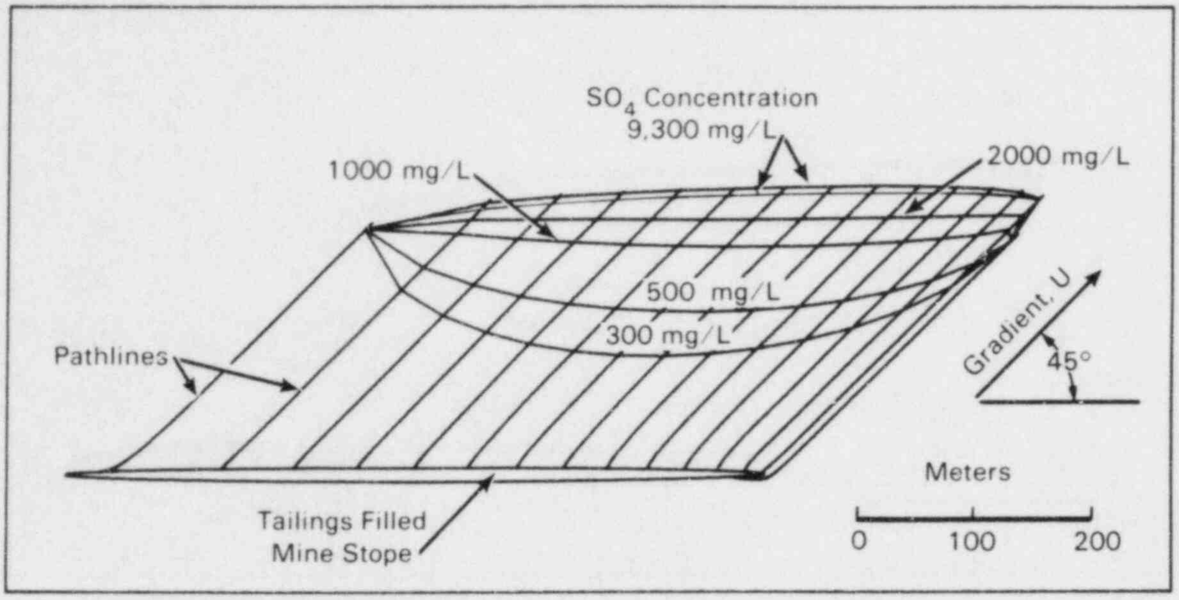

FIGURE 11. Sulfate Plume Shape and Concentrations in the z = 0 Plane, Downgradient from Disposed Uranium Tailings at Time = 1000 Years for a Stope Orientation Angle of 45°

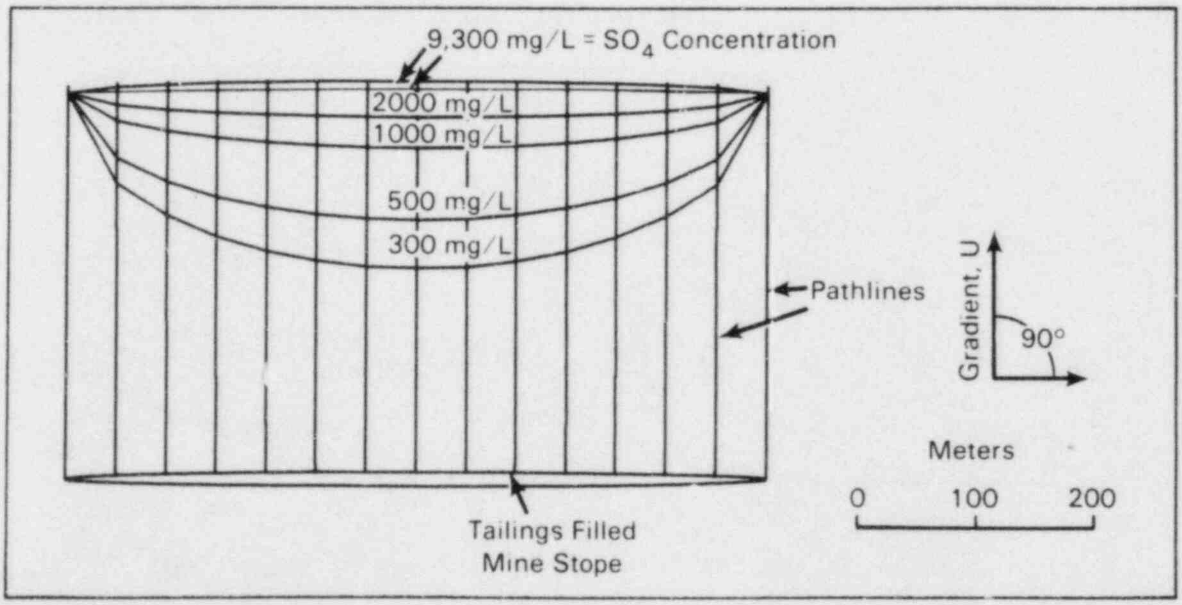

FIGURE 12. Sulfate Plume Stage and Concentrations in the z = 0 Plane, Downgradient from Disposed Uranium Tailings at Time = 1000 Years for a Stope Orientation Angle of 90°

presented as Equations (A.63), (A.64), and (A.65) in McKeon and Nelson (1984). This model is implemented on a array processor coupled with a VAX 11/780 computer. Such vector computing capacity increases computational speed and, hence, reduces the cost of simulation runs. This program is written in standard FORTRAN-77 with the exception of 16 statements that are readily removed for use on other computers as discussed in Appendix C.

The PATHLIN2 model in contrast to PATHLIN1 starts pathlines around the casing of the pumping well. Pathlines are started at a user-specified number of horizontal planes intersecting the well, with an equal number of pathlines started in each plane. Using the stream function, the pathline starting locations are defined so that both the fluid flux reaching the well in each horizontal plane is equal and the fluid flux between each streamline in one horizontal plane is equal. Accordingly the flux into the well from each and every streamtube entering the well is identical. The flow system is symmetric about the z = 0 plane; therefore, the steady pathlines or streamlines are only started on the top half of the perforated well casing. From the starting location, the pathline characteristic equations are numerically integrated backwards in time until either the pathline pierces the downgradient edge of the stope or the pathline misses the stope. From the point where a pathline pierces the stope (actually the exit location because we are integrating backwards in time) the entrance location, travel time, and distance through the stope are evaluated explicitly. The three simultaneous pathline differential equations are integrated using a fourth-order Runge-Kutta scheme.

CONSEQ PROGRAM

The CONSEQ program calculates the mass of contaminant and the concentration of contaminant in the fluid pumped from the well as a function of time. The final result of this analysis is a curve of the contaminant concentration in the water pumped from the well over time. This curve characterizes the rate at which a contaminant reaches the biosphere, the peak concentration, and the duration of time that a contaminant will be above a particular concentration level at the location where it reaches the biosphere.

The pathline travel time results from the PATHLIN2 program are used along with the tailings leaching curve in Figure 8. These data are used to calculate the concentration of a specific contaminant arriving at the well along each pathline as a function of time. The concentration of the leachate at the well along a pathline at a particular time, TREF, is calculated by solving Equation (23) for NCV:

$$NCV = \frac{TREF - [T2(i) - T1(i)]}{T1(i)} \qquad (25)$$

where

TREF =	the time of interest for calculating the concentration entering the well	T
NCV =	the number of column volumes of leachate that have arrived at the well along pathline i at time TREF	None
T2(i) =	the travel time from the upgradient edge of the stope to the well casing for pathline i	T
T1(i) =	the travel time across the stope for pathline i.	T

As discussed above, each pathline is associated with a streamtube, each streamtube providing an equal amount of fluid flux. Therefore, the concentration of contaminant arriving at the well at time TREF can be found by taking the mean of the concentration contribution at the well for all the pathlines at time TREF. The mass flux of contaminant arriving at the well is calculated by multiplying the concentration by the total pumping rate.

Example Application of CONSEQ Program

Four examples are included of the final results of the consequence analysis to illustrate the potential variations that may occur. Both the PATHLIN2 and the CONSEQ models have been run in each case. Each of the examples has essentially the same geometric and hydrologic conditions as the previous examples except that the orientation angle of the gradient with respect to the longitudinal axis of the mine stope is varied for the four cases. The hydrologic and geometric parameters used in these examples are as follows:

Regional gradient	U = 0.001
Hydraulic conductivity of the regional aquifer	K = 100 m/yr
Porosity of the aquifer	P = 0.2
Hydraulic conductivity of the tailings filled mine stope	K' = 5000 m/yr
Porosity of the tailings	P' = 0.3
Half length of the mine stope	a = 300 m
Radius of the mine stope	b = 6 m
Distance from the mine stope to the pumping well	D = 500 m
Total pumping rate	Q = 550 m^3/yr

The leaching curve for sulfate used in these examples is shown Figure 8, and the total pumping rate is held constant for each of the four cases. Because the depth of the plume varies significantly with each of the examples, the assumed perforated well length (i.e. the depth of the plume) is different for each case. To retain the same total pumping rate, Q, the pumping rate per unit lengths, q, of the well casing is necessarily different for each of the examples.

In each of the examples, the peak sulfate concentration in the fluid pumped from the well was significantly less than the peak concentration in the original tailings slurry liquor (see Figures 14 through 17). The reduction in peak concentrations in these examples is caused entirely by variations in the travel paths through the mine stope and to the well. The variations in travel paths cause the contaminated fluid pumped from the well to be diluted by uncontaminated water. Fluid with high levels of contaminant concentration (i.e., the initial tailings liquor) travels along all of the pathlines from the stope to the well, however, the arrival time at the well is generally different for each pathline. Along each pathline, the concentration of contaminant in the fluid arriving at the well evolves through the following stages:

1. Initially, while time T is such that $0 < T < T2(i) - T1(i)$, no contaminant has arrived at the well; only groundwater preceding the tailings plume enters the well.

2. At time $T = T2(i) - T1(i)$, the first and highest concentration level arrives at the well because of the shape of the leaching curve in Figure 8.

3. This highest concentration level continues while time T is such that $T2(i) - T1(i) < T < T2(i)$ (i.e., during the flat part of the tailings leaching curve).

4. At time $T = T2(i)$, the concentration level begins to decrease and continues to decrease until the leaching curve reaches the background concentration level.

In general, the timing of the stages in the above sequence is different for each pathline. Because the contaminants traveling different pathlines arrive at different times, the sequence begins at a different time for each pathline. The sequence begins first for the shortest, most direct pathline. The variations in travel paths and the corresponding reduction in peak concentrations pumped from the well are a final result of the variety of geometric and hydrologic parameters affecting the arrival times along the various pathlines. These include the ratio of the hydraulic conductivities, the length to width ratio of the mine stope, the strength of the pumping well, and the angle of the gradient with respect to the longitudinal axis of the stope. The following four examples illustrate variations caused by different angles of orientation with the gradient. Figures 13, 14, 15, and 16 show the SO_4 concentrations of the tailings leachate pumped from the well for angles of 0°, 20°, 45°, and 90°, respectively.

The 0° case has a peak sulfate concentration of 2040 mg/L, and the sulfate concentration is above a background level of 300 mg/L for 930 years. The 20° case has a peak concentration of 1975 mg/L and a duration of 850 years above background levels. The 45° case has a peak concentration of 2800 mg/L and

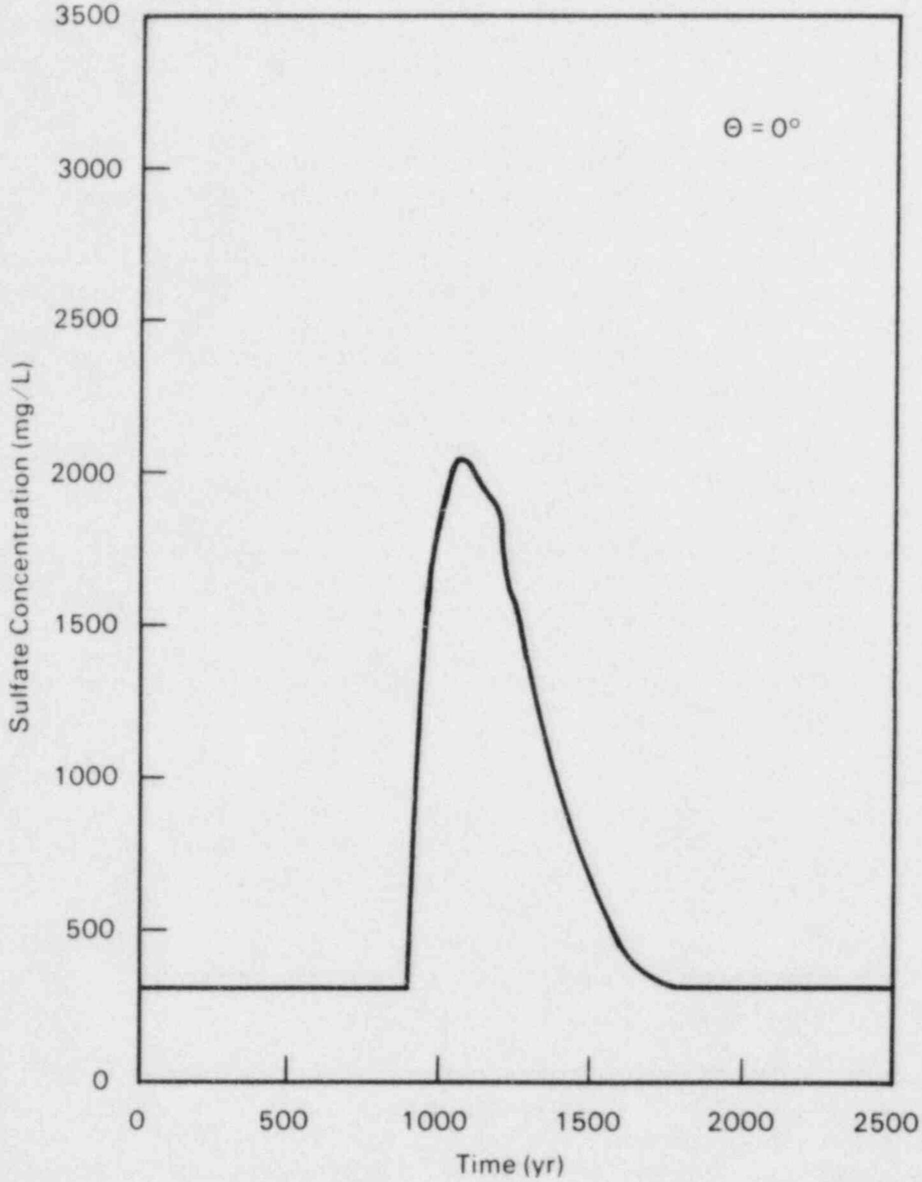

FIGURE 13. Worst-Case History of Sulfate Concentration Expected in a Well 500 m from a Tailings Disposal Stope Oriented at 0° to the Regional Groundwater Gradient

duration of 630 years that the sulfate concentration is above the background level. The highest peak concentration, 3200 mg/L, occurs in the 90° case, Figure 16. This case also has the shortest duration that the sulfate concentration is above the background level: 480 years.

In the 90° case, the pathlines pierce the stope at nearly right angles; hence, little refraction of the pathlines occurs as they enter and exit the mine stope. This results in comparatively short contaminant plumes and consequently shorter duration in the arrival distribution. The different travel

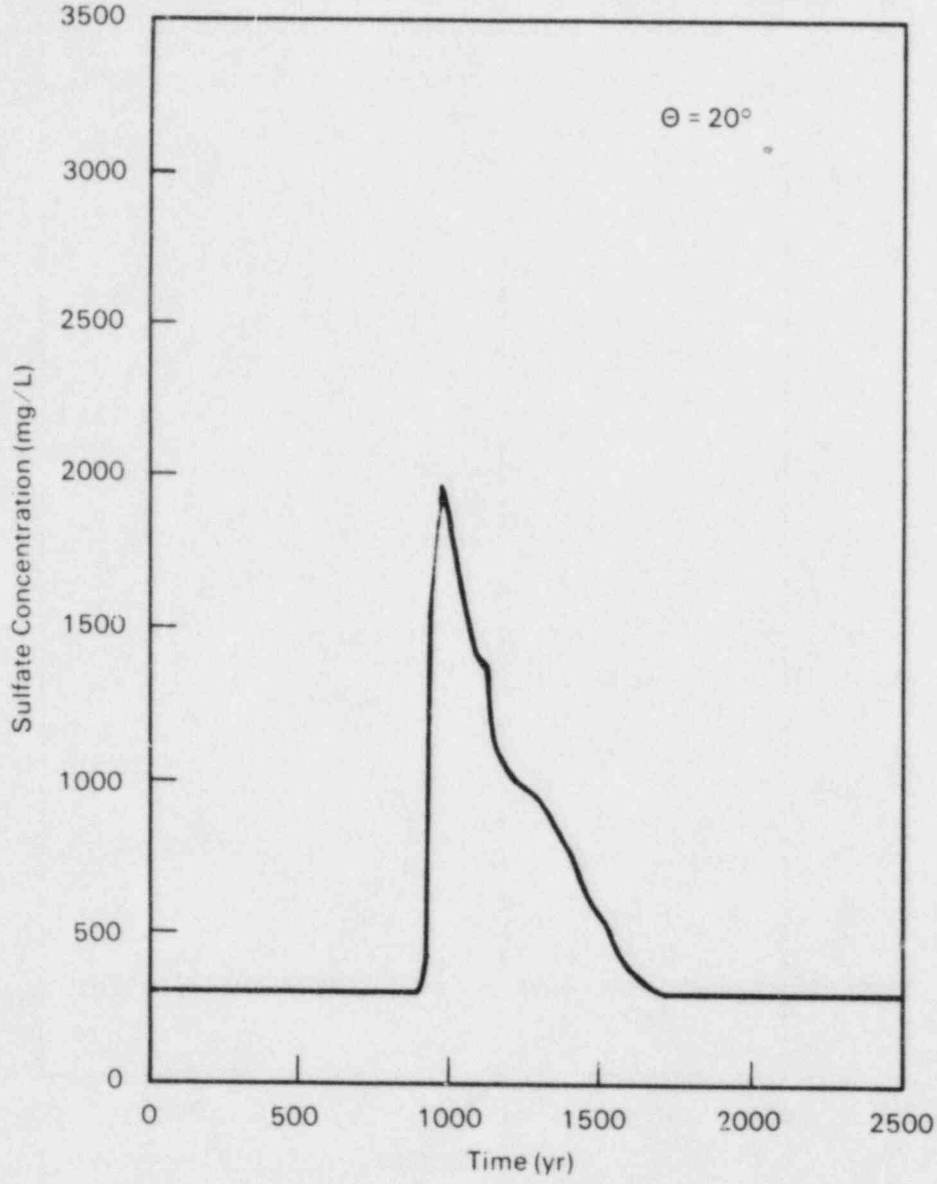

FIGURE 14. Worst-Case History of Sulfate Concentration Expected in a Well 500 m from a Tailings Disposal Stope Oriented at 20° to the Regional Groundwater Gradient

paths and resulting dilution at the well is caused primarily by stress of the pumping well in the 90° case. The hydraulic conductivit;, K; within the mine stope has little effect on travel paths of the contaminants, and the corresponding peak concentrations arriving at the well are higher than with smaller angles. In the 0°, 20°, and 45° cases, pathlines do not pierce the stope at right angles; hence, more refraction at the stope boundary occurs. This results in longer contaminant plumes and longer duration in the arrival

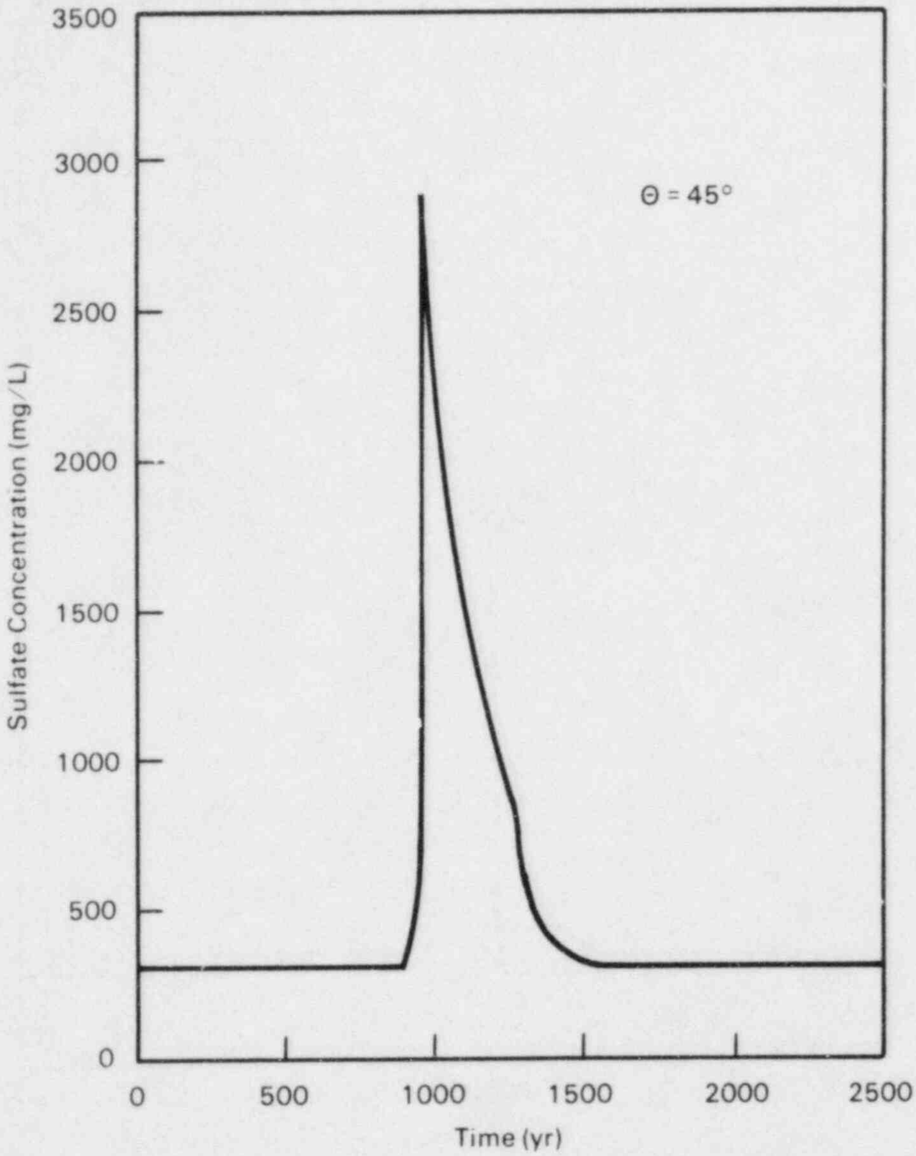

FIGURE 15. Worst-Case History of Sulfate Concentration Expected in a Well 500 m from a Tailings Disposal Stope Oriented at 45° to the Regional Groundwater Gradient

distributions. For the smaller angles, variations in travel paths are induced by both the pumping well and the conductivity variation within the mine stope. Therefore, more dilution occurs at the pumping well and correspondingly lower peak concentrations in the water pumped from the well.

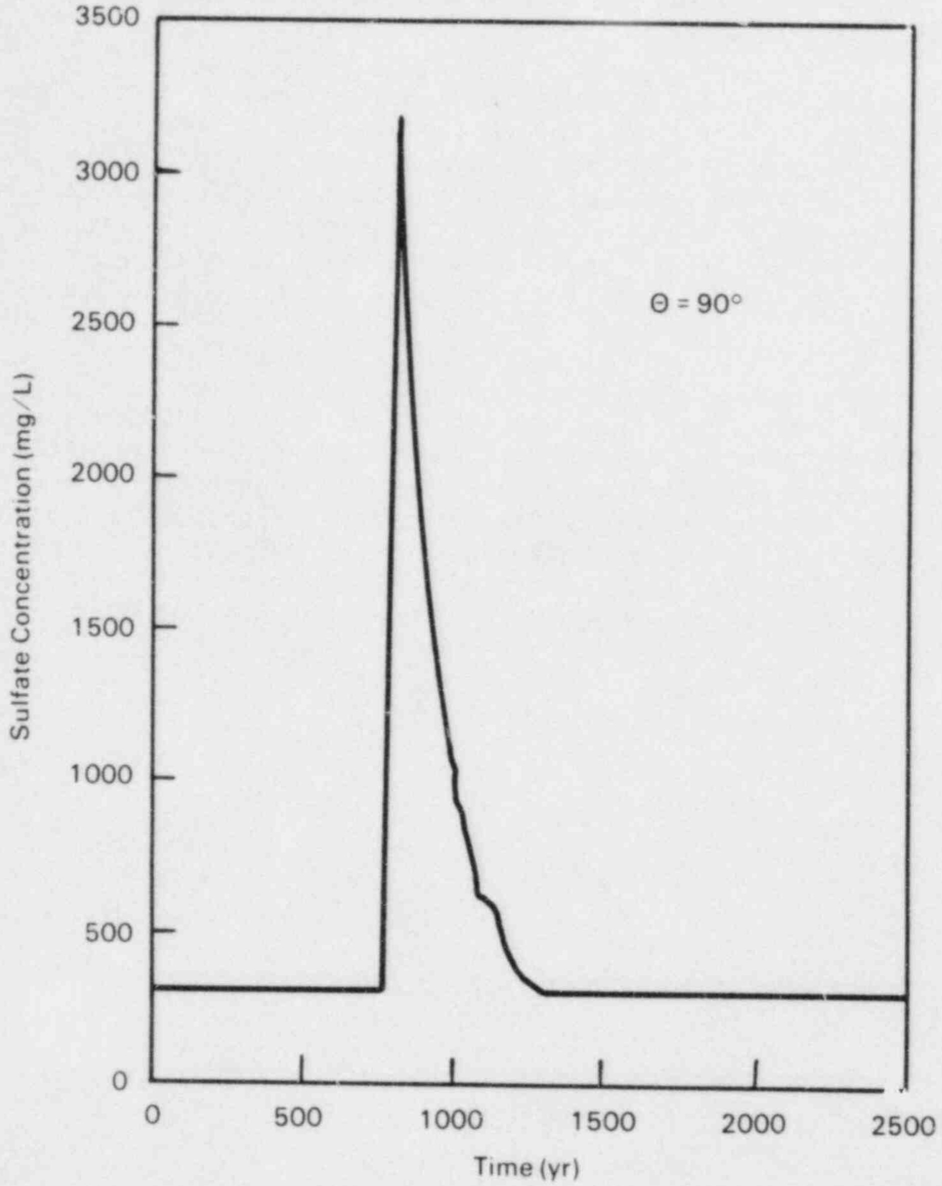

FIGURE 16. Worst-Case History of Sulfate Concentration Expected in a Well 500 m from a Tailings Disposal Stope Oriented at 90° to the Regional Groundwater Gradient

USE OF THE ANALYSIS METHOD PROVIDED

By providing easily used graphical results for rapidly determining overall leachate plume size and shape in combination with the interactive computer evaluation, we gain a rather complete assessment methodology. The graphical results enable an early overview of leachate plume location and size. Through use of the graphics as discussed, the worst-case scenarios can be specified for more detailed analysis. In the worst-case analysis, we have incorporated the leaching features of the tailings through scale up of the laboratory leaching column experiments.

Unfortunately, the geochemical interactions of the leachate with the aquifer buffering capability, etcetera, could not be included in our analysis capability. The methods for incorporating such results approximately into the plume analysis are worked out and could be readily incorporated into the interactive computer analysis. However, the geochemical/transport analysis from laboratory column data from a companion project at PNL was not completed in time to be included in this work. Accordingly, the extremely conservative assumption of ignoring leachate-aquifer interactions was necessary.

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APPENDIX A

DEFINITIONS OF TERMS

APPENDIX A

DEFINITIONS OF TERMS

Term	Definition	Units
A_o	is the parameter defined in McKeon and Nelson (1984) Equation (A.6).	None
A_λ	is the functional that is dependent upon λ and is defined in McKeon and Nelson [Equation (A.37), 1984].	None
a	is half the length of the ellipsoid in the x-coordinate direction (see insert in Figure 1).	L
$a' = \frac{a}{b}$	is the dimensionless half-length of the ellipsoid in the x' coordinate direction.	None
B_o	is the parameter defined in McKeon and Nelson [Equation (A.7), 1984].	None
B_λ	is the functional that is dependent upon λ and is defined in McKeon and Nelson [Equation (A.38), 1984].	None
b	is the radius of the tunnel or stope at $x = 0$ (see insert in Figure 1).	L
C_3'	is an appropriate dimensionless constant used in Equation (B.17) and (B.28).	None
D	is a distance from the center of the pumped well to the stope.	L
$D' = \frac{D}{b}$	is the dimensionless distance from the stope wall to the center of the pumped well.	None
K	is the hydraulic conductivity of the aquifer material.	L/T
K'	is the hydraulic conductivity of the tailings material in the mine tunnel or stope.	L/T
L	is the length of the pumped well that will intercept the entire depth of the leachate plume.	L
NCV	is the number of column volumes [see Equation (23)].	None
P	is the porosity of the aquifer material.	None
P'	is the porosity of the tailings inside the mine stope or tunnel.	None

		Units
Q	is the volume pumping rate for the well and is always positive.	L^3/T
$q = -\frac{Q}{L}$	is the volumetric source strength of the well.	L^2/T
R	is the distance from center of the well to the origin.	L
$R' = \frac{R}{b}$	is the dimensionless distance from the center of the well to the origin of the stope [see Equation (B.38)].	None
r_o	is the radius of the pumped well.	L
$r'_o = \frac{r_o}{b}$	is the dimensionless radius of the pumped well.	None
T	is time.	T
T(i)	is the travel time from the upgradient edge of the stope to a location on pathline 'i'.	T
T1(i)	is the travel time across the stope on pathline 'i'.	T
T2(i)	is the travel time from the upgradient edge of the stope to the well casing on pathline 'i'.	
TMAX	is the maximum travel time.	T
TREF	is a time of reference or elapsed time.	T
U	is the uniform hydraulic gradient in the aquifer that is at an angle, θ, with the positive x-axis.	L/L
W_m	is the maximum plume width that is intercepted by the well.	L
$W'_m = \frac{Wm}{b}$	is the dimensionless maximum plume width that is intercepted by the pumping well [see Equation (B.34)].	None
x	is the Cartesian horizontal space coordinate oriented with the longest axis of the prolate spheriod (see Figure 1).	L
x_o	is the x-coordinate of the centerline of the pumped well.	L
$x' = \frac{x}{b}$	is the dimensionless Cartesian coordinate.	None

		Units
$x'_o = \frac{x_o}{b}$	is the dimensionless x'-coordinate of the centerline of the pumped well.	None
y	is the other Cartesian horizontal coordinate (see insert in Figure 1).	L
$y' = y/b$	is the dimensionless cartesian coordinate.	None
y_o	is the y-coordinate of the centerline of the pumped well.	L
$y'_o = \frac{y_o}{b}$	is the dimensionless y'-coordinate of the centerline of the pumped well.	None
z	is the vertical Cartesian space coordinate (see insert in Figure 1).	L
$z' = \frac{z}{b}$	is the dimensionless vertical coordinate.	None
α	is the angle defined in Equations (B.20) and (B.21) and shown in the associated sketch.	Radians
Γ	is a representative plume length	L
$\varepsilon = \frac{K'}{K}$	is the ratio of the hydraulic conductivity of the tailings inside the prolate spheroid to the hydraulic conductivity of the regional aquifer.	None
γ	an angle defined by Equation (B.24).	Radians
λ	is the characteristic positive root in McKeon and Nelson [Equation (A.28), 1984] that conveniently enables describing any location.	L^2
θ	is the angle between the regional gradient U and the positive x-axis (see insert in Figure 1). It may be in either degrees or radians as specified in the particular equation.	---
ϕ	is the potential energy per unit weight of fluid.	L
$\phi' = \frac{\phi}{b}$	is the dimensionless potential.	None
ϕ_o	is the unit potential energy outside of the stope as in McKeon and Nelson [Equation (A.35), 1984].	L
ϕ_w	is the unit potential energy induced by the pumped well as in Equation (B.5).	L

		Units
$\phi'_w = \frac{\phi_w}{b}$	is the dimensionless potential energy from the pumped well.	None
$\Phi_o = \phi_o + \phi_w$	is the combined unit potential energy (i.e., due to the well and the more permeable tailings in the stope) for the region in the regional aquifers outside the stope.	L
$\Phi'_o = \phi'_o + \phi'_w$	is the dimensionless combined potential outside the stope.	None
ψ'	is the dimensionless stream function associated with the well	None
ψ'_{ws}	is the dimensionless stream function for only the source and doublet terms [see Equation (B.16)].	None
ψ'_w	is the dimensionless stream function for the combine uniform stream, doublet, and source [see Equation (B.17)].	None
ψ'_r	is the dimensionless stream function from the well of radius of r'_o and centered at (x'_o, y'_o).	None

APPENDIX B

REVISION AND EXTENSION OF MODEL EQUATIONS

APPENDIX B

REVISION AND EXTENSION OF MODEL EQUATIONS

The equations for the idealized three-dimensional model for evaluating the consequence of uranium tailings disposal in deep abandoned mine stopes were presented in Appendix A of NUREG/CR-3560 (Evaluation Methods for the Consequences of Below Water Table Mine Disposal of Uranium Mill Tailings) by McKeon and Nelson (1984). The equations presented in Appendix A of that document are simplified here, some minor typographical errors noted, and the equations extended to provide an analytical stream function at the well. Use of stream function at the well allows us to more accurately determine the flux. Extending the equations also provided equations to locate the downgradient pumping well at equivalent distances from the stope at any orientation with the regional gradient.

REDUCED SIMPLER EQUATIONS FOR INCLUDING A PUMPING WELL

We begin with Equation 9 on page 16 of the report by McKeon and Nelson (1984). That expression is

$$\begin{aligned}
\Phi_o = & - U y \sin \Theta - U x \cos \Theta \\
& + U \left((y - y_o) \sin \Theta + (x - x_o) \cos \Theta\right) \left[\frac{r_o^2}{(x - x_o)^2 + (y - y_o)^2}\right] \\
& + \left(\frac{(\varepsilon - 1)\, U A_\lambda \cos \Theta)}{1+A_o(\varepsilon - 1)}\right) \left(x - \left[\frac{r_o^2}{(x - x_o)^2 + (y - y_o)^2}\right] \cdot (x-x_o)\right) \\
& + \left(\frac{(\varepsilon - 1)\, U \sin \Theta\, B_\lambda}{1+B_o(\varepsilon - 1)}\right) \left(y - \left[\frac{r_o^2}{(x - x_o)^2 + (y - y_o)^2}\right] \cdot (y - y_o)\right) \\
& - \frac{q}{2\pi K} \ln \sqrt{\frac{(y - y_o)^2 + (x - x_o)^2}{(b - y_o)^2 + (x_o)^2}}
\end{aligned} \qquad \text{(B.1)}$$

Consider the latter part of the expression on line three of Equation B.1, that is

$$x - (x - x_o)\left[\frac{r_o^2}{(x - x_o)^2 + (y - y_o)^2}\right] \tag{B.2}$$

We note in the vicinity of the well (i.e., when x and y are both approaching x_o and y_o, respectively), the second part of Equation (B.2) is small in comparison to the first term, x. It is small for two reasons. First, near the well $(x - x_o)$ is small. Further, the doublet multiplier is bounded:

$$0 < \frac{r_o^2}{(x - x_o)^2 + (y - y_o)^2} \leq 1.0 \tag{B.3}$$

because the potential, Φ_o, in Equation (B.1) is not defined inside of the well of radius, r_o. The equality in Equation (B.3) denotes the case where the point (x,y) lies on the pumped well radius, r_o with the well center at (x_o, y_o). For all other locations of interest outside the well, the doublet multiplier diminishes as the square of the distance from the center of the distance away from the well. Direct numerical calculations further demonstrated that the second or doublet-type terms were extremely small for cases of practical interest where the downgradient pumping well was greater than 50 stope radii away from tailings filled stope.

Removal of the doublet terms from each of the terms in lines 3 and 4 of Equation (B.1) yields the simplified potential expression:

$$\begin{aligned}\Phi_o = &- U\, y \sin\Theta - U\, x \cos\Theta \\ &+ U\left((y - y_o)\sin\Theta + (x - x_o)\cos\Theta\right)\left(\frac{r_o^2}{(x - x_o)^2 + (y - y_o)^2}\right) \\ &+ \left(\frac{(\varepsilon - 1)\, U \cos\Theta\, A_\lambda}{1 + A_o(\varepsilon - 1)}\right) x + \left(\frac{(\varepsilon - 1)\, U \sin\Theta\, B_\lambda}{1 + B_o(\varepsilon - 1)}\right) y \\ &- \frac{q}{2\pi K} \ln \sqrt{\frac{(y - y_o)^2 + (x - x_o)^2}{(b - y_o)^2 + (x_o)^2}}\end{aligned} \tag{B.4}$$

This equation is the replacement in dimensional form of Equation (9) from McKeon and Nelson (1984). But if the potential [Equation (7), McKeon and Nelson 1984] is subtracted from (B.4), the revised potential at the well is as follows:

$$\Phi_w = U \left[(y - y_o) \sin \Theta + (x - x_o) \cos \Theta\right] \left[\frac{r_o^2}{(x - x_o)^2 + (y - y_o)^2}\right]$$

$$- \frac{q}{2\pi K} \ln \sqrt{\frac{(y - y_o)^2 + (x - x_o)^2}{(b - y_o)^2 + (x_o)^2}} \tag{B.5}$$

which is the dimensional expression for the potential, Φ_w, for the well and is the simpler equation replacing Equation (8) from McKeon and Nelson (p. 16, 1984).

A convenient set of dimensionless variables (McKeon and Nelson 1984) are

$$x' = \frac{x}{b} \tag{B.6}$$

$$y' = \frac{y}{b} \tag{B.7}$$

$$z' = \frac{z}{b} \tag{B.8}$$

$$\phi' = \frac{\phi}{b} \tag{B.9}$$

$$t' = \frac{K}{b} t \tag{B.10}$$

Using Equations (B.6) through (B.10) in Equation (B.4) gives the useful dimensionless form for Φ_o':

$$\Phi_o' = - U y' \sin \Theta - U x' \cos \Theta + \frac{U[(y' - y_o') \sin \Theta + (x' - x_o') \cos \Theta] (r_o')^2}{(x' - x_o')^2 + (y' - y_o')^2}$$

$$+ \frac{(\varepsilon - 1) UA_\lambda x' \cos \Theta}{1 + A_o (\varepsilon - 1)} + \frac{(\varepsilon - 1) U B_\lambda y' \sin \Theta}{1 +_o B (\varepsilon - 1)}$$

$$- \frac{q}{2Kb\pi} \ln \sqrt{\frac{(y' - y_o')^2 + (x' - x_o')^2}{(1 - y_o)^2 + (x_o')^2}} \tag{B.11}$$

This equation replaces Equation (A.97) on page A.15 in Appendix A of McKeon and Nelson (1984). We note that unfortunately there were also printing errors in the denominators of the Equation (A.96) and (A.97) of McKeon and Nelson (1984) [i.e., everywhere where the expression (1+ε) appeared in the denominator there should have been $(1-\varepsilon)$]. The dimensionless form of the potential caused by the well (i.e., ϕ_w') is found using Equations (B.6) through (B.10) in Equation (B.5):

$$\phi_w' = U[(y' - y_o') \sin \Theta + (x' - x_o') \cos \Theta] \left[\frac{(r_o')^2}{(x' - x_o')^2 + (y' - y_o')^2} \right]$$

$$- \frac{q}{2\pi Kb} \ln \sqrt{\frac{(y' - y_o')^2 + (x' - x_o')^2}{(1 - y_o')^2 + (x_o')^2}} \qquad (B.12)$$

where

$q = -\frac{Q}{L}$ is the well source strength per unit length of perforated well — L^2/T

Q is the volume pumping rate from the well and is always a positive value — L^3/T

L is the perforated length of the well — L

$r_o' = \frac{r_o}{b}$ is the dimensionless well radius. — None

The other terms are as defined in Appendix A of this report and are given in Appendix B of McKeon and Nelson (1984).

The replacement expression for the pathline simplified Equation (A.100) (McKeon and Nelson 1984) is gained from differentiating Equation (B.12):

$$\left(\frac{dx'}{dt'}\right)_w = - \frac{1}{P} \frac{\partial \phi_w'}{\partial x'} = \frac{2\, U\, (r_o')^2\, (y' - y_o') \sin \Theta\, (x' - x_o')}{P[(x' - x_o')^2 + (y' - y_o')^2]^2}$$

$$- \frac{U \cos \Theta\, (r_o')^2}{P[(x' - x_o')^2 + (y' - y_o')^2]} + \frac{2\, U\, (r_o')^2\, (x' - x_o')^2 \cos \Theta}{P[(x' - x_o')^2 + (y' - y_o')^2]^2}$$

$$+ \frac{q(x' - x_o')}{2\pi KPb\, [(y' - y_o')^2 + (x' - x_o')^2]} \qquad (B.13)$$

Similarly the simplified replacement for Equation (A.101) (Appendix A, McKeon and Nelson 1984) is for $\frac{d\phi'_w}{dy'}$ is upon differentiating Equation (B.12) above with respect to y':

$$(\frac{dy'}{dt'})_w = -\frac{1}{P}\frac{\partial\phi'_w}{\partial t'} = \frac{2\,U\,(r'_o)^2\,(y' - y'_o)^2\,\sin\Theta}{P[(x' - x'_o)^2 + (y' - y'_o)^2]^2} - \frac{U\,\sin\Theta\,(r'_o)^2}{P[(x' - x'_o)^2 - (y' - y'_o)^2]}$$

$$+ \frac{2\,U\,(r'_o)^2\,(y' - y'_o)\cos\Theta\,(x' - x'_o)}{P[(x' - x'_o)^2 + (y' - y'_o)^2]^2}$$

$$+ \frac{q\,(y' - y'_o)}{2\pi KPb\,[(y' - y'_o)^2 + (x' - x'_o)^2]} \qquad (B.14)$$

Now the simplified replacement for Equation (A.102) p. A.17, Appendix A of McKeon and Nelson (1984) after differentiating (B.12) above with respect to z' is

$$(\frac{dz'}{dt'})_w = -\frac{1}{P}\frac{\partial\phi'_w}{\partial z'} = 0 \qquad (B.15)$$

Equations (B.13), (B.14), and (B.15) are the simplified replacement equations for (A.100), (A.101), and (A.102) in Appendix A, pages A.16 and A.17, in McKeon and Nelson (1984) and are added respectively to Equations (A.63), (A.64) and (A.65) and use the definitions following Equation (A.65) (McKeon and Nelson 1984) to provide the complete set of three ordinary differential equations describing the pathline outside of the stope. This set of ordinary differential equations are solved using a fourth-order Runge-Kutta numerical integration in the PATHLIN2 program, discussed in Appendix C and listed in Appendix D.

ANALYTICAL STREAM FUNCTION FOR PUMPED WELL

The stream function for the pumped well is needed to accurately determine the cummulative flux into the well as a function of location around the well casing of radius, r'_o. It can be demonstrated that the complex conjugate or stream function, ψ'_{ws}, of Equation (B.12) is

$$\psi'_{ws} = -\frac{U\,(r'_o)^2\,[(y' - y'_o)\cos\Theta - (x' - x'_o)\sin\Theta]}{(x' - x'_o)^2 + (y' - y'_o)^2}$$

$$- \frac{q}{2\pi Kb}\arctan\left[\frac{(y' - y'_o)\cos\Theta - (x' - x'_o)\sin\Theta}{(x' - x'_o)\cos\Theta + (y' - y'_o)\sin\Theta}\right] \qquad (B.16)$$

If one adds the complex conjugate or stream function for a uniform flow and recognizes that the stream function is determined only to within an arbitrary constant, C'_3, then Equation (B.16) becomes

$$\psi'_w = C'_3 - U\,[(y' - y'_o)\cos\Theta - (x' - x'_o)\sin\Theta]$$

$$- \frac{U\,(r'_o)^2\,[(y' - y'_o)\cos\Theta - (x' - x'_o)\sin\Theta]}{(x' - x'_o)^2 + (y' - y'_o)^2}$$

$$- \frac{q}{2\pi Kb}\arctan\left[\frac{(y' - y'_o)\cos\Theta - (x' - x'_o)\sin\Theta}{(x' - x'_o)\cos\Theta + (y' - y'_o)\sin\Theta}\right] \qquad (B.17)$$

Now we reduce Equation (B.17) by letting

$$x' = x'_r,\; y' = y'_r,\text{ and } (x'_r - x'_o)^2 + (y'_r - y'_o)^2 = (r'_o)^2 \qquad (B.18)$$

which provides the stream function at the well. That is, ψ'_r multiplied by $\frac{r'_o}{r'_o}$ or unity gives

$$\psi'_r = C'_3 - 2\,U\,r'_o\left[\frac{y'_r - y'_o}{r'_o}\cos\Theta - \frac{(x'_r - x'_o)}{r'_o}\sin\Theta\right]$$

$$- \frac{q}{2\pi Kb}\arctan\left[\frac{\frac{y'_r - y'_o}{r'_o}\cos\Theta - \frac{x'_r - x'_o}{r'_o}\sin\Theta}{\frac{(x'_r - x'_o)}{r'_o}\cos\Theta + \frac{(y'_r - y'_o)}{r'_o}\sin\Theta}\right] \qquad (B.19)$$

But from Figure B.1:

$$\sin \alpha = \frac{y'_r - y'_o}{r'_o} , \tag{B.20}$$

and

$$\cos \alpha = \frac{x'_r - x'_o}{r'_o} \tag{B.21}$$

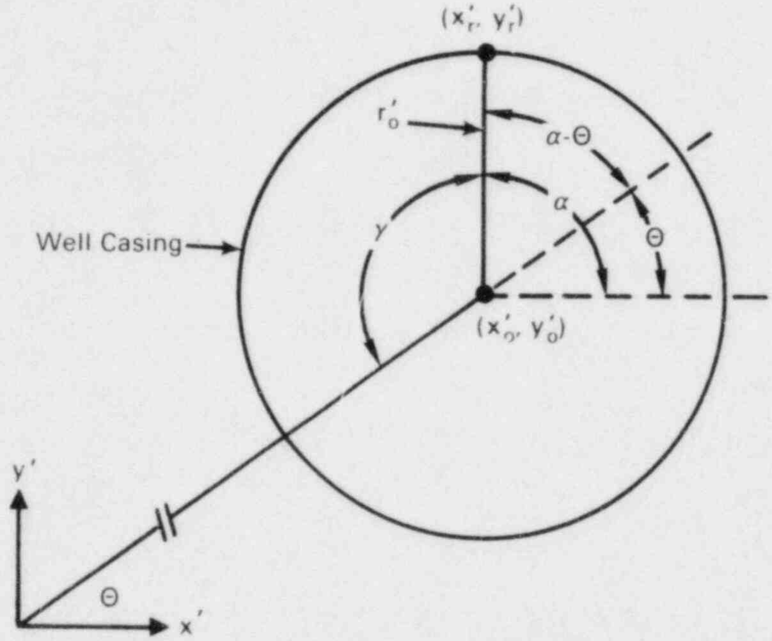


FIGURE B.1. Schematic Diagram Defining Stream Function Angles at Well Casing

Substituting Equations (B.20) and (B.21) and using the trigonometric difference identities gives

$$\psi'_r = C'_3 - 2 \; U \; r'_o \; (\sin \alpha \cos \Theta - \cos \alpha \sin \Theta)$$

$$- \frac{q}{2\pi Kb} \arctan \; \frac{\sin (\alpha - \Theta)}{\cos (\alpha - \Theta)} \tag{B.22}$$

or

$$\psi'_r = C'_3 - 2Ur'_o \sin (\alpha - \Theta) - \frac{q}{2\pi Kb} (\alpha - \Theta) \tag{B.23}$$

where now both α and Θ are in radians.

Now let

$$\gamma = \pi - (\alpha - \Theta) \tag{B.24}$$

and

$$q = - \frac{Q}{L} \tag{B.25}$$

where Q is the volume of fluid per unit time pumped from the well and is always positive (L^3/T), and L is the perforated length of the well from which fluid is withdrawn from the aquifer (L). Substituting Equations (B.24) and (B.25) into (B.23) yields

$$\psi'_r = C'_3 - 2Ur'_o \sin (\gamma - \pi) + \frac{Q}{2\pi KbL} (\gamma - \pi) \tag{B.26}$$

The constant in (B.26) can be evaluated using the conditions

$$\psi'_r = 0 \text{ when } \gamma = 0 \tag{B.27}$$

or

$$C_3 = \frac{Q\pi}{2\pi bKL} \tag{B.28}$$

Substituting (B.28) into (B.26) and reducing gives

$$\psi'_r = \frac{Q}{2\pi KbL} \gamma - 2 U r'_o \sin \gamma \tag{B.29}$$

which is the desired stream function expression for flux into the well.

The expression in Equation (B.29) can be used two ways: either to calculate the cummulative flux entering the well at some point (x'_r, y'_r) where a steady pathline reaches the well, or to locate starting points for pathlines around the well so that equal fluxes enter the well between successive steady pathlines. The latter is most useful in the tailings disposal consequence analysis. To obtain the correctly spaced pathline starting coordinates around the well, increments of the stream function flux [i.e., the left-hand term of Equation (B.29)] are selected and the associate values for γ are obtained by solving the transcendental expression in Equation (B.29).

The stream function for the pumped well is also useful in determining the maximum width of an upstream plume that is intercepted by the pumping well. To do this, we rewrite Equation (B.29) replacing r'_o by r' to get

$$\psi'_r = \frac{Q}{2\pi KbL} \gamma - 2Ur' \sin \gamma \tag{B.30}$$

Downgradient from the pumped well, there is a stagnation point. That is, when $\gamma = \pi$, the value of the stream function from Equation (B.30) is

$$\psi'_r = \frac{Q}{2KbL} \tag{B.31}$$

The equation for the streamline passing through the stagnation point downstream from the pumped well is then found by substituting (B.31) into (B.30) and rearranging:

$$r' \sin \gamma = \frac{Q}{4KbLU} \left(\frac{\gamma}{\pi} - 1\right) \tag{B.32}$$

This equation is the expression for the streamline passing through the stagnation point downgradient from the pumped well. In fact, it represents the last streamline that enters the well, so they are also the outermost streamlines upslope from the well incepting water. Accordingly, in the limit as γ approaches zero, we see in Equation (B.32) that the left-hand side approaches the largest y' coordinate of the streamline; whereas on the right-hand side the first term inside the parenthesis is zero. If we denote the product of $r' \sin \gamma$ by $W'_m/2$ and require that as $\gamma \to 0$ then r' increases such that $W'_m/2$ is a constant, then in the limit from Equation (B.32):

$$W'_m = \left|- \frac{Q}{2KbLU}\right| \tag{B.33}$$

or in terms of the dimensional unit volume flux using Equation (B.25)

$$W_m = \frac{|q|}{2KU} \tag{B.34}$$

This completes the results needed from the stream function for the downgradient pumping well. An expression is next needed to locate the pumped well a uniform distance away from the prolate spheroid filled with tailings.

PLACEMENT OF THE DOWNGRADIENT WELL

To realistically compare the leachate plume results for different stope orientations in the regional ground-water gradient, the downgradient well must be appropriately placed. An expression to obtain the well location (x'_o, y'_o), for a prescribed location D' away from the closest location of the tailings filled stope is required. The closest location (x'_o, y'_o) to the mine stope will be in the $z' = 0$ plane. Therefore, in the $z' = 0$ plane, the ellipse on which the well is located is given by

$$\frac{(x'_o)^2}{(D' + a')^2} + \frac{(y'_o)^2}{(D' + 1)^2} = 1 \tag{B.35}$$

where

$D' = \frac{D}{b}$ is the dimensionless distance from the stope wall

$a' = \frac{a}{b}$ is the dimensionless half length of the stope.

It is convenient to define a radial distance, R', such that

$$x_o' = R' \cos \Theta$$

$$y_o' = R' \sin \Theta \qquad \text{(B.36)}$$

with Θ being, as before, the angle between the gradient U and the x'-coordinate axis. Substitution of (B.36) into (B.35) gives

$$(R')^2 \left[\frac{(D' + 1)^2 \cos^2\Theta + (D' + a')^2 \sin^2\Theta}{(D' + a')^2 (D' + 1)^2} \right] = 1 \qquad \text{(B.37)}$$

and solving for R' yields

$$R' = \frac{(D' + a')(D' + 1) \sqrt{(D' + 1)^2 \cos^2\Theta + (D' + a')^2 \sin^2\Theta}}{(D' + 1)^2 \cos^2\Theta + (D' + a')^2 \sin^2\Theta} \qquad \text{(B.38)}$$

Given a' and Θ, which are known for any particular problem, and selecting the dimensionless distance, D', (that from the edge of the stope in the z' = 0 plane), R' can be calculated using Equation (B.38). The value of R' calculated is the radial dimensionless distance being in the z' = 0 plane from the center point, x' = 0, y' = 0, in the stope along the line making an angle, Θ, with the x'-axis. The coordinates for the well location, (x_o', y_o') are calculated using R' from Equation (B.38) and Θ in Equation (B.36). For use as input to the interactive computer codes, the dimensional forms for R, x_o and y_o are

$$R = R'b$$

$$x_o = x_o' b \qquad \text{(B.39)}$$

$$y_o = y_o' b$$

APPENDIX C

PROGRAM DESCRIPTION AND INPUT GUIDE

APPENDIX C

PROGRAM DESCRIPTION AND INPUT GUIDE

Four FORTRAN-77 programs have been developed as tools for analyzing the migration of contaminants from the mine stope into the regional aquifer and from the regional aquifer to the biosphere via a pumping well. These four programs are named

1. PATHLIN1
2. FRONTS
3. PATHLIN2
4. CONSEQ

The input data variable names described in this appendix are the actual FORTRAN variable names used in the programs. Because of the restrictions of FORTRAN naming conventions, the variable names are not, in general, the same as the terms used in the body of the report and described in Appendix A. To facilitate identification, the FORTRAN variable names are often similar to the terms in the report.

The PATHLIN1 program evaluates the pathline equations for a stope embedded in a regional aquifer. Pathlines are started on the upgradient boundary of the mine stope where the groundwater enters the tailings and the subsequent travel paths are calculated through the stope and into the regional aquifer. The results define the x, y, and z coordinates of the advance of the pathlines at each computational time step.

The FRONTS program uses the results of the PATHLIN1 program to calculate the location of contaminant fronts in the plume. This program incorporates a leaching curve (as an input file) describing the concentration of a specific contaminant in the leachate from the mine stope as a function of the number of pore volumes that have passed through the stope. The results from the FRONTS program are data files that can be used to plot pathlines and lines of equal contaminant concentration at a particular time of interest.

The PATHLIN2 program evaluates the pathline equations for a stope embedded in a regional aquifer with a pumping well located downgradient from the mine stope. Pathlines are started at the casing of the pumping well and integrated backwards in time until they either reach the mine stope or miss the stope and are discarded. The results retained define the x, y, and z coordinates of the pathlines at each computational time step, and the characteristic pathline travel times used that are input to the CONSEQ program.

The CONSEQ program calculates the mass of contaminant and the concentration of contaminant in the fluid pumped from the well as a function of time. This program incorporates a leaching curve and the travel time results from the PATHLIN2 program. The results from CONSEQ are data files that can be used to plot the contaminant concentration in the pumped fluid or the mass flux reaching the biosphere as a function of time.

Two of the programs, PATHLIN1 and PATHLIN2, have been implemented on an array processor that is coupled with a VAX 11/780 computer. These two programs have been developed specifically for this type of computer system. The changes required to make these programs compatible with other computer systems (i.e., standard FORTRAN-77) are quite simple. A total of ten lines in PATHLIN1 and sixteen in PATHLIN2 must be deleted, and those lines are noted by comments within the code listing. The lines that would require deletion in PATHLIN1 are five IMPLICIT INTEGER*2 statements, one in the main program and four in subroutines; the CALL APINIT and CALL APRLSE statements in the main program; and the statements, APIN C1, APIN C6, and APOUT C4 in subroutine RKSTR1. The lines that would require deletion in PATHLIN2 are eleven IMPLICIT INTEGER*2 statements, one in the main program and ten in subroutines; the CALL APINIT and CALL APRLSE statements in the main program; and the statements APIN C1, APIN C6, and APOUT C4 in subroutine RKSTR1.

PATHLIN1 PROGRAM

The basic equations used in this model are described in the body of the report. Only those equations related to ellipsoidal-shaped heterogeneous zone are incorporated; the equations related to the pumping well are not superimposed in this model. As noted previously the model is implemented on an array processor. This increases computational speed and reduces the associated costs.

To implement the model on the array processor, the major portion of the computational work was developed as a separate group of three subroutines. These three subroutines operate on the array processor. For each pathline, data describing starting locations and other parameters are input as a common block to the array processor. The array processor performs the computationally intensive work of numerically integrating the pathline from starting location to final location. The data describing pathline coordinates as a function of time are then passed as a common block from the array processor back to the host computer. All of the data passed to and from these three subroutines must be passed through common blocks. No data can be passed as parameters in the subroutine call statement from the main body of the program.

Pathlines are symmetric about the $z = 0$ plane; therefore, pathline solutions are only computed for those pathlines for which $z \geq 0$. From the starting location on the interior vertical plane, the entrance and exit locations, travel time, and distances through the stope are evaluated explicitly for each pathline. From the point where each pathline exits the stope, the pathline characteristic equations are numerically integrated forward in time until the maximum time (input parameter named TIMAX) is reached. The three simultaneous differential equations are integrated using a fourth-order Runge-Kutta scheme.

The model prompts the user to specify a file name, such as CASE1. The model then adds the four character extension ".INP" to the user-specified file name; in this case the input file would be named CASE1.INP. Hereafter, the user-specified file name is denoted by two closed brackets < >.

Input Data

The PATHLIN1 program uses one input file named < >.INP with the following format and data requirements.

Card Number	Record Number	Format	Variable Name	Description
1	1	free format	ANGL	Angle of the gradient with the x axis in degrees, 0 to 90
	2		U	Regional gradient (L/L)
	3		RK	Hydraulic conductivity of the regional aquifer (L/T)
	4		RKPRME	Hydraulic conductivity of the mill tailings in the heterogeneous zone (L/T)
	5		PORS1	Porosity of the aquifer
	6		PORS2	Porosity of the mill tailings
	7		A	One-half the length of the ellipsoid used to model the mine stope (L)
	8		B	Maximum radius of the ellipsoid used to model the mine stope (L)
	9		CA	Radius of the ellipsoid (CA must be equal to B) (L)
	10		STPCTL	A stepping control parameter to control the exponential increase in time step size. Used in the equation STEP = C * exp(I/STPCTL) where C is the initial step size and I is the number of steps taken (a value of 30 has worked well in the examples)
2	1	free format	MAXSTPS	Maximum number of steps (1999 is used in the example)
	2		RSIZE	Initial time step size (T) (2.0 years is used in the examples)

Card Number	Record Number	Format	Variable Name	Description
3	1	free format	NR	Number of columns at which pathlines will be started by subroutine GRID
	2		NZ	Number of rows at which pathlines will be started by subroutine GRID
	3		TIMAX	Integration time limit (T)

Output Data

The PATHLIN1 program creates four output files, named < >.GRD, < >.ARV, < >.FLX, and < >.PTH. The < >.GRD file is a formatted file containing the starting coordinates of each pathline. The data in this file include the Cartesian coordinates defining the points where each pathline enters and exits the stope, the travel time through the stope, and the distance traveled through the stope.

The < >.ARV file is a formatted file containing the final pathline coordinates. The data in this file include the Cartesian coordinates, the travel time, the magnitude of the pore velocity at the final coordinates, and the x, y, and z components of the pore velocity.

The < >.FLX file is a formatted file containing the pathline travel times. The data in this file include the pathline starting times (internally set to zero), the travel time through the stope, and the travel time to the final location. This file is used as input to the FRONTS program.

The last output file, < >.PTH, is an unformatted file containing data describing the travel path of each pathline. The data are written to the unformatted file with four records per line. The first record contains the time; the second, third and fourth records contain the x, y, and z coordinates at that time. The pathlines are listed consecutively and can be distinguished by noting that individual pathlines begin when time is equal to zero.

FRONTS PROGRAM

The FRONTS program calculates the concentration of contaminant and the location of contaminant fronts in the x-y plane. The basic equations used in this model are described in the body of the report.

Two options are available in the model. The first option incorporates a leaching curve describing the concentration of a specific contaminant in the leachate from the mine stope as a function of the number of pore volumes that have passed through the stope. The pathline travel time results from the PATHLIN1 program are used along with the leaching curve. These data are used to calculate fronts describing the contaminant concentration along each pathline as a function of time. The second option calculates and plots equal travel time fronts. The model prompts the user to specify which option is to be used. The location of the contaminant fronts are plotted using calls to DIG (Device Independent Graphics) subroutines.

The model prompts the user to specify a file name, such as CASE1. The model then adds the four character extension ".FLX" to the user-specified file name; in this case the input file name would be CASE1.FLX (this particular file is created by the PATHLIN1 program).

Input Data

The FRONTS program uses four input files named GRF.INP, < >.CLS, < >.FLX, and < >.PTH with the following format and data requirements.

GRF.INP File

The data in this file are used to characterize the leaching curve. This file must be created by the user.

Card Number	Record Number	Format	Variable Name	Description
1	1	free format	C(i)	Concentration (M/L**3)
	2		CV(i)	Column Volume

Card 1 is repeated for each point on the leaching curve. A blank line is used to terminate the input data.

< >.CLS File

The data in this file are used to draw a boundary around the pathline and fronts plot. This file must be created by the user.

Card Number	Record Number	Format	Variable Name	Description
1	1	free format	NUMPTS	Number of points in the boundary to be plotted.
2	1	free format	X(i)	x coordinate
	2		Y(i)	y coordinate

Card 2 is repeated for each point on the boundary. The appropriate size of the boundary can be determined from the final pathline coordinates in the < >.ARV file ouput from the PATHLIN1 model.

< >.FLX File

The data in this file are used to characterize the pathline travel times.

Card Number	Record Number	Format	Variable Name	Description
1	1	free format	T0(i)	Initial time (T)
	2		T1(i)	Travel time through the mine stope (T)
	3		T2(i)	Final travel time (T)

Card 1 is repeated for each pathline. This file is created by the PATHLIN1 program.

< >.PTH File

This is an unformatted file created by the PATHLIN1 program. The file contains data describing the travel path of each pathline.

Output Data

The FRONTS program creates two output files named FRONT.PLT and < >.FNT. The FRONT.PLT file is an unformatted file created by the DIG subroutines. This file contains the data describing the fronts that can be sent to a plotting device. The < >.FNT file is a formatted file containing the coordinates of the user-specified fronts (either equal travel time or concentration fronts).

PATHLIN2 PROGRAM

The basic equations used in this model are described in the body of the report. The equations related to the pumping well are superimposed on the equations related to ellipsoidal-shaped heterogeneous zone in this model. As noted previously, the model is implemented on an array processor. This increases computational speed and reduces the associated costs. The same requirements for array processor subroutines discussed above with the PATHLIN1 model apply to PATHLIN2.

The pathline starting locations are defined around the casing of the well located downgradient from the stope. Using the stream function, the pathline starting locations are defined such that the fluid flux between each streamline is equal. The flow system is symmetric about the x-y plane at $z = 0$; therefore, pathlines are started on only the top half of the well casing. From the well casing, the pathline characteristic equations are numerically integrated backward in time until the pathline either pierces the downgradient edge of the stope or misses the stope. From the point where a pathline pierces the stope (actually the exit location because we are integrating backward in time), the entrance location, travel time, and distance through the stope are evaluated explicitly. The three simultaneous differential equations are integrated using a fourth-order Runge-Kutta scheme.

The model prompts the user to specify a file name, such as CASE1. The model then adds the four character extension ".INP" to the user-specified file name; in this case the input file name would be CASE1.INP.

Input Data

The PATHLIN2 program uses one input file named < >.INP with the following format and data requirements.

Card Number	Record Number	Format	Variable Name	Description
1	1	free format	ANGL	Angle of the gradient with the x-axis in degrees, 0° to 90°
	2		U	Regional gradient (L/L)
	3		RK	Hydraulic conductivity of the regional aquifer (L/T)
	4		RKPRME	Hydraulic conductivity of the mill tailings in the heterogeneous zone (L/T)
	5		PORS1	Porosity of the aquifer
	6		PORS2	Porosity of the mill tailings
	7		A	One-half the length of the ellipsoid used to model the mine stope (L)
	8		B	Maximum radius of the ellipsoid used to model the mine stope (L)
	9		CA	Radius of the ellipsoid (CA must be equal to B) (L)

Card Number	Record Number	Format	Variable Name	Description
	10		STPCTL	A stepping control parameter to control the exponential increase in time step size. Used in the equation STEP = C * exp(I/STPCTL) where C is the initial step size and I is the number of steps taken (a value of 30 has worked well in the examples)
2	1	free format	Q	Pumping rate per unit length of well (L**3/T/L)
	2		XO	x-coordinate of the well (L)
	3		YO	y-coordinate of the well (L)
	4		RADIUS	Radius of the well (L)
3	1	free format	MAXSTPS	Maximum number of steps (1999 is used in the example)
	2		RSIZE	Initial time step size (T) (1.5 years is used in the examples)
4	1	free format	NR	Number of columns at which pathlines will be started by subroutine GRID
	2		NZ	Number of rows at which pathlines will be started by subroutine GRID

Output Data

The PATHLIN2 program creates four output files: < >.GRD, < >.ARV, < > .FLX, and < >.PTH. The < >.GRD file is a formatted file containing the starting coordinates of each pathline (i.e., the grid of starting coordinates). The data in this file are the Cartesian coordinates defining the point where each pathline pierces the well casing.

The < >.ARV file contains the pathline starting and arrival data. This file contains the time and spatial coordinates where each pathline enters the upstream side of the stope, exits the downstream side of the stope, and arrives at the well.

The < >.FLX file is a formatted file containing the pathline travel times. The data in this file include the pathline starting times (internally set to zero), the travel time through the stope, and the travel time to the well. This file is used as an input to the CONSEQ program.

The last output file, < >.PTH, is an unformatted file containing data describing the travel path of each pathline. Data are written to the unformatted file with four records per line. The first record contains the time; the second, third, and fourth records contain the spatial coordinates at that time. The pathlines are listed consecutively and can be distinguished by noting that individual pathline data begin at time equal to zero. The calculated travel time and coordinates that were integrated backward in time are reversed in this file so that they are read forward in time. The pathline starting coordinates at time equals zero are on the upstream side of the mine stope, and the final coordinates are at the well casing with time increasing.

CONSEQ PROGRAM

The CONSEQ program is used to calculate the mass of contaminant and the concentration of contaminant in the fluid pumped from the well as a function of time. The basic equations used in this model are described in the body of the report.

This program incorporates a leaching curve describing the concentration of a specific contaminant in the leachate from the mine stope as a function of the number of pore volumes that have passed through the stope. The pathline travel time results from the PATHLIN2 program and the leaching curve are used to calculate the concentration of a specific contaminant arriving along each pathline at the well as a function of time. The concentration of contaminant in the fluid pumped from the well is calculated by summing the concentration from each pathline and taking the mean. This analysis assumes that the fluid is perfectly mixed by the pumping well.

The model prompts the user to specify a file name, such as CASE1. The model then adds the four character extension ".FLX" to the user-specified file name, in this case the input file name would be CASE1.FLX (note this file is created by the PATHLIN2 program).

Input Data

The CONSEQ program uses two input files named GRF.INP and < >.FLX with the following formats and data requirements.

GRF.INP File

The data in this file are used to characterize the leaching curve. This file must be created by the user.

Card Number	Record Number	Format	Variable Name	Description
1	1	free format	C(i)	Concentration (M/L**3)
	2		CV(i)	Column Volume

Card 1 is repeated for each point on the leaching curve. A blank line is used to terminate the input data.

< >.FLX File

The data in this file are used to characterize the pathline travel times.

Card Number	Record Number	Format	Variable Name	Description
1	1	free format	T0(i)	Initial time (T)
	2		T1(i)	Travel time through the mine stope (T)
	3		T2(i)	Travel time to the well (T)

Card 1 is repeated for each pathline. This file is created by the PATHLIN2 program.

Output Data

The CONSEQ program creates two output files named < >.DAT and < >.PLT. The < >.DAT file is a formatted file containing the contaminant concentration and mass of contaminant in the fluid pumped from the well as a function of time. The < >.PLT file is a formatted file containing the contaminant concentration and the corresponding time. These data can be used to plot the concentration of contaminants reaching the biosphere through the pumping well.

SUMMARY OF MODEL PROGRAMS, SUBROUTINES AND FUNCTIONS

Program PATHLIN1	INPUT FILES	OUTPUT FILES
Pathline integration from mine stope into aquifer	< >.INP	< >.ARV < >.GRD < >.FLX < >.PTH

SUBROUTINES	FUNCTION
DVERK1	Performs Runge-Kutta integration on array processor
ELLIP2	Calculates points on ellipse for plotfile
FUNCT1	Evaluates pathline characteristic equations
FUNCT2	Evaluates pathline characteristic equations on array processor
GRID	Defines starting coordinates inside the stope, calculates travel time across stope
RKSTR1	Starts pathlines at starting location and controls integration step size on array processor
TANGPT	Calculates points on ellipsoid where flow is tangent to surface

Program FRONTS	INPUT FILES	OUTPUT FILES
Locates equal travel time or concentration fronts	GRF.INP < >.FLX	FRONT.PLT < >.FNT < >.PTH

SUBROUTINES	FUNCTION
CURVE	Interpolates pore volume for a given concentration from leaching curve
SCALE	Draws scale on plot
NUMBER	DIG (Device Independant Graphics) subroutine
PLOT	DIG subroutine
PLOTND	DIG subroutine
PLOTS	DIG subroutine
SYMBOL	DIG subroutine

Program PATHLIN2	INPUT FILES	OUTPUT FILES
Pathline integration from well casing to mine stope	< >.INP	< >.ARV < >.GRD < >.FLX < >.PTH

SUBROUTINES	FUNCTION
BONDRZ	Defines bounding pathlines in the z direction
CIRCLE	Draws circle for plot file
DVERK	Performs Runge-Kutta integration
DVERK1	Performs Runge-Kutta integration on array processor
FCN	Evaluates the stream function
FUNCT1	Evaluates pathline characteristic equations
FUNCT2	Evaluates pathline characteristic equations on array processor
GRID	Defines starting coordinates at the well casing
LNINTP	Solves transcendental equation (stream function) for specific cumulative fluxes
RKSTR1	Starts pathlines at starting location and controls integration step size on array processor
TVLTM	Calculates travel time across stope and final coordinates

Program CONSEQ	INPUT FILES	OUTPUT FILES
Calculates time dependent concentration at well	GRF.INP < >.FLX	< >.DAT < >.PLT

SUBROUTINES	FUNCTION
none	

APPENDIX D

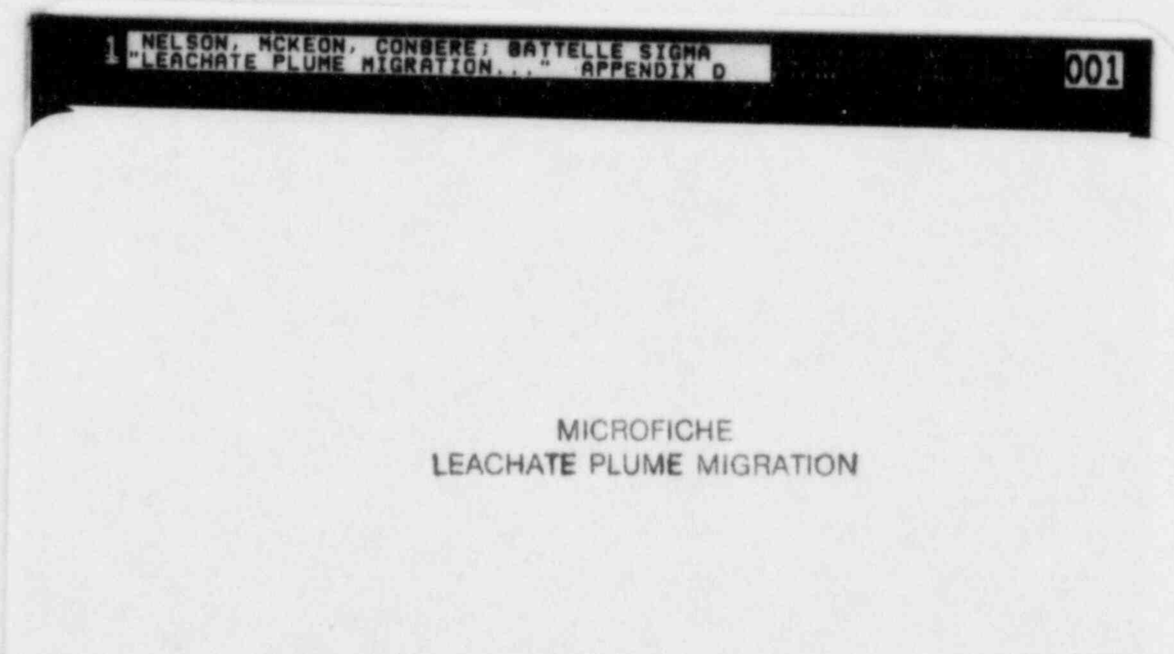
LISTINGS OF PROGRAMS AND EXAMPLE PROBLEMS FILES

APPENDIX D

LISTINGS OF PROGRAMS AND EXAMPLE PROBLEMS FILES

A complete listing of the PATHLIN1, PATHLIN2, FRONTS, and COSEQ programs are included on the enclosed microfiche.

Sample input and output files for each of the programs are also included on the microfiche. The input and output files for the PATHLIN1 and FRONTS models are for flow through the stope into the regional aquifer with the hydraulic gradient oriented 20° to the x-axis. These files are named EXR20< >. The input and output files for the PATHLIN2 and CONSEQ models are for flow through the stope with a downgradient pumping well with the hydraulic gradient oriented 45° to the x-axis. The files are named EXW45.< >.



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1. REPORT NUMBER (Assigned by TIDC, add Vol. No., if any): NUREG/CR-4061 PNL-5318

2. TITLE AND SUBTITLE: Leachate Plume Migration Downgradient from Uranium Tailings Disposal in Mine Stopes

3. LEAVE BLANK

4. DATE REPORT COMPLETED: MONTH January, YEAR 1985

5. AUTHOR(S)
R. W. Nelson
T. J. McKeon
W. Conbere

6. DATE REPORT ISSUED: MONTH February, YEAR 1985

7. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

8. PROJECT/TASK/WORK UNIT NUMBER

9. FIN OR GRANT NUMBER: FIN B2370

10. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)

Division of Radiation Programs and Earth Sciences
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

11a. TYPE OF REPORT

b. PERIOD COVERED (Inclusive dates)

12. SUPPLEMENTARY NOTES

13. ABSTRACT (200 words or less)

A method previously developed at Pacific Northwest Laboratory has been simplified and extended to better evaluate the environmental consequences of below-water-table disposal of uranium mill tailings in mine stopes. The method described uses analytical expressions for the velocity potential and examines numerically the convective transport of tailings liquor and leachate through the aquifer and into a water supply well located downgradient from the mine stope. The overall dependence of the leachate plume size and shape on the hydrologic parameters and the tailings disposal geometry are presented in graphical form for use in preliminary assessments. The graphical results are also used to set up worst-case scenarios for return of the leachate constituents to the biosphere via the pumped water supply well. The interactive computer models developed to evaluate such worst-case conditions are presented, discussed, and used to evaluate four typical situations.

14. DOCUMENT ANALYSIS - a. KEYWORDS/DESCRIPTORS
Leachate Movement
Below-water-table
Waste Disposal
Environmental Consequences

b. IDENTIFIERS/OPEN-ENDED TERMS

15. AVAILABILITY STATEMENT: Unlimited

16. SECURITY CLASSIFICATION: (This page) Unclassified; (This report)

17. NUMBER OF PAGES

18. PRICE

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

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NUREG/CR-4061

LEACHATE PLUME MIGRATION DOWNGRADIENT FROM URANIUM TAILINGS DISPOSAL IN MINE STOPES

FEBRUARY 1985