A VALIDATED THEORY OF UNDERGROUND MINE FLOODING

Adrian Brown

Golder Associates
12345 West Alameda Parkway
Lakewood, Colorado 80228, U.S.A.

ABSTRACT

When an underground mine floods, the level of water rises in the mine and shaft, trapping air in the mine. This paper presents the derivation of an analytical expression to predict the air pressure in the mine as flooding takes place. The theory is checked by reference to a carefully instrumented mine flooding conducted in a small underground mine in Arizona in 1976. It is believed that the validated analytical expression for air and water pressure in a flooding mine has applications in mine safety, mine dewatering, mining groundwater impact evaluations and underground nuclear waste disposal repository design.

INTRODUCTION

The flooding of mines has been a major safety and operational problem since mining began. Because sudden inrushes are usually unpredictable, there are few, if any, carefully recorded examples of underground mine flooding reported in the literature. A detailed knowledge of the mechanics of mine flooding is of value to earth scientists and hydrologists for a number of reasons including:

- Understanding mine fill-up after inrushes, for safety engineering purposes.
- Design of pumping strategy for mine recovery after flooding.
- Understanding mine fill-up to allow prediction of post-mining impacts on groundwater levels.
- Evaluation of resaturation time for design of underground nuclear waste repositories and for computation of radionuclide release.

An analytical expression has been derived for the increase in pressure in a mine as it floods, and for the decrease in pressure as the mine is dewatered. This theoretical expression has been checked against an actual flooding of a small mine in Arizona to demonstrate its validity. The expression is then used to investigate the behavior of this hydraulic system.

THEORY AND GENERAL SOLUTION

The system analyzed is shown in schematic form in Figure 1. It is very simple. Water flows into the mine, compressing the air in the mine and causing the water level in the mine to rise. At the same time, some of the inflow water moves into the shaft, and causes the shaft water level to rise. The water pressure in the mine, the air pressure in the mine, and the water pressure created by the column of water in the shaft are all in equilibrium.

This system has been analyzed and a theoretical equation relating the air pressure (and water pressure) in the mine with the elapsed time since flooding began and with geometric parameters. The analysis of the case of constant flow being drawn from the shaft (as would happen in a mine dewatering activity) has also been included to complete the equation. The derivation of the equation and the definition of the parameters used is presented in Appendix 1.

FLOODING OF THE FLORENCE MINE

It is fortunate that a well recorded case history of mine flooding exists to allow verification of the analytical expression developed in Appendix 1. Most mine floods are unexpected, and the task of saving the mine is usually more urgent than that of monitoring the air pressure in the mine. However, the case history which exists was obtained from the flooding of a small exploratory shaft and underground mine at Florence, Arizona. This mine was used to extract a bulk sample of ore for use in the planning of a large open pit, and at the end of the sampling was deliberately allowed to flood. Air pressure in the mine was monitored for some 20 days after the pumps were removed from the mine. This monitoring was originally performed to obtained needed geohydrology parameters for the orebody. The pressure data is presented on Figure 2. The background information for the mine was:

Inflow prior to flooding	= 2,750 m^3/day
Estimated equilibrium pressure	= 1·2 MPa
Volume of mine	=19,000 m^3
Volume of shafts	= 500 m^3
Total volume	=19,500 m^3

Using the equation presented in the Appendix, and these parameters, two histories were computed for the expected air pressure in the mine. These are shown on Figure 3. The fit is good, except in two respects.

1. Early fit is poor. This probably is a result of the fact that air was deliberately bled from the mine early in the flooding by way of a plastic air-pipe. This would cause actual pressure build-up to lag predicted.

2. The fit when the pressure approaches equilibrium is poor. This is believed to result from differences between the theory and the actual geohydrologic situation. No account is taken in the analysis of the recharge of the water table due to the cecessation of pumping from the mine. Thus the late time match is expected to be poor.

It is believed that the good correspondence between the predicted and actual pressure histories provides strong validation for the analytical model.

FLOODING AND DRAINAGE BEHAVIOR

The validated analytical model has been used to develop an understanding of the behavior of the shaft/mine/air system.

Impact of Depth of Mine Below Water Table

The first factor to be investigated was the effect of depth. This is shown in dimensionless form in Figure 4. As can be seen, the greater the value of "α", the difference between initial and static pressure in the mine expressed as atmospheres, the closer the pressure-time response approaches a step function. (note that one atmosphere approximately equals the pressure exerted by ten meters of water).

This indicates that in deep mines, the major pressurization of the air is delayed until the mine and shaft system is largely refilled with water.

Impact of Relative Size of Mine and Shaft

The way in which flooding occurs is strongly dependent upon the relative volume of the mine and the shaft. The effect on flooding history of varying the ratio from no mine ($V_m/V = 0$) to no shaft ($V_m/V = 1$) is presented in Figure 5. The shaft-dominated systems pressurize more rapidly at first, but take longer to approach final equilibrium than do the mine-dominated systems. Note that in general, most mines have less than 5% of their total volume in the portion of the shaft below the water table. (ie. V_m/V usually exceeds 0.95).

Impact of Pumping From the Shaft

When a mine floods unintentionally, it is common to pump from the shaft to try to save the mine. The analytical expression developed includes allowance for this activity, and several analyses have been performed to show the effect of such pumping. Figure 6 shows the effect on flooding of pumping at rates less than the inflow rate at the start of flooding. Clearly the effect of flooding can be delayed with fairly modest flows, but it can only be prevented by flows in excess of the initial flood flow. Figure 7 shows the effects of pumping out a fully flooded mine. Again, flows in excess of the initial flood flows are needed to recover the mine. A minimum of 1.5 to 2 times the initial flood flow appears necessary to dewater the mine in a timely fashion. Finally, Figure 8 shows the time required to drain a flooded mine as a function of flow extracted. The time is somewhat sensitive to the depth of the mine, as shown by the different curves for different values of "α". This relationship is not sensitive to the mine/shaft volume relationship. Again, this figure clearly shows that flows in excess of 1.5 times the initial inrush flow are needed to dewater a flooded mine.

CONCLUSION

This paper has presented a validated analytical model of mine flooding and recovery by pumping. The model has been used to demonstrate the behavior of this system under various assumptions. The predictive equation can be used in many mine flooding situations, and has clear applications in the areas of mine safety, flooded mine recovery, post-abandonment groundwater impact, and prediction of refill time for nuclear repositories.

ACKNOWLEDGEMENT

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LIST OF FIGURES

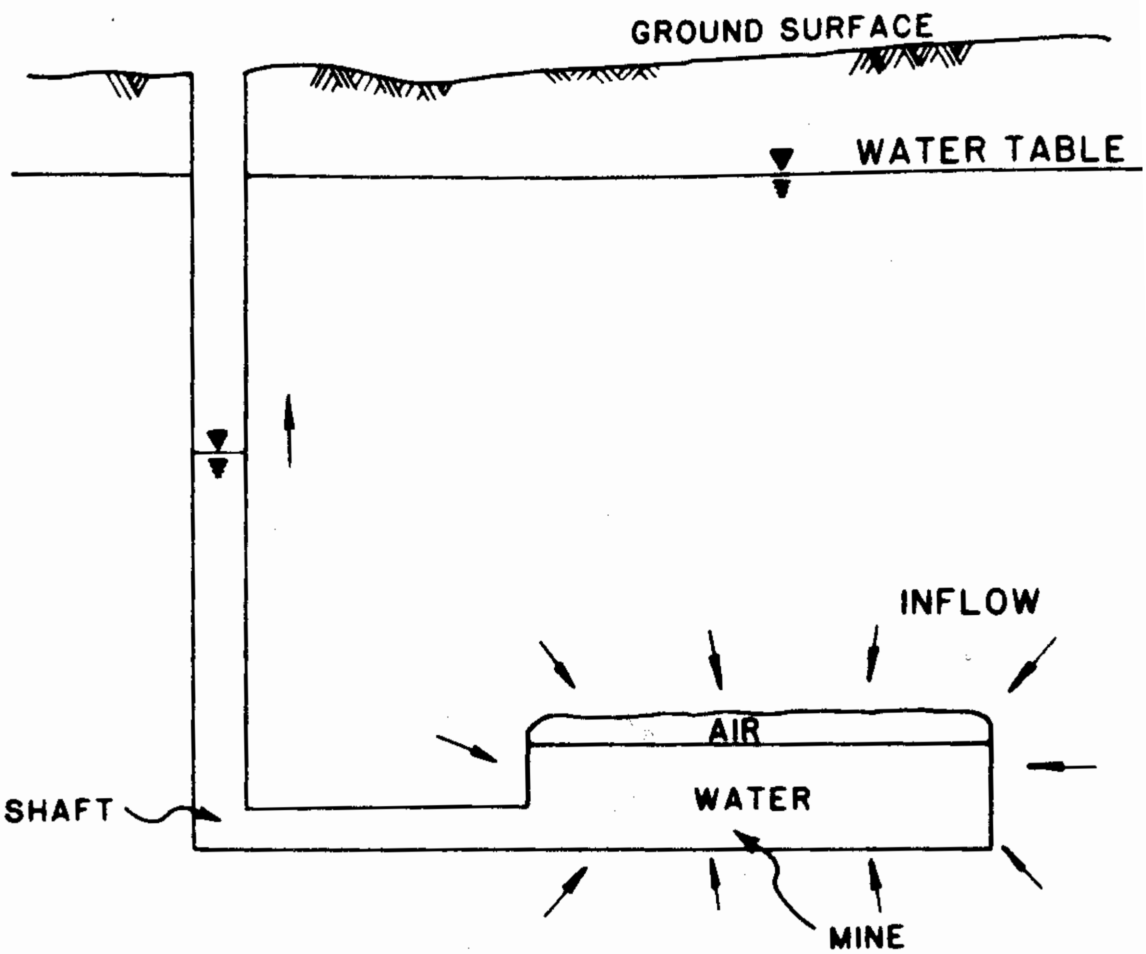


Figure 1
SCHEMATIC OF MINE FLOODING

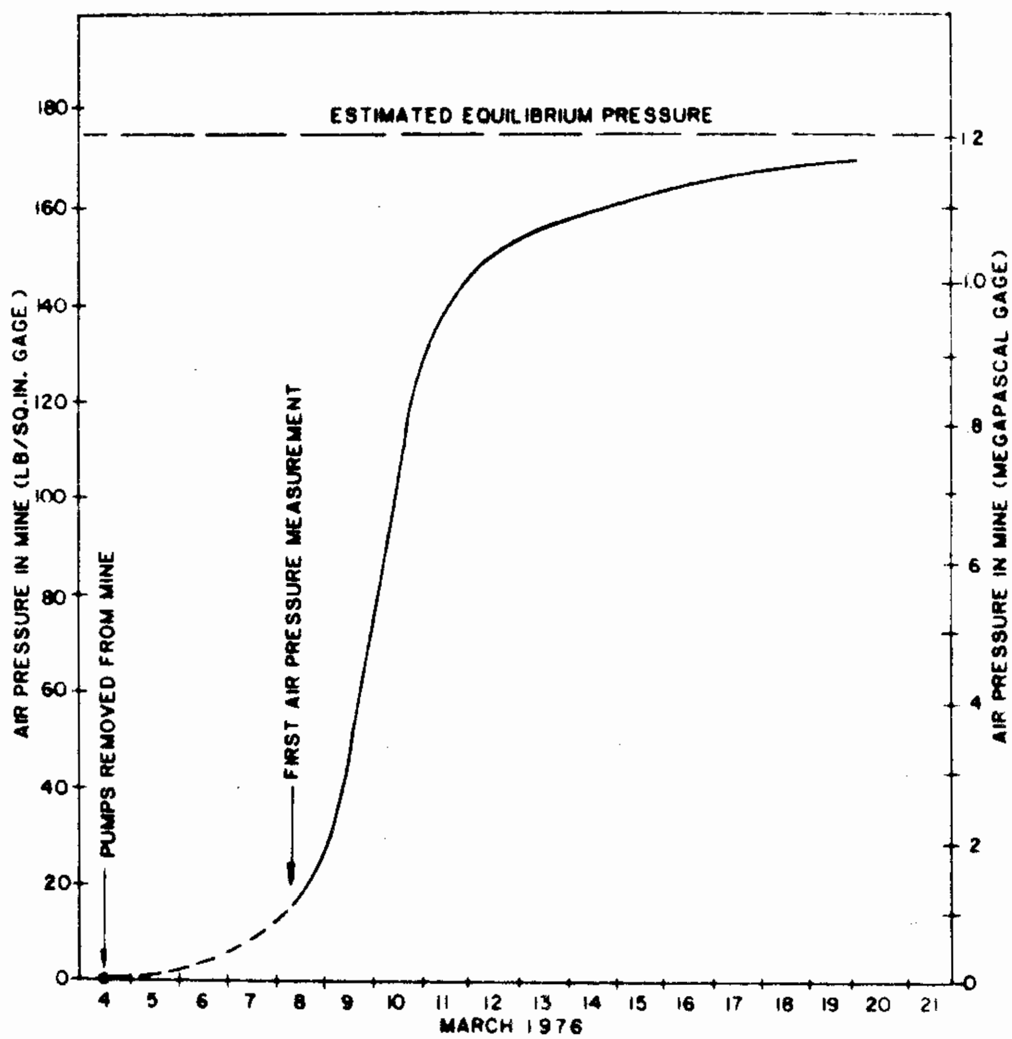


Figure 2
HISTORY OF BUILDUP OF AIR PRESSURE-FLORENCE MINE FLOODING

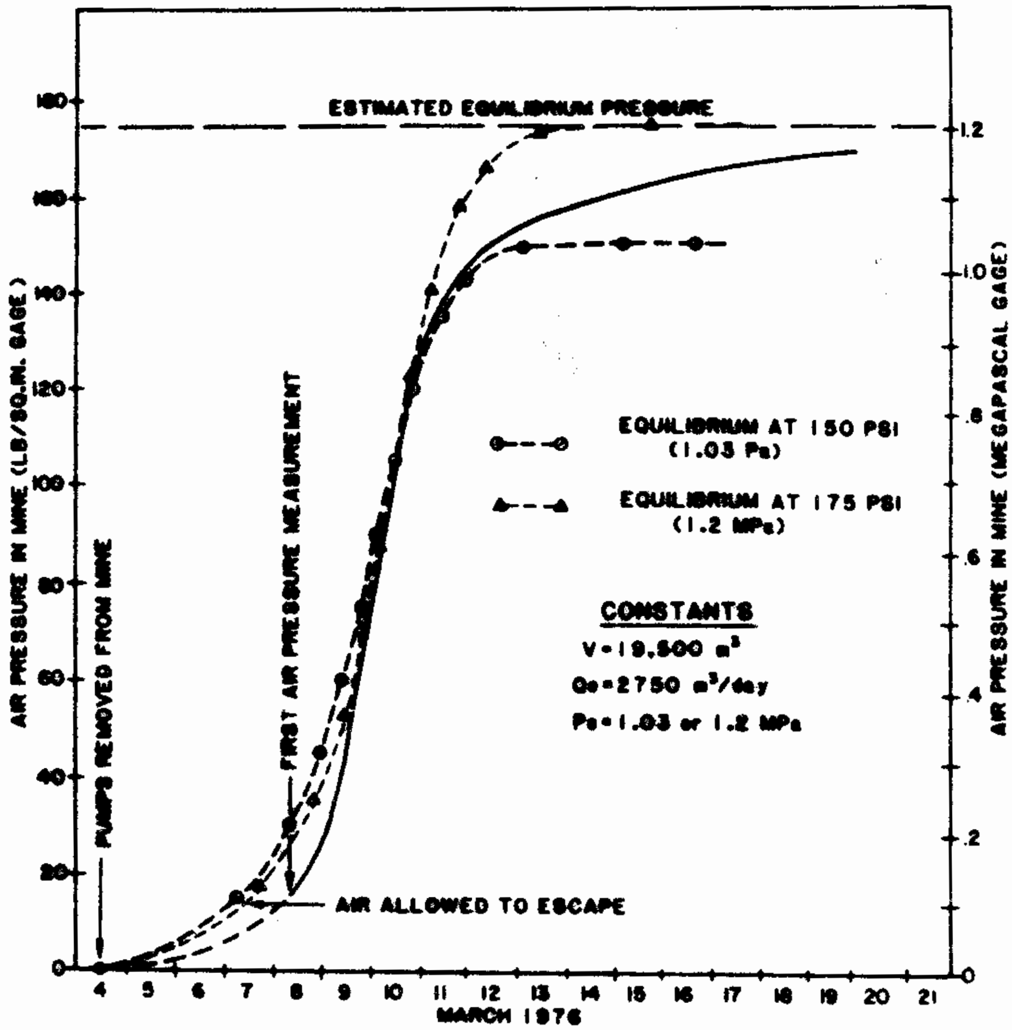


Figure 3
COMPUTED AIR PRESSURE IN MINE USING KNOWN PARAMETERS

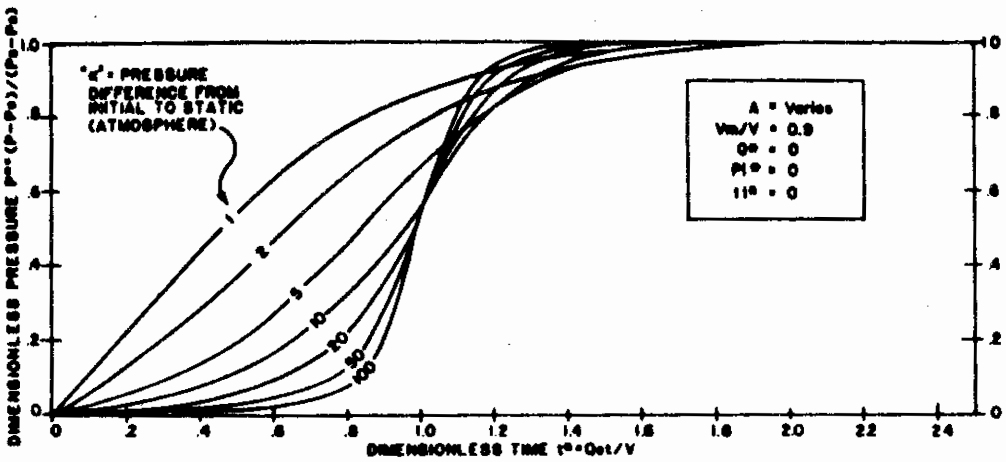


Figure 4
PLOT OF FLOODING FOR VARIOUS DEPTHS OF MINE

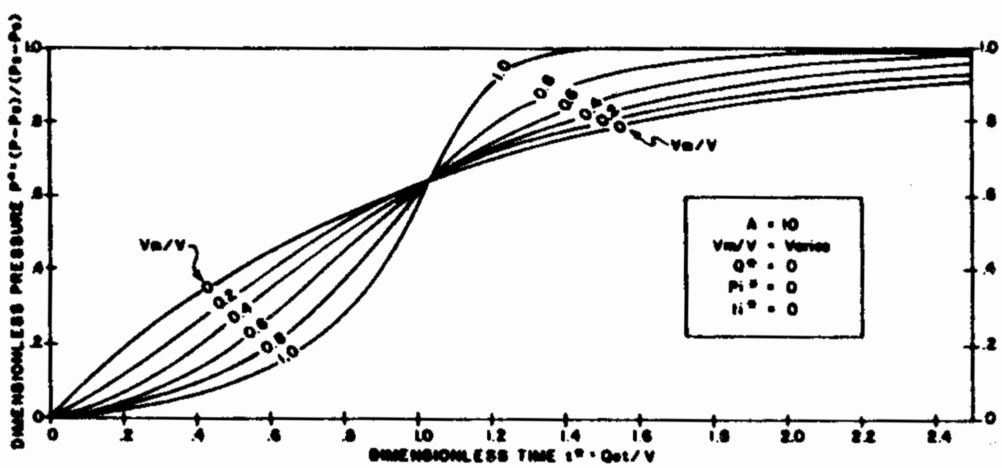


Figure 5
PLOT OF FLOODING FOR VARIOUS MINE SHAFT VOLUME RATIOS

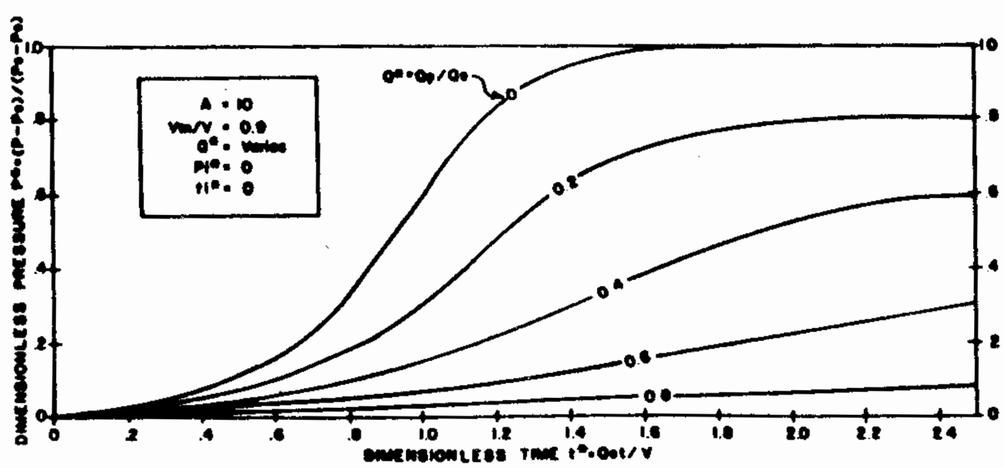


Figure 6
PLOT OF FLOODING OF MINE FOR VARIOUS PUMPING RATES

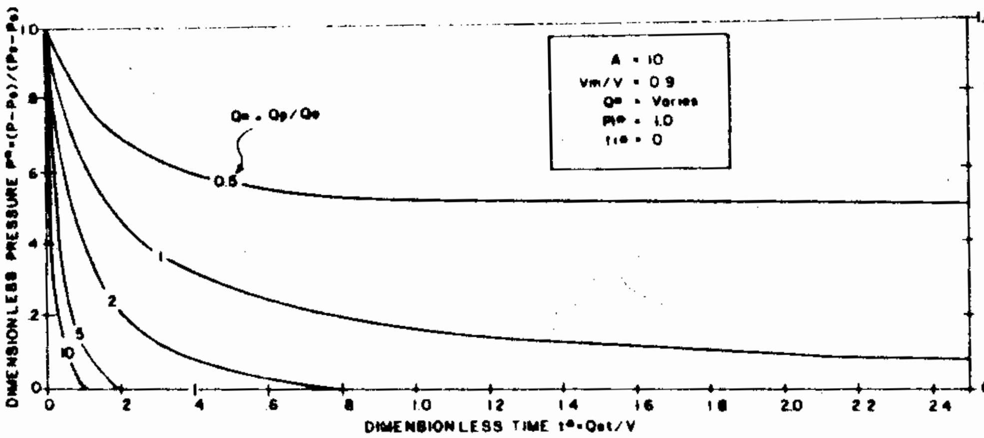


Figure 7
PLOT OF MINE DEWATERING FOR VARIOUS PUMPING RATES

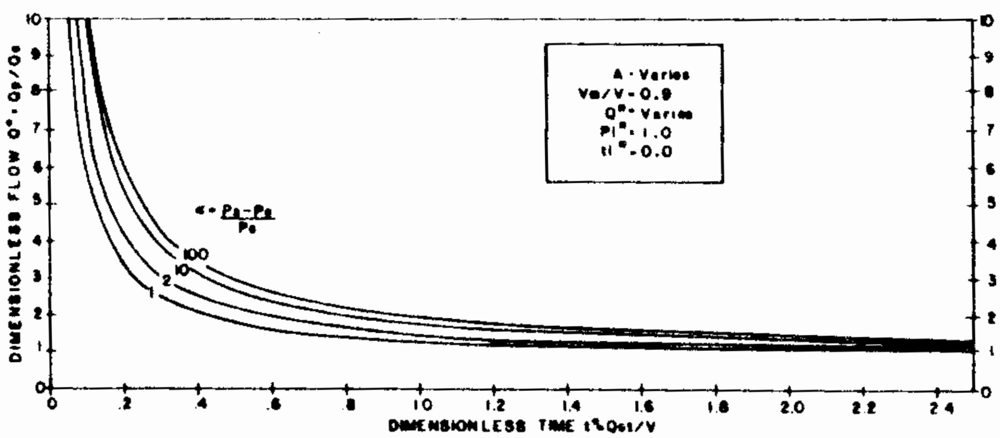


Figure 8
TIME REQUIRED TO DRAIN MINE FOR VARIOUS PUMPING RATES AND DEPTHS

APPENDIX A

ANALYSIS OF MINE FLOODING AND DEWATERING

A1 INTRODUCTION

As a mine floods, two basic phenomena are occuring simultaneously. First, the inflow to the mine traps and compresses the air in the mine. Second, some of the inflow flows up the shaft(s), in such a way as to equilibrate the air pressure trapped in the mine. This analysis develops the functional relationship between the air pressure in the mine and time, given initial inflow and the geometric conditions.

A2 MODEL

The model which is analysed is defined on Figure A1. A number of assumptions are made to simplify the analysis.

- The height of the mine is small compared with the length of the shaft.
- The air is trapped in the mine--it neither dissolves nor escapes.
- The shaft is of constant cross-sectional area.
- The water table is constant during the fill-up.
- Water is incompressible.
- Resistance to flow in the shaft, drift and mine is negligible.

A3 ANALYSIS

A3.1 Dimensionless Pressure Parameters

Several dimensionless parameters will be used in the following analysis in order to simplify and generalize results. These parameters are introduced here.

The first is a parameter to describe the pressure of fluid in the mine (both air and water). It is defined as

$$P^* = \frac{P - Po}{Ps - Po} \qquad (1)$$

when P^* = dimensionless pressure

P = pressure in the mine

Po = minimum pressure in the mine (atmospheric)

Ps = final static pressure

It is also convenient to have a ratio which expresses the pressure change between initial and final as a function of the initial pressure. Thus we define

$$\alpha = \frac{Ps - Po}{Po} \qquad (2)$$

This represents the maximum pressure change in the mine, expressed in atmospheres.

Two useful relationships which follow from these equations are

$$P = Po\ (1 + \alpha P^*) \qquad (3)$$

and

$$1 - P^* = \frac{Ps - P}{Ps - Po} \qquad (4)$$

A.3.2 Dimensionless Time Parameters

It is also convenient to use a dimensionless time parameter to describe the system. After some experimentation, a suitable parameter can be found by comparing the actual time to the time taken to fill the mine and shaft completely with water if the inflow rate remained at its initial rate throughout. Referring to Figure A1, we can thus define dimensionless time as

$$t^* = Qo\ t/V \qquad (5)$$

where t^* = dimensionless time

Qo = flow to mine at $t = o$

t = time since flooding started

V = total volume of shaft and mine

A3.3 Inflow to the Mine

The inflow to the mine is a function of the difference between the pressure in the mine and the static pressure at final equilibrium.

Thus: $Q = Qo\ (Ps-P)/(Ps-Po)$ (6)

where Q = flow to the mine

Qo = initial flow to the mine

In terms of the dimensionless parameters,

$$Q = Qo\ (1-P^*) \tag{7}$$

A3.4 Pumping from the Mine

We also need to include the effect of pumping from the mine in order to allow analysis of dewatering subsequent to the flooding. If we assume constant rate pumping from the mine, we have that total inflow into the mine/shaft system is

$$Q = Qo\ (1-P^*) - Qp \tag{8}$$

when Qp = flow pumped from mine (const). To render this dimensionless, it is convenient to define

$$Q^* = Qp/Qo \tag{9}$$

Then equation 8 becomes

$$Q = Qo\ (1 - P^* - Q^*) \tag{10}$$

A3.5 Compression of Gas in the Mine

As water flows into the mine the air in the mine is compressed as the pressure rises. Assuming an ideal gas, we have that

$$P\ Va = Po\ Vm \tag{11}$$

where

Va = volume of air in the mine at time $t = t$

Vm = volume of air in the mine at time $t = o$

Converting to dimensionless pressure using equation (4) gives

$$Va = \frac{Vm}{(1 + \alpha P^*)} \tag{12}$$

It is useful later to have this in differential form.

Differentiating with respect to P* produces

$$dVa = - \frac{\alpha\ Vm\ dP^*}{(1 + \alpha P^*)^2} \tag{13}$$

As the change in volume of air is equal and opposite to the change in volume of water in the mine, we have that

$$-dVm = \frac{\alpha\ Vm\ dP^*}{(1 + \alpha P^*)^2} \qquad (14)$$

A3.6 Pressure Equilibrium

As a result of the assumption that the head loss due to flow in the shaft, connecting drift, and mine are negligible, we have that the water pressure in the shaft at the mine elevation is the same as the mine air and water pressure. Thus

$$\rho gh + Po = P \qquad (15)$$

Substituting dimensionless parameters and rearranging produces

$$h = \alpha\ Po\ P^*/\rho g \qquad (16)$$

Later it is useful to have this equation in differential form:

$$dh = \frac{\alpha\ Po}{\rho g}\ dP^* \qquad (17)$$

A3.7 Basic Differential Equation of the System

The behavior of the system can be best evaluated by injecting an incremental volume of water into the mine. This causes an incremental increase in the water level in the shaft and an incremental compression of the air in the mine.

This partitioning of the injected water is illustrated by the hatched volumes in Figure 1. Algebraically, the conservation of mass requires that

$$dV = dVs + dVm \qquad (18)$$

Now from the geometry of the shaft,

$$dVs = As\ dh \qquad (19)$$

where As = area of the shaft.

From equation (17) we therefore conclude that

$$dVs = \frac{\alpha\ Po\ As}{\rho g}\ dP^* \qquad (20)$$

Substituting equations (14) and (20) in equation (18) and simplifying produces

$$dV = \left\{\frac{Po\ As}{\rho g} + \frac{Vm}{(1 + \alpha P^*)^2}\right\} \alpha dP^* \qquad (21)$$

By the definition of flow

$$\frac{dV}{dt} = Q \qquad (22)$$

Therefore substituting equation (10) in equation (22) and the result into equation (21) produces

$$Qs\ (1 - P^* - Q^*) = \left\{\frac{Po\ As}{\rho g} + \frac{Vm}{(1+\alpha P^*)^2}\right\} \alpha\, \frac{dP^*}{dt} \qquad (23)$$

This equation can be simplified by noting that the volume of the shaft is given by

$$Vs = H\ As \qquad (24)$$

Now as the pressure at the base of the shaft is Ps when h = H, and is Po when h = 0, so that

$$\rho g H + Po = Ps \qquad (25)$$

Combining equations (24) and (25) gives

$$Vs = (Ps - Po)\ As/\rho g \qquad (26)$$

This can be simplified by using equation (2) to give

$$Vs = \frac{\alpha Po\ As}{\rho g} \qquad (27)$$

Combining equations (23) and (27) gives

$$Qo\ (1 - P^* - Q^*) = \left\{Vs + \frac{\alpha Vm}{(1+\alpha P^*)^2}\right\} \frac{dP^*}{dt} \qquad (28)$$

Rearranging gives

$$\frac{dt}{dP^*} = \frac{1}{Qo\ (1 - P^* - Q^*)} \left\{Vs + \frac{\alpha Vm}{(1+2P^*)^2}\right\} \qquad (29)$$

Dividing by the total volume V where

$$V = Vs + Vm \qquad (30)$$

gives the final differential equation

$$\frac{Qo}{V}\ \frac{dt}{dP^*} = \frac{1}{(1 - P^* - Q^*)} \left\{\frac{Vs}{V} + \frac{\alpha}{(1+\alpha P^*)^2}\ \frac{Vm}{V}\right\} \qquad (31)$$

A3.8 Solution of the Differential Equation

The solution of the differential equation requires separation of the variables and integration:

$$\frac{Qo}{V}\int dt = \frac{Vs}{V}\int\frac{dP^*}{(1 - P^* - Q^*)} + \alpha\,\frac{Vm}{V}\int\frac{dP^*}{(1 - P^* - Q^*)(1+\alpha P^*)^2} \quad (32)$$

The only problem here is integration of the second term on the right hand side, which requires factorizing the expression and integrating each factor. After this has been performed the solution is

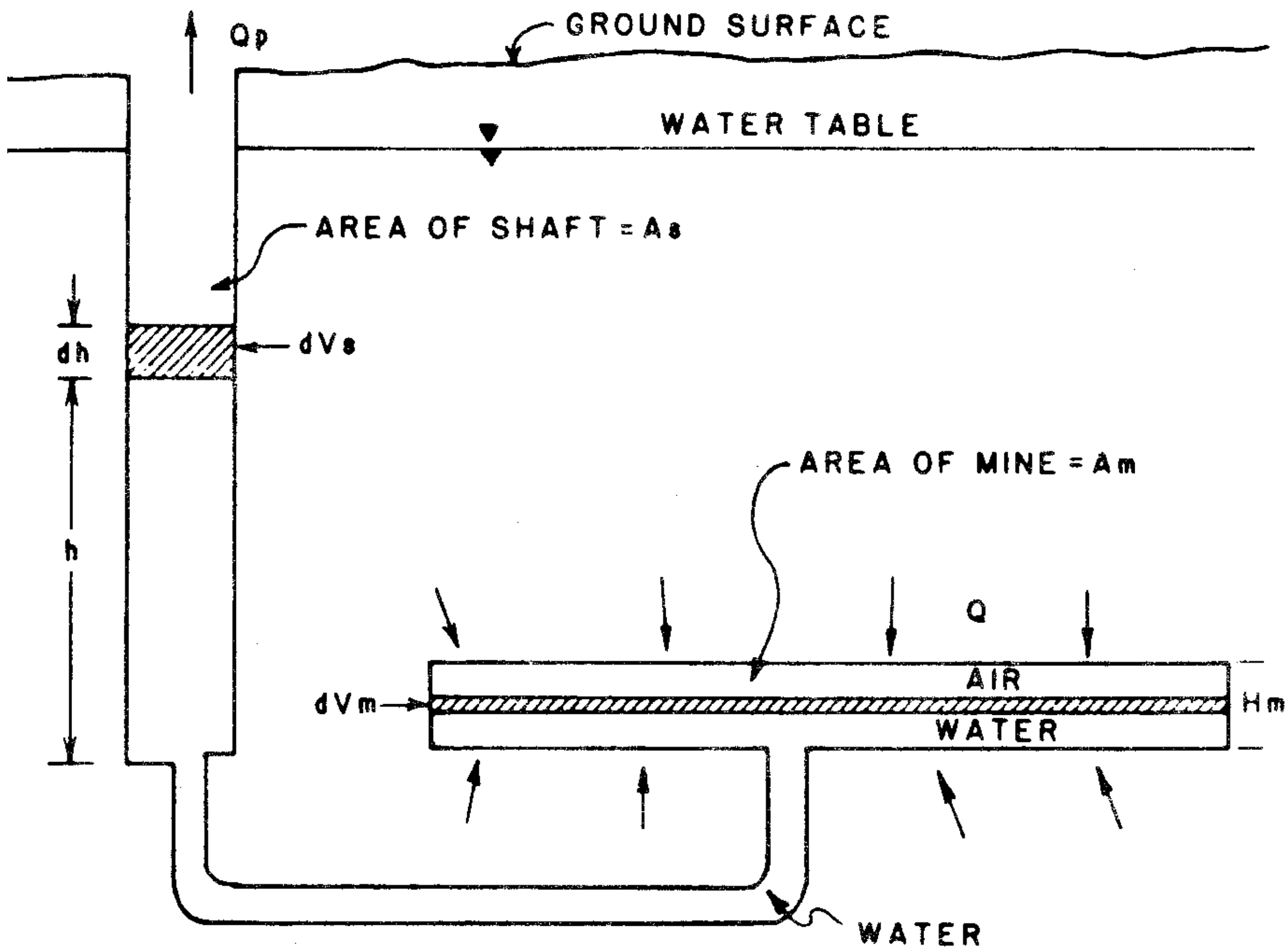
$$t^* = -\frac{Vs}{V}\ln|1 - P^* - Q^*| - \frac{\alpha Vm}{V(1+\alpha-\alpha Q^*)(1+\alpha P^*)}$$

$$-\frac{\alpha Vm}{Vs\ (1+\alpha-\alpha Q^*)^2}\left\{\ln|1 - P^* - Q^*| - \ln\ (1+\alpha P^*)\right\}$$

$$+ \text{ constant} \quad (33)$$

Note that this equation has an apparent singularity when $1 + \alpha - \alpha Q^* = 0$. However t^* is in fact continuous through this point, and the value can be found by computing t^* for an infinitesimally different value of Q^* or α.

H



NOTES: 1. Original Volume of Mine = Vm
2. Original Air Pressure in Mine = Po
3. Present Volume, Pressure in Mine = Va, P
4. Mine height is negligible compared with shaft.
5. Analysis assumes connecting drift starts full.
6. Inflow is assumed to be to mine (although this is not an important restriction).
7. Resistance to flow in shaft, drift, and mine is negligible.
8. Water table assumed static.

Figure A I

MINE FLOODING MODEL

NOMENCLATURE

Am	Area of the mine
As	Area of the shaft
dh	Infinitesimal change in water level in the shaft
dP*	Incremental dimensionless pressure change
dV	Incremental total volume change
dVa	Incremental volume of air in mine
dVm	Infinitesimal change in volume in the mine
g	Acceleration due to gravity
H	Equilibrium water depth in shaft (to mine level)
h	Height of water in the shaft at time t
Po	Atmospheric pressure
Ps	Final pressure in mine at static equilibrium with no pumping
P*	Dimensionless pressure = (P-Po)/(Ps-Po)
Q	Inflow to the mine
Qo	Inflow to mine prior to flooding
Qp	Steady pumped flow from mine
Q*	Dimensionless steady pumped flow from mine = Qp/Qo
t	Generalized time since flooding or dewatering started
t*	Dimensionless time = Qo t/V
V	Total volume of mine/shaft complex available to be flooded = Vs + Vm
Va	Volume of air in mine
Vm	Volume of mine
Vs	Volume of shaft
α	Static pressure ratio = (Ps-Po)/Po
ρ	Density of water