FIELD PROCEDURES MANUAL
GAS TRANSFER MEASUREMENTS

WASTE ROCK, HEATH STEELE
NEW BRUNSWICK

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WASTE ROCK PILES
HEATH STEELE MINES
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EXECUTIVE SUMMARY

Oxidation of pyritic waste rock and the subsequent generation of acid mine drainage (AMD) is controlled to a large extent by the availability and transport of oxygen to the reaction sites. An understanding of the interaction of the gas transfer mechanisms within a waste rock pile is key to developing cost effective management strategies to control AMD.

The purpose of this document is to provide the rationale and description of the various techniques and procedures proven to be effective for measuring the bulk physical parameters of 1) thermal conductivity, 2) gas diffusion, and 3) gas permeability which are recognized as being the principal parameters required to define gas transfer. Measurement of thermal conductivities provides a means for determining oxidation rates from measured temperature distributions since oxidation, being exothermic, leads to a temperature rise which in turn relates to the thermal conductivity of the bulk material. To reach oxidation sites within the waste rock piles, oxygen must flow through available pore spaces. There are two mechanisms which lead to this flow through gas filled pore space. The first is diffusion where the flux results from the oxygen gradient consequent on oxygen consumed in the oxidation process. The second, addressed through the measurement of gas permeability, is advection where the flux results from a pressure gradient set up in the pile.

In addition, techniques and procedures are provided in the report for monitoring temperature and oxygen concentrations within the pile. Since the pyritic oxidation reaction consumes oxygen and generates heat, measurement of oxygen concentrations and temperature profiles within a waste rock pile can provide insight into the oxidation process and the pollution potential from waste rock material.

This document provides details of field installations and procedural guidelines for the measurement and monitoring of these principal gas transfer mechanisms associated with waste rock oxidation. Section 1 provides a general introduction. Section 2 provides the scientific background to the techniques used for in situ measurements of the key bulk physical parameters (thermal conductivity, gas diffusion, gas permeability). Section 3 outlines the field installation techniques and instrumentation required while Section 4 outlines how the measurements are carried out and gives general guidance to data interpretation. The details of the measurement techniques, instrumentation and data reduction to obtain the bulk parameters are contained in the appendices. These appendices are sufficiently detailed to be used in the field as selfstanding guides.

Computer models such as FIDHELM (developed by Australian Nuclear Science and Technology Organization, ANSTO) can be used to predict the impact of pyritic waste rock oxidation processes as well as evaluate various options for controlling acid drainage contamination. The measured field parameters described in this report are required as inputs to the model.

RÉSUMÉ

L'oxydation de la roche stérile pyriteuse et la production ultérieure de drainage minier acide (DMA) sont dans une large mesure régies par la disponibilité de l'oxygène et son transport jusqu'aux sites des réactions chimiques. Il est essentiel de comprendre l'interaction des mécanismes des échanges gazeux survenant dans une halde de stériles, pour pouvoir élaborer des stratégies rentables de gestion permettant de réduire la formation du drainage minier acide.

Dans ce document, on cherche à donner une explication et une description des divers procédés et techniques qui se sont avérés efficaces pour mesurer les paramètres physiques d'ensemble 1) de la conductivité thermique, 2) de la diffusion des gaz et 3) de la perméabilité aux gaz; ce sont les principaux paramètres reconnus comme nécessaires pour définir les échanges gazeux. La mesure des conductivités thermiques fournit un moyen de détermination des vitesses d'oxydation à partir des distributions des températures mesurées, puisque l'oxydation, étant exothermique, produit une hausse de la température qui, à son tour, affecte la conductivité thermique du matériau d'ensemble. Pour atteindre les sites d'oxydation à l'intérieur des haldes, l'oxygène doit s'écouler par les espaces poreux existants. Il existe deux mécanismes permettant cet écoulement à travers des espaces poreux remplis de gaz. Le premier est la diffusion, ou cours duquel le courant gazeux résulte du gradient d'oxygène produit par la consommation d'oxygène lors des processus d'oxydation. Le second, étudié par la mesure de la perméabilité aux gaz, est l'advection. Dans ce cas, le courant est produit par un gradient de pression établi dans la halde.

En outre, ce rapport présente des techniques et procédés de surveillance de la température et des concentrations d'oxygène dans la halde. Puisque les réactions d'oxydation de la pyrite consomment de l'oxygène et génèrent de la chaleur, la mesure des concentrations d'oxygène et des profils de température dans une halde peuvent nous renseigner sur les processus d'oxydation et sur le potentiel polluant des stériles.

Dans ce document, sont présentés des détails des installations sur le terrain et des directives sur les procédés de mesure et de surveillance des principaux mécanismes d'échanges gazeux associés à l'oxydation des stériles. La section 1 constitue une introduction générale. La section 2 donne le contexte scientifique des techniques utilisées pour mesurer in situ les paramètres physiques essentiels d'ensemble (conductivité thermique, diffusion des gaz, perméabilité aux gaz). Dans la section 3, sont esquissées les techniques d'installation sur le terrain et l'appareillage requis; la section 4 nous indique la manière dont les mesures sont effectuées et nous guide de façon générale dans l'interprétation des données. Les annexes contiennent les détails des techniques de mesure, de l'appareillage et de la réduction des données, qui permettront d'obtenir les paramètres d'ensemble. Ces annexes sont suffisamment détaillées pour pouvoir servir sur le terrain de guides complets.

Des modèles informatiques tels que le FIDHELM (élaboré par l'Australian Nuclear Science and Technology Organization, ANSTO) peuvent servir à prédire l'impact des processus d'oxydation des roches stériles pyriteuses et à évaluer diverses options en matière de réduction de la pollution par les eaux de mine acides. Les paramètres mesurés sur le terrain, et décrits dans ce rapport, sont des données d'entrée nécessaires à l'élaboration du modèle.

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1. INTRODUCTION

1.1. Purpose

Current research has shown that the oxidation of pyritic waste rock and the subsequent generation of acid mine drainage (AMD) is controlled to a large extent by the availability and transport of oxygen to the reaction sites. Consequently, an understanding of the interaction of the gas transfer mechanisms within a waste rock pile is key to developing cost effective management solutions for the control of acid drainage from pyritic waste rock.

This document provides details of field installations and procedural guidelines for the measurement and monitoring of the principal gas transfer mechanisms associated with the oxidation of pyritic waste rock. The purpose of this document is to provide the rationale and description of the various techniques and procedures proven to be effective for measuring the bulk physical parameters of gas diffusion, gas permeability and thermal conductivity which are recognized as being the principal parameters required to define gas transfer. In addition, techniques and procedures are provided in the report for monitoring temperature and oxygen concentrations within the pile. Temperature and oxygen concentrations are key indicators of the rate of the oxidation reaction.

Computer models such as FIDHELM (developed by Australian Nuclear Science and Technology Organization (ANSTO) can be used to predict the impact of pyritic waste rock oxidization processes as well as evaluate various options for controlling acid drainage contamination. The measured field parameters described in this report are required as inputs to the model.

1.2. Rationale for Gas Transfer Measurements

The oxidation of iron pyrite (FeS_2) is central to the generation of acid drainage from pyritic mine wastes. The process leads directly to the generation of acid and is responsible for the conversion of largely insoluble metal sulphides to metal sulphates which are much more soluble, particularly under acid conditions. The oxidation of iron pyrite requires oxygen and water and, being exothermic, generates heat as well as acid.

There are three principal factors that govern the rate of oxidation of pyrite rock, namely:

- availability of oxygen
- availability of water
- biomass of catalyzing bacteria

For a typical pyritic mine waste dump, the mass of oxygen required to oxidize all the pyritic material is about a thousand times greater than the oxygen initially available in the pore space of the pile, while the water required is only about a tenth of that available in the pore space (Tables 1 and 2). Thus for complete oxidation of pyritic wastes, oxygen needs to flow from the surface of the wastes (where it is available in air) to oxidation sites within the wastes. A slow rate of oxygen supply from the surface leads to a low oxidation rate and hence a low rate of generation of contaminants within the wastes.

Table 1 Physical Properties of a Dump of Mine Waste

Symbol	Definition	Value	Units
L	Dump Height	15	m
A	Dump Area	25	ha
ρ_r	Bulk Density of Dump Material	1500	kg m^{-3}
ρ_{rs}	Sulphur Density as pyrite	30 (2%)	kg m^{-3}
q	Infiltration Rate	0.5	m y^{-1}
ε_a	The porosity of the dumped material	0.40	
ε_w	Water filed porosity at specified infiltration	0.10	
K_g	Saturated hydraulic conductivity of dump	10	m d^{-1}
D_a	Oxygen diffusion coefficient in the dump	$5x10^{-6}$	m2 s^{-1}
μ_o	Oxygen Concentration in Air	0.265	kg m^{-3}
ε	Mass of oxygen consumed per unit mass of sulphur oxidized	1.75	

Table 2 Typical Time Scales Associated with Pyritic Oxidation in a Dump of Mine Waste

	Intrinsic Oxidation Rate (kg of oxygen m^{-3} s^{-1})		
	low $1x10^{-8}$	medium $10x10^{-8}$	high $100x10^{-8}$
Time to use up initial pore space oxygen	92 d	9.2 d	0.92 d
Time to oxidize all the pyrite	166 y	150 y	142 y

Mass of oxygen required to oxidize pyrite	200,000 t
Mass of oxygen initially in the pore space of the waste	300 t
Mass of water required to oxidize pyrite	32,000 t
Mass of water initially in the pore space of the wastes	375,000 t
Time to oxidize all the pyrite if the intrinsic oxidation rate is infinitely high	142 y
Time to completely oxidize a 4 mm diameter particle assuming a shrinking core model	66 d
Time for bacterial population to increase by a factor of one million	about 20 d
Time for flow at base to respond to an increased infiltration rate at surface	about 1 d
Transit time for water from top to base of dump if whole depth is unsaturated	about 3 y
Transit time for water to pass along the length of the base if the base is saturated	about 5 y

To reach the oxidation sites oxygen must flow through the pore space of the wastes. While there is a flux of oxygen into the waste pile from the oxygen dissolved in water infiltrating the surface of the pile, this flux is typically a thousand times lower than the oxygen flux through the gas filled pore space. There are two mechanisms which lead to oxygen flow through the gas filled pore space, namely diffusion and advection. The oxygen gradient which results from the oxygen consumation in the oxidation process produces a diffuser flux. Advection flux results from a pressure gradient set up in the waste pile such as that which can result from temperature gradients in the waste dump due to heat released in the oxidation process. This form of advection is usually termed convection and has been observed in a number of waste rock dumps (Harries and Ritchie 1981, Furlotte et al. 1991). In principle, pressure gradients resulting from wind driven air flow over the dump surface should be high enough to generate significant advective gas fluxes within the dump. In practice, there has been no quantitative evidence to date to show that such a process occurs.

It has been shown that diffusion of oxygen through the gas filled pore space supports oxidation at a rate high enough to explain the generation of contaminants in the leachate from a pyritic waste rock dump (Ritchie 1977, Harries and Ritchie 1981, Davis and Ritchie 1986). It has also been shown that convection also supports oxidation rates at an environmentally significant level (Harries and Ritchie 1981, Pantelis and Ritchie 1992). Pantelis and Ritchie have further indicated that at air permeabilities below about 10^{-9} m^2, diffusive transport of oxygen dominates over convective transport in determining the overall oxidation rate in large dumps of waste rock.

The magnitude of the diffusive flux is determined in part by the oxygen concentration gradient and in part by the gas diffusion coefficient (units of m^2/s) of the waste rock pile. Similarly, the advective flux is determined in part by the pressure gradient and in part by the gas permeability (units of m^2) of the waste rock pile. Hence, if the oxygen flux through the pore space of the waste dump is to be quantified, both the gas diffusion coefficient and the gas permeability of the waste rock pile need to be evaluated. Both are bulk physical properties of the waste rock pile in the sense that both are functions of the porosity and of the geometry of the porosity (often called the tortuosity). While reasonable estimates can be obtained for both parameters from soil physics literature, the only reliable evaluation is by in situ measurement.

Whereas the oxygen flux through the waste rock pile depends on the magnitude of the gas diffusion coefficient and the gas permeability of the pile, the heat flux, and hence the temperature gradient, depends on the thermal conductivity of the waste pile. Thermal conductivity is also a bulk physical property of a waste rock pile which is most reliably evaluated by field measurement.

While a pile of mine waste, particularly waste rock, is expected to be heterogeneous with respect to composition and size distribution, experience has shown that the bulk physical parameters of gas diffusion coefficient, gas permeability and thermal conductivity are well defined and slowly varying parameters over a length scale appropriate to the evaluation of oxidation rates, and hence pollution generation rates, in piles of pyritic mine wastes. Moreover, in many situations, the oxidation process in a large pile is essentially one dimensional. In such a situation, a knowledge of the gas diffusion coefficient and the thermal conductivity allows the intrinsic oxidation rate of the waste material to be evaluated from measured oxygen and temperature profiles. With a knowledge of the intrinsic oxidation rate and the bulk physical parameters, it is possible to predict the overall oxidation rate in the waste rock pile over the long term.

1.3. Manual Outline

The following sections of this "Field Procedures Manual" describe the methodology, and procedures for measurement of the various parameters within a waste rock pile essential to understanding the pollution generation potential of waste rock material.

- Section 1 provides a general introduction to the topic
- Section 2 provides the scientific background to the techniques used for in situ measurements of the three key bulk physical parameters, namely gas diffusion, gas permeability and thermal conductivity.
- Section 3 outlines the field installation techniques and instrumentation required for the measurements, while

- Section 4 outlines how the measurements are carried out and, in the case of the oxygen and temperature measurements, provides general guidance to interpretation of the field data.

The details of the measurement techniques, instrumentation and data reduction to obtain the bulk parameters are contained in the appendices. These appendices are sufficiently detailed to be used in the field as selfstanding guides to the establishment of measurement systems and protocols. There is a degree of overlap between the body of the report and the appendices.

2. MEASUREMENT METHODOLOGIES

2.1. Oxygen/Temperatures

Since the pyritic oxidation reaction consumes oxygen and generates heat, measurement of oxygen concentrations and temperature profiles within a waste rock pile can provide insight into the oxidation process and the pollution potential from waste rock material.

The measurement of pore gas oxygen concentrations within a waste rock pile can be accomplished by simply by drawing gas samples from gas-filled pores of the waste rock pile and analyzing them using a field-portable oxygen analyzer to get an accurate assessment of actual oxygen concentration. A simple system such as this has the advantages of being relatively inexpensive, easily portable and able to provide accurate data at the time of measurement.

Two different methods have been used for measuring temperatures in waste rock piles. The first requires that thermocouples be buried as fixed installations in the backfill of drilled probe holes. This provides a direct measurement of the temperature at the point in question. The second method uses a single thermistor which is lowered down a lined probe hole.. The method measures the temperature of the air column in a lined probe hole and therefore requires the air in the column to be in thermal equilibrium with the surrounding pile material. Temperature measurements from thermocouples can be measured more rapidly but provide less spatial data than can be obtained by traversing a thermistor. Harries and Ritchie (1981) who have described the measurement and interpretation of temperature profiles using thermistors, have shown that the air column in a hole of about 40 mm diameter can support a temperature gradient of at least +4°C per metre depth without any convective air movement in the hole. Hence, in most practical cases, the air in the hole is in thermal equilibrium with the surrounding pile material.

2.2. Gas Permeability

The gas permeability, K (m2), of a porous medium such as a waste rock pile is a coefficient which relates the gas convective velocity, v (m/s-1), to an applied pressure gradient and can be described by Darcy's law which in one dimension can be written as:

$$v = -\frac{K}{\mu_a}\left(\frac{\partial p}{\partial z} + \rho g\right) \tag{1}$$

where ρ, μ_a and p are the density (kg/m^3), viscosity (kg/ms) and pressure of the gas (Pa) respectively, and g is the acceleration due to gravity (m/s^2).

Gas permeability depends on the percentage, continuity and size of the gas-filled pore space within the pile. The size distribution of the pores is relevant because the flow rate depends on the dynamic viscosity of the gas. As a consequence, for a given pressure difference, there will be a disproportionately higher mass flux through larger pores compared with the smaller capillaries where wall effects have a greater influence. In the process of diffusion, all gas-filled pore spaces participate equally, irrespective of pore size. As a consequence, the dependence of gas permeability on the gas-filled porosity is much stronger than is the dependence of the gas diffusion coefficient.

The relations between gas-filled porosity, permeability and diffusion are well summarized by Hillel (1980):

> There is a fundamental difference between the functional dependence of a soils permeability (or conductivity) upon pore geometry and the corresponding function for diffusion coefficient. As the permeability pertains to pressure-induced convective-viscous flow, it obeys Poiseuille's law which states that the flow varies as the fourth power of the pore radius. Hence the permeability is strongly dependent on pore size distribution. Diffusion, on the other hand, depends primarily on the total volume and tortuosity of continuous pores available for diffusion. The reason that diffusion does not depend on pore size distribution is that the mean free path of molecules is of the order 1-5 x 10^{-7} m, which is much less than the radii of the pores which generally account for most of the soils air filled porosity.

The technique to measure gas permeability involves injecting gas into a waste rock pile at a known flow rate and measuring the resulting gas pressure rise in the material in that region; the lower the gas permeability of the material in the pile, the higher the pressure measured for a given flow rate.

Field measurements of air permeability in a number of waste rock piles at mine sites world wide have ranged from 10^{-12} to 10^{-8} m^2 with an error on individual values of generally less than ±15%.

2.3. Gas Diffusion

The constant of proportionality relating oxygen flux to oxygen concentration gradient is termed the oxygen diffusion coefficient, D_{O_2}. Direct determination of the diffusion coefficient for oxygen is difficult because the oxygen is consumed by the pyritic oxidation reactions at rates which vary in both space and time. The difficulty arises in distinguishing between changes in oxygen concentrations caused by oxygen transport from those caused by oxygen consumption. Introducing an inert tracer gas such as sulphur hexafluouride (SF_6) simplifies the task by removing this ambiguity.

The technique to measure gas diffusion coefficients in situ in waste rock piles requires two vertical probe holes to be spaced at a distance of between 1.5 and 3.5 m apart. Tracer gas is injected at some depth in one of the holes (at least three metres below the pile surface) and its subsequent arrival at the second hole is monitored. The depth and position of injection and monitoring are chosen so as to minimize the effects of pile boundaries, such as a compacted cover, or an underlying aquifer or air boundary, where rapid changes in gas diffusion properties, may complicate the analysis of field measurements. The separation between the injection and monitoring probe holes must be large enough that the gas diffuses through materials representative of the types and distribution found in the waste rock pile, but not so large that measurements have to be carried out for an extended period. For separations between 1.5 and 3.5 metres, measurements need to be made over a 2 to 3 day interval.

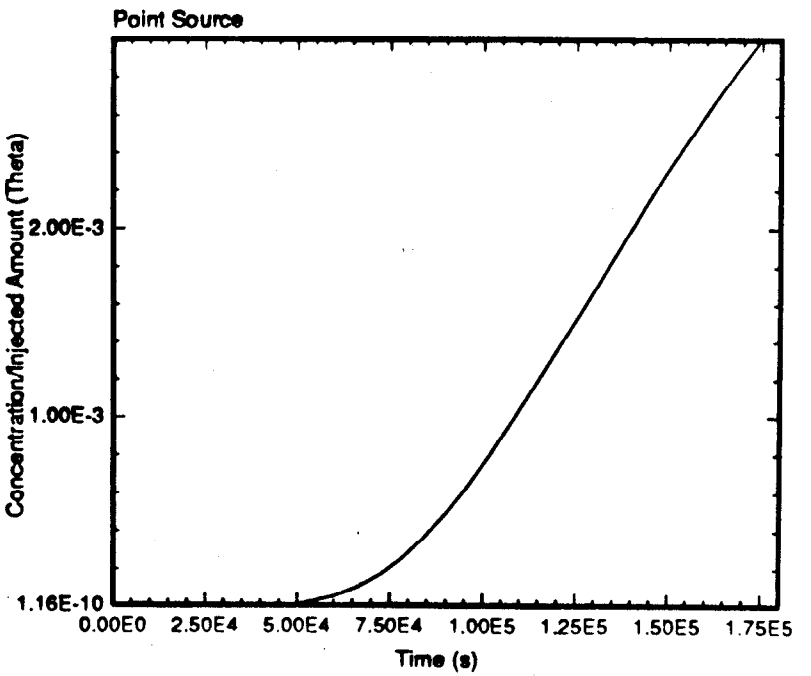
The effects of convective gas movement on the tracer concentration distribution can be complicated and difficult to separate from those of diffusion. To ensure that the tracer gas moves solely due to diffusion, the measurements should be made in regions of a pile where the magnitude of convection is expected to be small. Regions away from the sides slopes and any capped areas are most likely to be suitable.

The quantity of tracer injected; the distance between injection and measurement points; the value of the diffusion coefficient; and the measurement time all influence the tracer concentrations measured. In most circumstances the most suitable parameter to vary to ensure that the tracer concentrations lie within the measurement range of the detector is the quantity of tracer gas injected. Figure 1 is an example of how the quantity of tracer gas injected varies with time at a distance $r = 2.5$ m, and diffusion coefficient $D = 3.0 \times 10^{-6}$ m^2/s.

Tracer gas concentrations are measured by drawing gas samples from the sampling ports directly into a portable gas chromatograph (GC) which measures the quantity of SF_6 in an aliquot of known volume. The diffusion coefficient in the pile, D_{SF_6}, can then be determined for each measured SF_6 concentration at distance r and time t, knowing the initial amount of SF_6 injected. The measured SF_6 diffusion coefficient must be corrected to give the required oxygen diffusion coefficient, D_{O_2}, on the basis that both gases diffuse through a background gas which can be approximated as air. The diffusion rates of the two gases into air (subscripted a) can be found in the literature (e.g. Reible and Shair, 1982, and Washburn, 1929) and applied using the following relationship:

$$D_{O_2} = \left(\frac{D_{O_{2a}}}{D_{SF_{6a}}} \right) D_{SF_6} \qquad (2)$$

Measured values of the oxygen diffusion coefficient in waste rock piles can be expected to range from 2×10^{-6} to 4×10^{-6} m^2/s, with errors on individual values of less than ±30%.



NOLAN, DAVIS & ASSOCIATES

FIG. 1 TRACER CONCENTRATION PER UNIT AMOUNT INJECTED IN A PILE

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2.4. Thermal Conductivity

Various methods have been developed for the measurement of the thermal conductivity of soil, rocks and insulating materials. In general, the methods involve emitting heat from a line source at a constant rate and monitoring the resulting temperature rise and the subsequent temperature decrease after the heater is switched off (Blackwell 1954, Boggs et al 1980).

The heat conduction equation can be readily solved for a line source of heat to give the temperature distribution as a function of time. For a homogeneous porous medium and a continuous constant line source of heat (parallel to the z-axis passing through the point (x1,y1)), the solution to the heat conduction equation is given by

$$T(r,t) = T_0 - \frac{Q}{4\pi\lambda} E_i\left(\frac{r^2}{4\kappa t}\right) \tag{3}$$

where T is the temperature at time t, T_O is the initial temperature, κ is the thermal diffusivity, Q is the constant heat supply rate, λ is the thermal conductivity, and the radius r is given by $r = \sqrt{(x-x_1)^2 + (y-y_1)^2}$. The exponential integral E_i is defined as

$$-E_i(-\chi) = \int_{\chi}^{\infty} \frac{e^{-\mu}}{\mu} d\mu \tag{4}$$

Here, thermal diffusivity and thermal conductivity are related by the bulk density (r) and specific heat (C): $\kappa = \frac{\lambda}{\rho C}$.

For large values of t, such that $t >> \frac{r^2}{4\kappa}$, the temperature is given by

$$T(t) = T_0 + \frac{Q}{4\pi\lambda}(\ln t + \beta) \tag{5}$$

where b is a constant which can be regarded as including the effect of the thermal resistance at the interface between the pile material and a cylindrical liner surrounding the linear heat source (Jaeger, 1956).

If the heat source is switched off at ts and $(t - t_s) >> \frac{r^2}{4\kappa}$, the temperature at time t during the cooling phase ($t > t_S$) is given by

$$T(t) = T_0 + \frac{Q}{4\pi\lambda} \ln\left(\frac{t}{t - t_s}\right) \tag{6}$$

Thermal conductivity in the porous medium can be determined either from the temperature rise at the heat source using equation (3) or from the temperature decrease at the position of the heat source during cooling, after the heat is switched off, using equation (6).

Values of thermal conductivity in waste rock piles can be expected to range from 0.6 to 3.0 W/(m·K), with error on individual determinations of less than 5%.

3. FIELD INSTALLATIONS

3.1. Site Assessment

The measurement of the key bulk physical parameters related to gas transfer in waste rock piles requires the drilling of several probe holes and the subsequent installation of monitoring equipment in these holes. The location, number, depth and configuration of the these probe holes is very site specific and depends on site conditions and the monitoring objectives.

3.1.1. Temperature and Oxygen Probes

The goals of any monitoring program relating to gas transfer mechanisms must be clearly stated and understood prior to making decisions with respect to the type and number of probes and where they should be located. The rationale for locating probe holes for monitoring the rate of oxidation through change in temperature and oxygen concentration measurements in a waste rock pile differs from holes used to measure the bulk physical parameters.

The location of the probe holes for measuring temperature and oxygen should take into consideration:

- age of waste rock
- composition of waste rock
- site hydrogeology
- volume of waste rock
- budget
- regulatory requirements

It is recommended that a phased approach be taken when identifying the requirements for probe holes for temperature and oxygen measurements. The initial phase would be essentially a global approach whereby sufficient monitoring probes are located so as to provide the necessary data to characterize the site. For the initial assessment it is recommended that no fewer than three probe holes be installed at strategic locations within a waste rock pile. Additional probe holes can be added to address specific site conditions or to provide a wider coverage of the site.

The depth of the probe hole is dependant on site conditions. Where groundwater is present, the probe should be installed from the pile surface into its lowest anticipated groundwater interface to provide temperature measurements at this important boundary. Where no groundwater is present, the probe hole should extend from the ground surface to the below base of the waste rock pile. In such cases, the probe holes should be extended 1 to 2m into the underlying soils or bedrock in order to determine the continuity of the measured variables across the boundary, into the native material.

3.1.2. Air Diffusion, Air Permeability and Thermal Conductivity Probes

Research to date has shown that bulk physical parameters such as air diffusion, air permeability and thermal conductivity are properties intrinsic to the waste rock pile. Consequently the number of probe holes required to characterize a site can be less than for the oxygen/temperature measurements. For a typical waste rock site it is recommended that the bulk physical parameters be measured at a minimum of three locations, evaluated to be representative of the site. At each test location, two probe holes, spaced 1.5 - 3.5 m apart are required. The criteria for the depth of the probe holes is the same as for the oxygen/temperature probes, namely to below the lowest anticipated groundwater interface or the base of the waste rock pile. Where bulk physical parameters are to be measured, it is recommended that at least one of the two probes at each monitoring location be installed so that subsequent temperature and oxygen measurements can be recorded.

A further consideration for the depth of probe holes for the measurement of bulk physical parameters is convection. If convection is expected or suspected, it is recommended that the probe holes be drilled through the entire thickness of the pile in order to establish complete profiles. If convection is not suspected within the pile, the probe holes should be put down to 7 to 8 metres below the top surface of the waste rock piles. Generally, the older the material in the waste rock pile, the deeper the probe hole must be drilled in order to obtain representative results.

The location and depth of the probe holes is also influenced by both waste rock pile location and geometry as well as site construction characteristics. Depending upon the geometry of a waste rock pile, there may be some advantages to drilling across the pile in a transect to allow the construction of two-dimensional profiles of important physical parameters. If there are several

different generations or types of materials within the pile, the probe holes should be located to intercept each of these areas.

3.2. Drilling in Waste Rock Piles

Air rotary percussion hammer which uses air as the primary drilling fluid is the recommended drilling technique for the installation of probe holes within a waste rock pile. Air is the primary drilling fluid. Air is forced down the drill pipe and escapes through small ports at the bottom of the drill bit thereby lifting the cuttings and cooling the bit. The cuttings are blown out the top of the hole and collect at the surface around the borehole. Air rotary is favoured over other drilling techniques because it does not require the use of water or water-based drilling fluids.

The diameter of the drilled probe hole should be about 150 mm. This allows a sufficient annulus for the installation of the backfill materials without bridging down the hole. If the diameter of the hole is much larger than 150 mm, the interpretation of some of the in situ measurements is affected, in particular the thermal conductivity. The probe holes should, where possible, be drilled uncased. However, the main difficulty that may arise from drilling an uncased hole is the temporary loss of air circulation when porous sections of the waste rock are encountered during drilling. The loss of circulation will inhibit the return of drill cuttings to surface and may cause the drill stem to jam in the probe hole. In this situation it is recommended that drilling proceed slowly and that the drill stem be moved frequently up and down in the hole as the depth of hole progresses. This approach will reduce the potential for jamming.

Compressed air is the only drilling fluid recommended for use during the drilling program. The use of any other drilling fluid such as water, or polymer mud is not recommended due to the potential for these materials to alter the physical and chemical characteristics of the formation in the vicinity of the probe hole. Samples of drill cuttingss, roughly 500g per hole, should be recovered at one metre intervals throughout the drilling. The samples may subsequently be analyzed for sulphur, which is an indicator of pyritic content and tested for their acid generation/acid consumption potential

3.3. Probe Installations

The subsequent field measurement of temperature and oxygen concentrations, and/or bulk physical parameters, requires the installation of a standard 40 mm inside diameter PVC liner throughout the entire depth of drilled hole. Approximately 1.5 m of liner should be left protruding above the ground surface with water tight friction caps placed on each end of the liner. It is recommended that the liner be installed in the drilled hole prior to moving the drill rig. This is particularly important in unconsolidated deposits where sections of the hole may collapse after the drill stem has been removed, thus blocking the subsequent installation of the liner. With the drill rig on site, the hole can be redrilled removing any blockages.

The PVC liner is the conduit by which instrumentation for temperature measurements by a series of thermocouples or by a thermistor are carried out. The PVC liner is used to install the thermocouples at the various depths within a pile. Prior to inserting PVC liner in the drilled hole, thermocouples are attached to the exterior of the liner at the depths where temperature measurements are required. Thermocouples should be acid resistant and designed for burial in contact with water. Spacing of the thermocouples is dependent on a number of factors including the total depth of waste rock and the coverage of temperature profile data required. There are also physical considerations such as the number of thermocouples which can be physically attached to the exterior of the PVC liner and how the thermocouples will be read. For instance, for manual measurements it would be prudent to limit the number of thermocouples to 5 to 6 per liner to avoid possible confusion in identifying each thermocouple by field staff. On the other hand, should an automatic data logger be used, the number of thermocouples is limited only by the capacity of the data logger. For temperature measurements using a thermistor, the only requirement for installation is that the interior of the PVC liner be clean and free of any blockages which could impede the thermistor.

Gas measurements, such as oxygen or sulphur hexafluouride, require a series of 3 mm diameter nylon tubing secured to the exterior of the PVC liner. The measurement of oxygen concentrations requires one port at each depth within the probe hole. However, for the measurement of gas diffusion and gas permeability, two ports at each depth are required. In the case of two ports the nylon tubing is attached on opposite sides of the liner, starting at the base of the probe hole. The spacing of ports for gas measurement is dependent on a number of variables, the most important of which is the depth of the waste rock. To ensure that the probes are

installed and backfilled properly, it is recommended that a minimum spacing of 1 m between probes be provided.

Backfilling around the completed monitoring probe installation provides a high permeability chamber around the openings of each of the gas sampling tubing, while at the same time isolating the chambers from each another. A schematic of the recommended backfilling scheme is shown on Figures 2 and 3. In summary, for each sampling port, a 500 mm gravel pack should be installed in the borehole annulus, with the sampling port located at mid depth of the gravel. A clean sand pack should be placed above and below the gravel pack with a 50 mm bentonite seal placed above and below the sand. The thickness of the sand pack is a function of the spacing of the sampling ports. For port spacing of 1 m, a 450 m total sand pack is required while a 1.5 m spacing requires a 950 mm sand pack.

During backfilling operations, a detailed record should be maintained of the levels of backfill placed within the probe hole and the overall volumes of backfill materials placed. The data is used to determine the effective radius of the outer boundary of the backfilled chambers, which is required for the analysis of air permeability measurements. Each probe hole should be sealed with 300 to 400 mm of bentonite at surface to prevent surface water infiltration and reduce inflow of air.

A durable plate, for mounting of the sampling valve assembly at the top of the PVC liner, is required (Figure 2). The plate should be at least 1 mm thick to secure the Schraeder valves tightly to the connectors through the plate. Each of the nylon gas sampling tubes attached to the exterior of the PVC liner is terminated with a Schraeder valve. The mounting plate should be constructed from a material that is rigid and will not degrade from long term exposure to the environment. Materials such as brass, stainless steel or PVC are recommended.

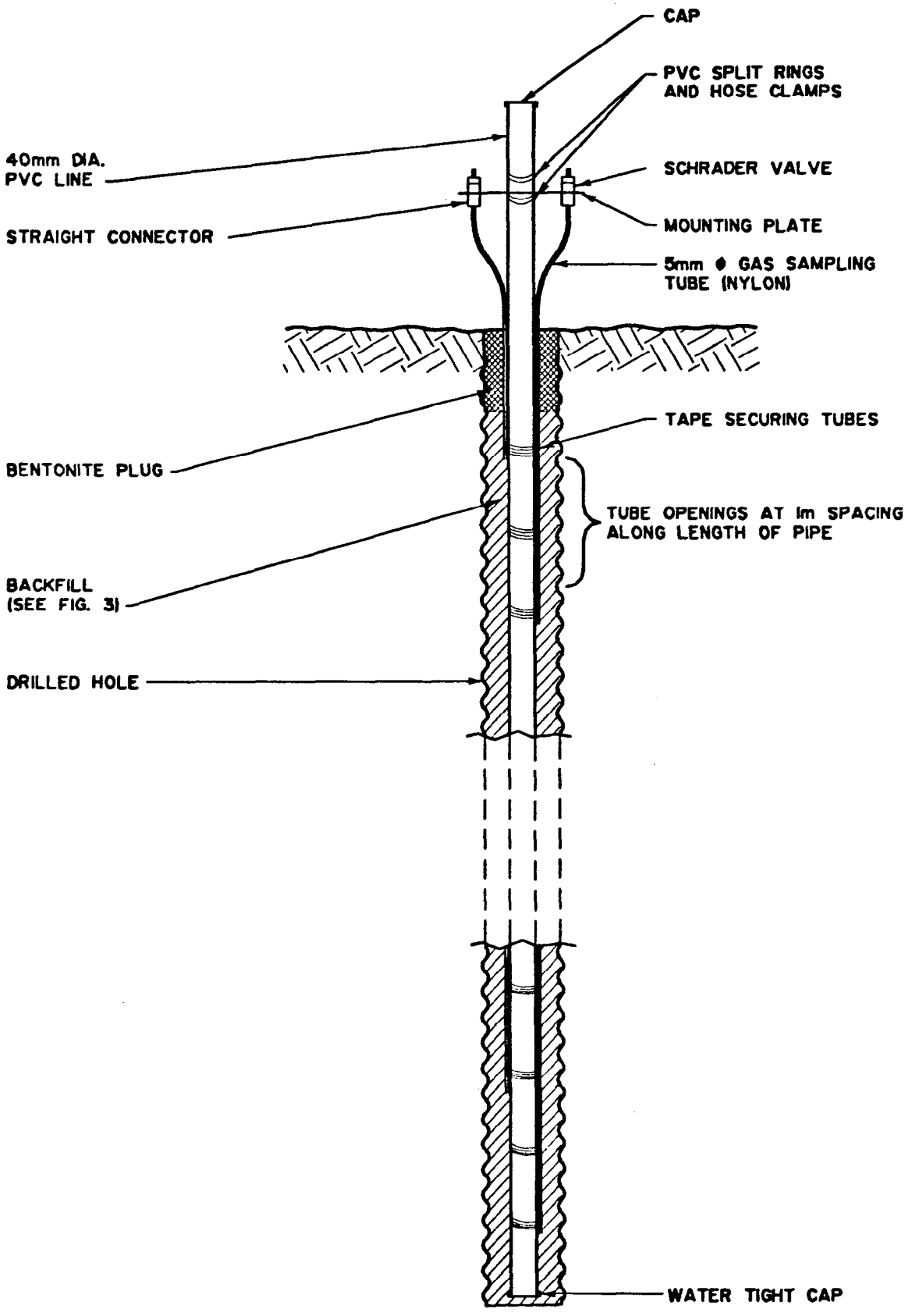

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FIG. 2 - PROBE HOLE LINER SCHEMATIC

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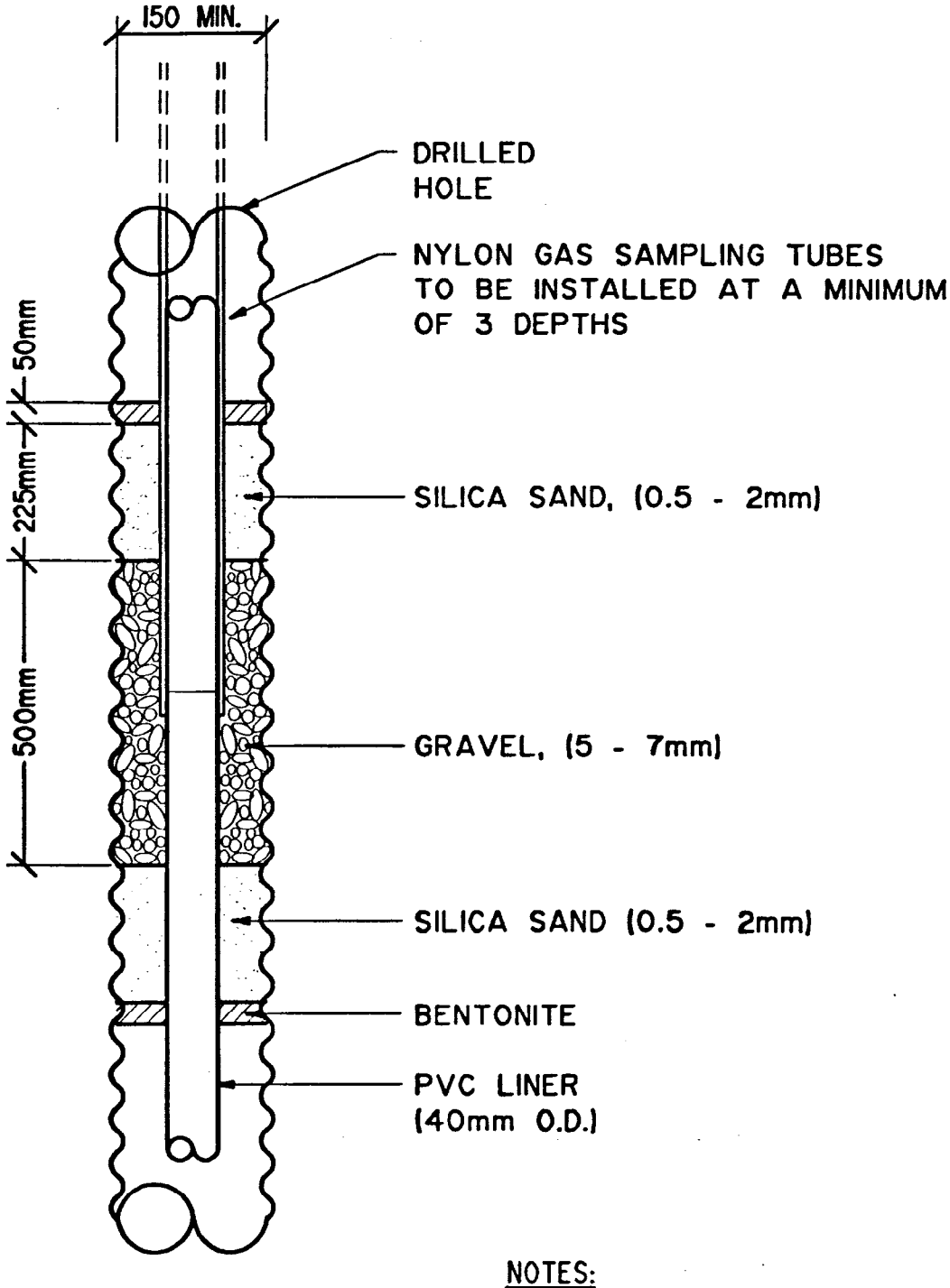

NOTES:

1. ONE TUBE ONLY REQUIRED AT EACH LEVEL FOR OXYGEN CONCENTRATION MEASUREMENTS.
2. TWO TUBES REQUIRED AT EACH LEVEL FOR AIR PERMEABILITY MEASUREMENTS.

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FIG. 3 - TYPICAL BACKFILL OXYGEN / TEMPERATURE MONITORING PROBES
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NEWCASTLE, NB

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4. INSTRUMENTATION

4.1. Oxygen/Temperature

The pore gas oxygen concentration measurement system is based on the use of commercially available portable oxygen analyzers such as Model 320B manufactured by Teledyne Analytical Instruments, which uses a micro-fuel cell to sense oxygen. Pore gas samples are collected from the nylon tubes installed in the probe holes using a vacuum hand pump and are passed over the micro fuel cell. This micro fuel cell consumes oxygen from the gas sample and generates a proportional electric current or voltage. The oxygen concentration is read directly from the instrument. Oxygen concentrations are measured to a precision of 0.01% and experience has shown this degree of precision is acceptable. A schematic of the measurement system is shown on Figure 4.

Details on procedures for making pore gas oxygen concentration measurements are provided in Appendix II along with a description of an automatic oxygen analyzer specifically for use with the type of probe hole installations specified in this field manual. The automatic analyzer is based on the same principle of operation as the Teledyne instrument, is software controlled and allows up to 21 gas ports to be sampled and analyzed automatically on a single probe hole.

Temperatures can be measured in waste rock piles using either installed thermocouples in the probe holes as fixed installations or by using a single thermistor lowered down the probe hole liner. The instrumentation for reading the temperatures is simple in both cases, being either a device to read the temperature of the thermocouple directly, or one to measure the resistance of the thermistor which can then be converted to temperature using a measured calibration relationship. Using buried thermocouples has the advantage of speed of data collection but lacks the spatial resolution which can be obtained using a thermistor, given that a thermistor can be lowered to any selected depth increments.

Appendix II describes the use of thermistors for the measurement of temperature profiles in probe holes. An automatic temperature logger which is designed to measure temperature profiles in probe holes is also described in Appendix II. The instrument is software controlled and

mechanically lowers a thermistor string down the installed liner, logging the temperature at each metre depth.

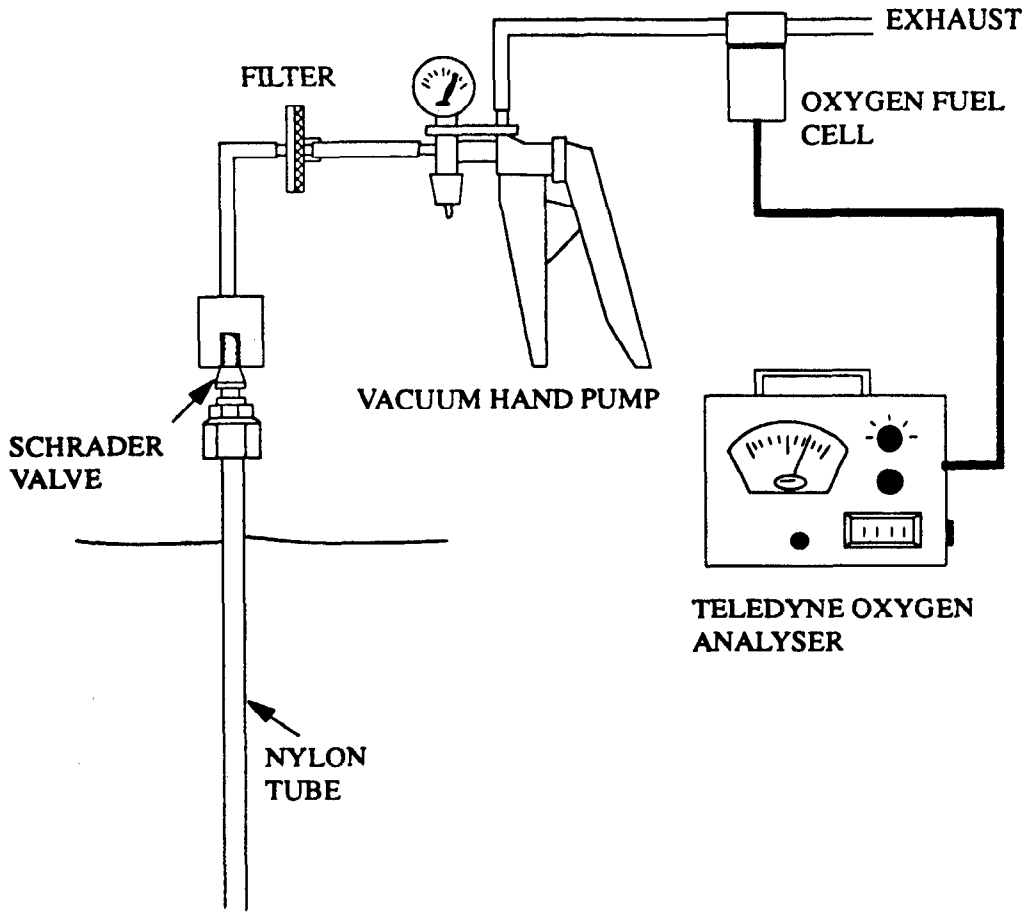

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FIG. 4 PORE GAS OXYGEN CONCENTRATION MEASURING SYSTEM SCHEMATIC

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4.2. Gas Permeability

Air permeability in waste rock is measured by introducing an air or gas such as nitrogen into the waste rock at a specific point and then recording pressure increases of other ports within the rock. The schematic arrangement used for the measurement of gas permeability and includes a schematic of the special arrangements for backfill installation is provided in Figure 5.

The air or nitrogen is introduced into the pile through the Schrader valve connectors on the 3 mm diameter nylon gas tubes with flow rates measured with an electronic flowmeter. The advantage of using nitrogen is that it does not promote oxidation in the waste rock system. The pressure rise in the vicinity of the injection point is measured with a sensitive differential pressure transducer in the nylon tube adjacent to the injection port. To check for air flow short-circuiting along the liner through the backfill and past the bentonite plugs, gas pressures are also monitored at the ports above and below the injection port. The data acquisition system links the electronic transducers to a portable DOS-based computer with floppy disk drive through an analogue-to-digital interface card. A more detailed description of the system can be found in Appendix III.

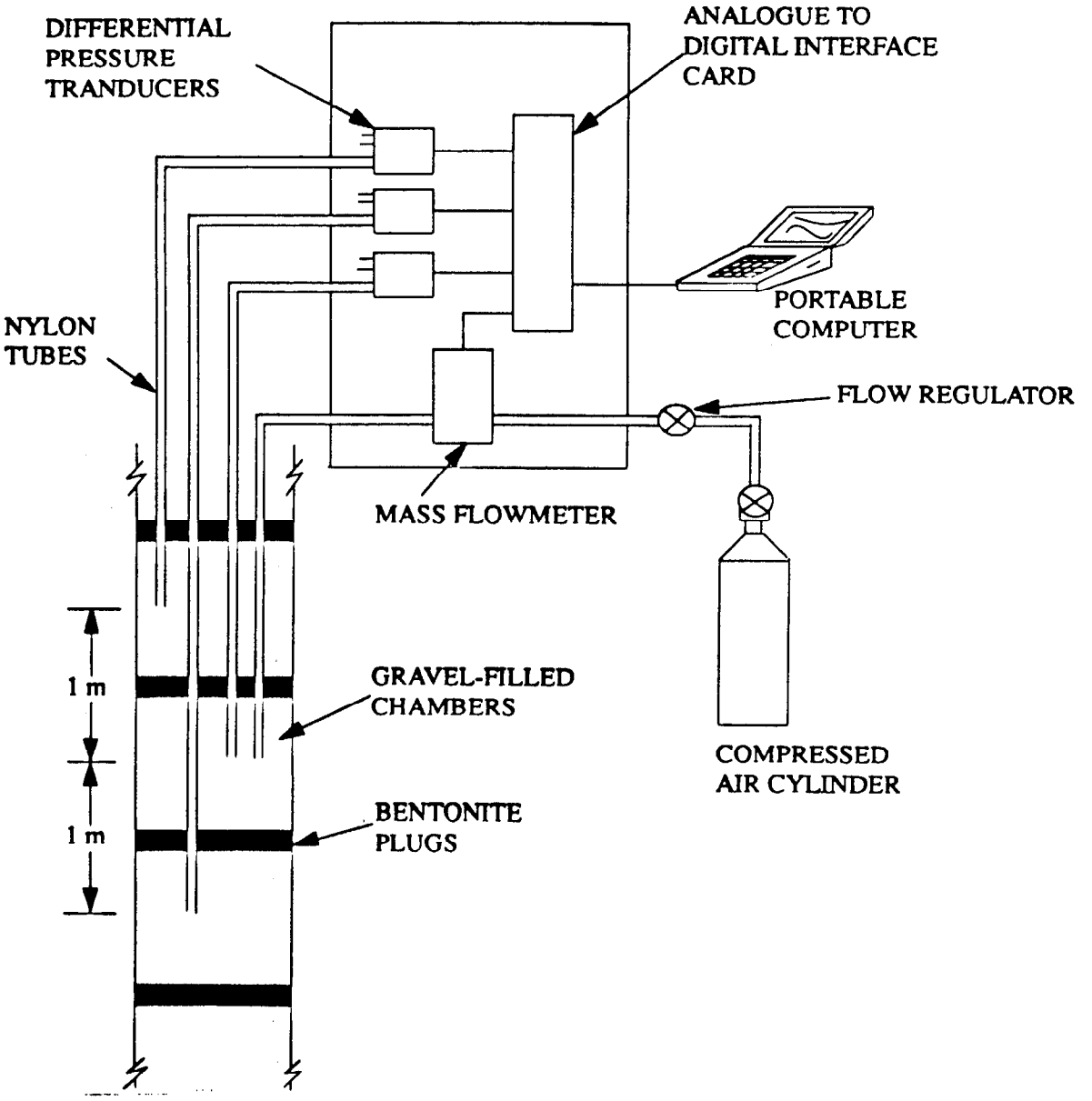

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FIG. 5 GAS PERMEABILITY MEASURING APPARATUS SCHEMATIC DIAGRAM

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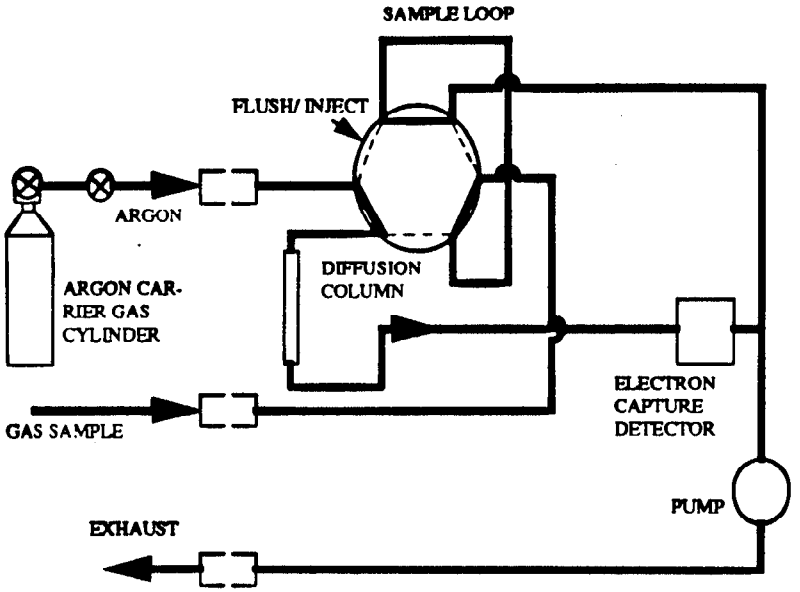
4.3. Gas Diffusion

The determination of oxygen diffusion coefficients in situ is based on the measurement of the concentration of SF_6 tracer gas. These concentrations are measured using a commercially available electron capture detector Gas Chrommitograph (GC) optimized for SF_6 detection.

Gas chromatography is a method of separating components of mixtures of volatile compounds. The principal component of the apparatus is the diffusion column. In the instrument shown on Figure 6, the column is a long stainless steel tube packed with a permeable adsorbent powder. A stream of inert gas, argon in this case, known as the carrier gas flows continuously through the column. The sample of gas is injected into the column as a slug in the carrier gas stream by means of a multi-way valve. In a mixed sample, the gas constituents are free to behave independently, depending on the characteristics of each species. For a given carrier, each constituent gas moves at a different speed, depending on its interaction with the diffusion coefficient, so they arrive at the detector at different times. The electron capture detector at the exit of the column produces a roughly Gaussian response when an electronegative gas such as oxygen or sulphur hexafluouride is introduced. Thus, the system can separate electronegative gas components in a sample if the difference between the time of arrival of these gases at the detector is great enough for the response peaks to be resolved. In the instrument described herein, oxygen arrives first, followed by SF_6 some five seconds later, and the two are well resolved. It is noted that no response by the GC to other gases in waste rock piles has been seen, making gas identification straight-forward. The concentration of SF_6 in the sample is determined by comparing the area under the relevant peak with a calibration curve.

The response of the detector needs to be calibrated against known concentrations of SF_6 in the laboratory. Data acquisition is via an analog-to-digital data acquisition board (ANSTO General Purpose Parallel Port Interface) and a portable DOS-based computer. Purpose-written software produces plots of the chromatography response after each sample is measured providing an immediate indication of the SF_6 concentration and measurement reliability.



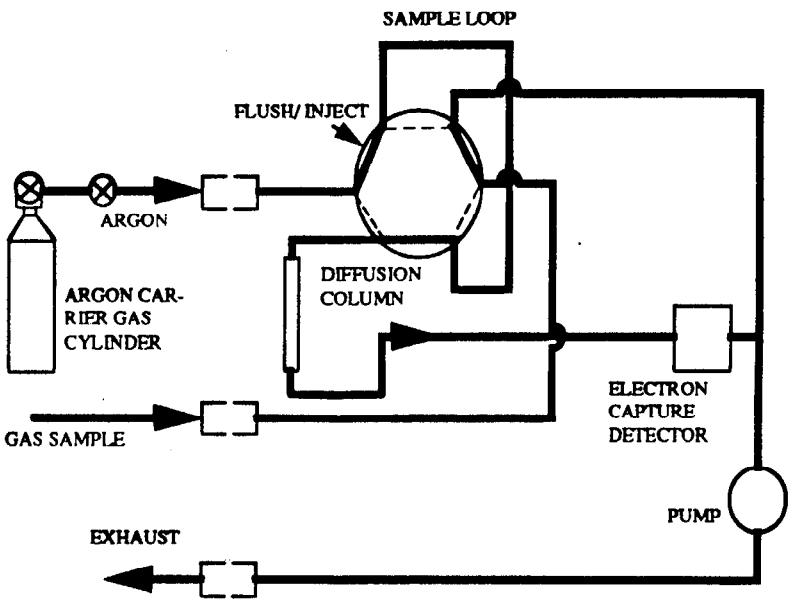


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FIG. 6 COMPONENT LAYOUT SCHEMATIC
ANSTO SF_6 DETECTION SYSTEM

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4.4. Thermal Conductivity

To measure the thermal conductivity of material deep within waste rock piles, a thermal conductivity probe has been designed to be lowered to the desired depth in the drilled probe hole liners described elsewhere. This probe is designed to have a small diameter and a large length-to-diameter ratio to minimize end effects and allow the probe to be modelled as a line source of heat. The probe is 1.15 m long and consists of eight longitudinal nichrome heating wires supported on Teflon disks mounted at 15 cm intervals along a steel rod (Figure 7). A foam strip glued around the edge of each disk provides a tight fit in the liner and prevents the convection of heat along the probe. The nichrome wires are joined in pairs at the bottom of the probe and the four pairs are connected in parallel across the regulated voltage supply. A relay in the control box is used to switch the heater on and off and is software controlled from a laptop computer.

Heat is transferred from the wires in the probe to the plastic hole liner by a combination of convection from the heated wires and conduction across the air boundary layer at the surface of the liner. The convection current generated by the heating wires results in most of the air in the vicinity of the probe reaching a relatively uniform temperature. It is expected, however, that there is a significant temperature drop across the air boundary layer at the liner wall during the heating phase. The temperature difference between the centre of the probe and the undisturbed waste rock will, however, be approximately constant during most of the heating phase provided that the power remains constant.

Three thermistors are mounted on the probe (spaced 30 cm apart) to measure temperatures in the probe hole. The resistances of the thermistors are scanned every four minutes and logged by the computer as well as the supply voltage to the probe and the time of scan. Software controls both the Datataker and the control box.

The constant voltage supplied on the probe is designed to be kept at 7 V. At this voltage, the power supplied to the probe when the heater is turned on is 6.35 W per m of probe. This heating rate is sufficient to give a significant temperature rise in the surrounding material yet low enough to avoid heat transfer by vapour transport (Blackford and Harries 1985). At this low rate of heating, the temperature at the probe after some time depends on the properties of the pile

material rather than those of the liner and the adjacent backfill materials (Blackford and Harries 1985).

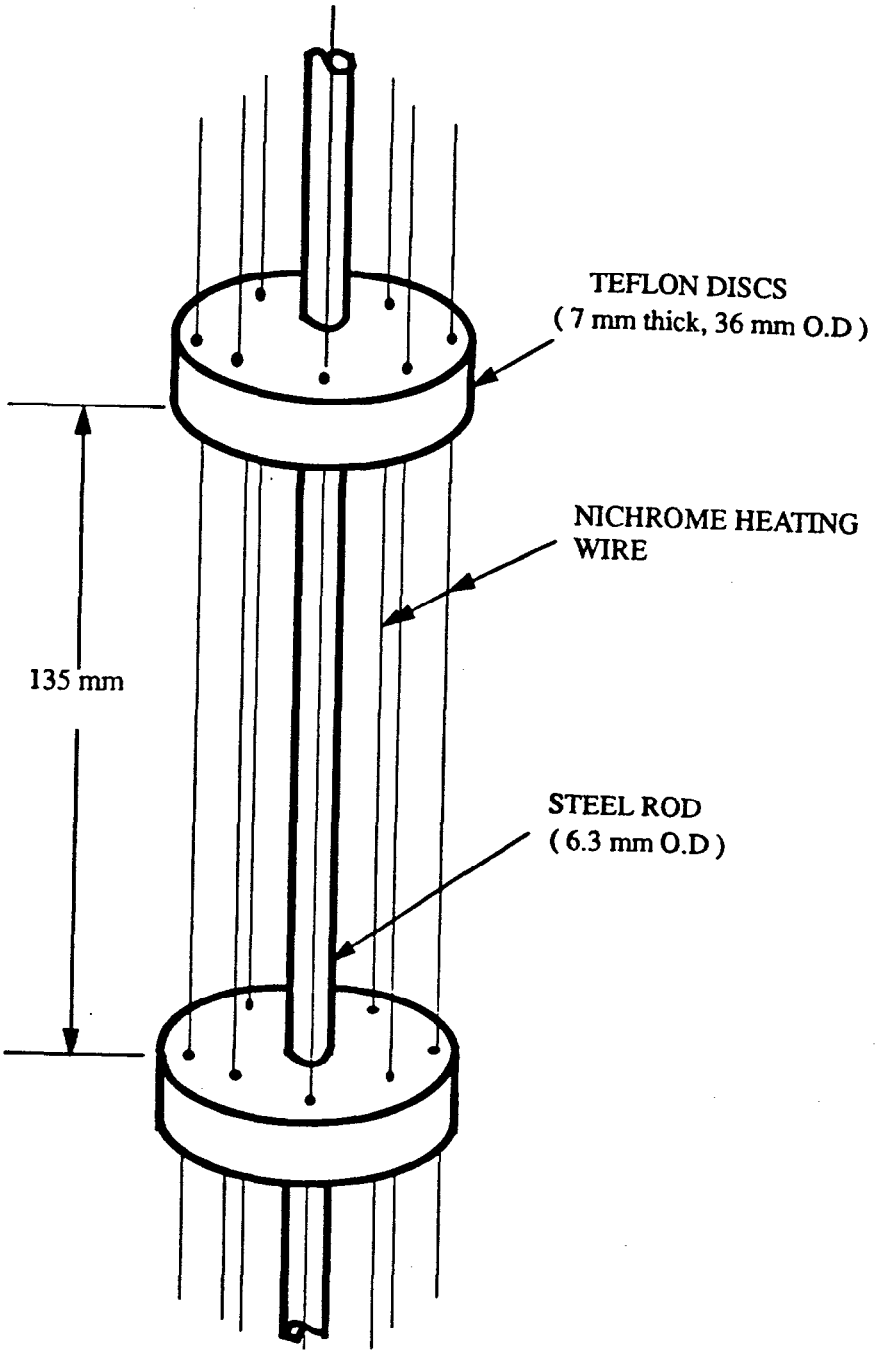

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FIG. 7 THERMAL CONDUCTIVITY PROBE SECTION

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5. FIELD MEASUREMENT AND INTERPRETATION

5.1. Oxygen/Temperature

The field measurement of both oxygen concentrations and temperatures within a waste rock pile is a very simple and cost effective approach to monitoring the oxidation process within waste rock. It should be noted however, that the two measurements are indicator measurements and are used comparatively against baseline data. The measurements by themselves do not provide a direct indication of the rate of reaction or volume of AMD being generated. However the base data can be used in conjunction with a knowledge of the bulk physical parameters, to predict these rate of reaction and volume of AMD being generated with a sophisticated computer model such as FIDHELM.

Data collected using buried thermocouples is likely to be more suitable for providing a qualitative description of processes occurring within an oxidizing waste rock pile. Thermocouples installed in backfill have the disadvantage that any failure within a pile is unlikely to be repairable. The derivation of oxidation rates from measured temperature distributions in waste rock piles requires the field data to have a high degree of accuracy. Experience has shown that such accuracy can be better achieved with thermistors.

The measurement of temperatures with thermocouples can be carried out manually using a hand held thermocouple chrometer such as a DigiSense Model BA 8528-40, or automatically through a thermocouple thermometer attached to an automated data logger. The frequency of measurement is dependent on a number of factors such as site location, fluctuation in temperature and budget. While the initial investment for a data logger system is higher than for manual measurements, over the long term, the costs of the data logger system will tend to be less than the manual system. Several other factors to consider are the location of power source for the apparatus; whether the stored data will be downloaded at the site or whether remote access through modems and telecommunication lines will be practical.

Manual measurements on the other hand require a site measurement by qualified staff. There are many factors which must be considered in the manual measurement. Key consideration from an economic point of view, is the location of site relative to staff and frequency of testing.

Experience has shown that temperatures within a waste rock pile, particularly within the surficial zones are influenced by seasonal variations. Thus it is recommended that temperature measurement be carried out on a monthly basis. With this level of information, meterological data can then be used to evaluate seasonal effects.

While the objective of a manual system is to obtain sufficient data, the objective of an automated system is to maintain the amount of data recovered to a level which can be readily managed. Automated data loggers can be programed to record and store temperature measurements at whatever frequency desired from recording every second, hour, day or week. The decision as to what frequency depends on the storage or memory capacity of the data logger and how the data is recovered.

It should be noted that even fully automated systems require periodic maintenance. For systems operating in a northern climate such as Canada, it is recommended that at least one and preferably two maintenance trips per year be provided.

The temperature measured within a waste rock pile is a positive indication of the status of the pyritic oxidation process. Generally, the higher the temperature, the greater the magnitude of the reaction process taking place. As noted previously, seasonal effects also have to be accounted. However, depending on site location and ground freezing index, the average temperature of frost free ground at 2 to 3 m below ground surface is about +5°C. Any temperature above this would be indicative of an oxidation process. Temperatures of 25 to 30°C and above are indicative of highly reactive rock.

Oxygen concentration measurement from the ports within the waste rock pile are also indicative of the oxidation process. For example, relatively high levels of oxygen in the waste rock pore space could indicate either a low oxygen consumption rate (low intrinsic oxidation rate) for the waste rock material or ready access of air to the waste rock interior. In the latter case high temperatures will indicate the high overall oxidation rate consequent on a high intrinsic oxidation rate and ready access to oxygen.

5.2. Gas Permeability

As previously mentioned the measurement technique for gas permeability involves injecting gas into the dump at a known flow rate and measuring the resulting gas pressure rise in the material in that region. The gas permeability values can be obtained by comparing the field measurements with the results of a numerical model of the system. The modelling done by ANSTO used the computer code PDE/PROTRAN, which is a system for the solution of partial differential equations whereby spatial discretization is performed by the finite element (Galerkin) method, using triangular elements. This enabled the physical geometry of probe hole installations to be well-represented and allowed for the independent variation of the permeabilities of the backfill and pile materials.

A relationship between gas permeability, gas flow rate and pressure rise can thus be obtained and applied to the field data to develop the required values. Additional details on this relationship and a discussion of its application is provided in Appendix III.

5.3. Gas Diffusion

Sulphur hexafluouride concentration measurements are made in a pile as a function of space and time via the gas sampling ports installed in the probe holes. Gas samples are drawn from the ports in the appropriate probe hole using a hand-held vacuum pump which is plumbed through the gas chromatograph. Samples are taken at several depths greater than 3 m below the surface of the pile and at several times to ensure that the diffusion coefficients determined are representative of the dump bulk material rather than of a local anomaly.

For example, it is possible for a drilled probe hole to pass through a boulder. Any gas diffusion determinations made using data from gas sampling ports lying within such a boulder are likely to be perturbed by the presence of the boulder. This is because the technique requires the measurement of a transient system and is carried out over the relatively short time of a number of days. It is recommended that a note be kept in the drilling log when a probe hole passes through a boulder in its vicinity not be used for either tracer injection or sampling in subsequent determinations of gas diffusion coefficients. Experience has shown that the presence of boulders

in close proximity to probe holes does not perturb measured temperature and oxygen profiles. These profiles have been observed to take up their "steady-state" shapes within a few weeks of a probe hole being installed.

The details of the use of a GC for the determination of gas diffusion coefficients are described in more detail in Appendix IV.

5.4. Thermal Conductivity

The thermal conductivity measurement involves lowering the probe down the probe hole liners installed in the pile. The probe is maintained at the desired depth long enough for the probe to reach thermal equilibrium with its surroundings, typically about 20 minutes. Once equilibrium is reached the heater is switched on for a typical time of about 10 hours. The detailed procedure for field measurements is given in Appendix V.

The temperature at the probe is monitored to give a temperature curve for the heating phase. After the heater is switched off, the temperature at the probe is also monitored to give the temperature curve for the cooling phase. Both the heating and cooling curves are used to give independent estimates of the thermal conductivity of the pile material.

Although three thermistors are used to monitor the temperature at the probe, in most cases it is sufficient that the temperature measured by the middle thermistor be used in the analysis to determine the thermal conductivity of the material in the pile. The data collected can be presented as a temperature curve by plotting temperature measured at the probe versus the time after heating was switched on. A typical temperature curve is shown in Figure 8. The two distinct sections correspond to the heating and cooling phases of the measurement, both of which can be analyzed separately to obtain estimates of the thermal conductivity.

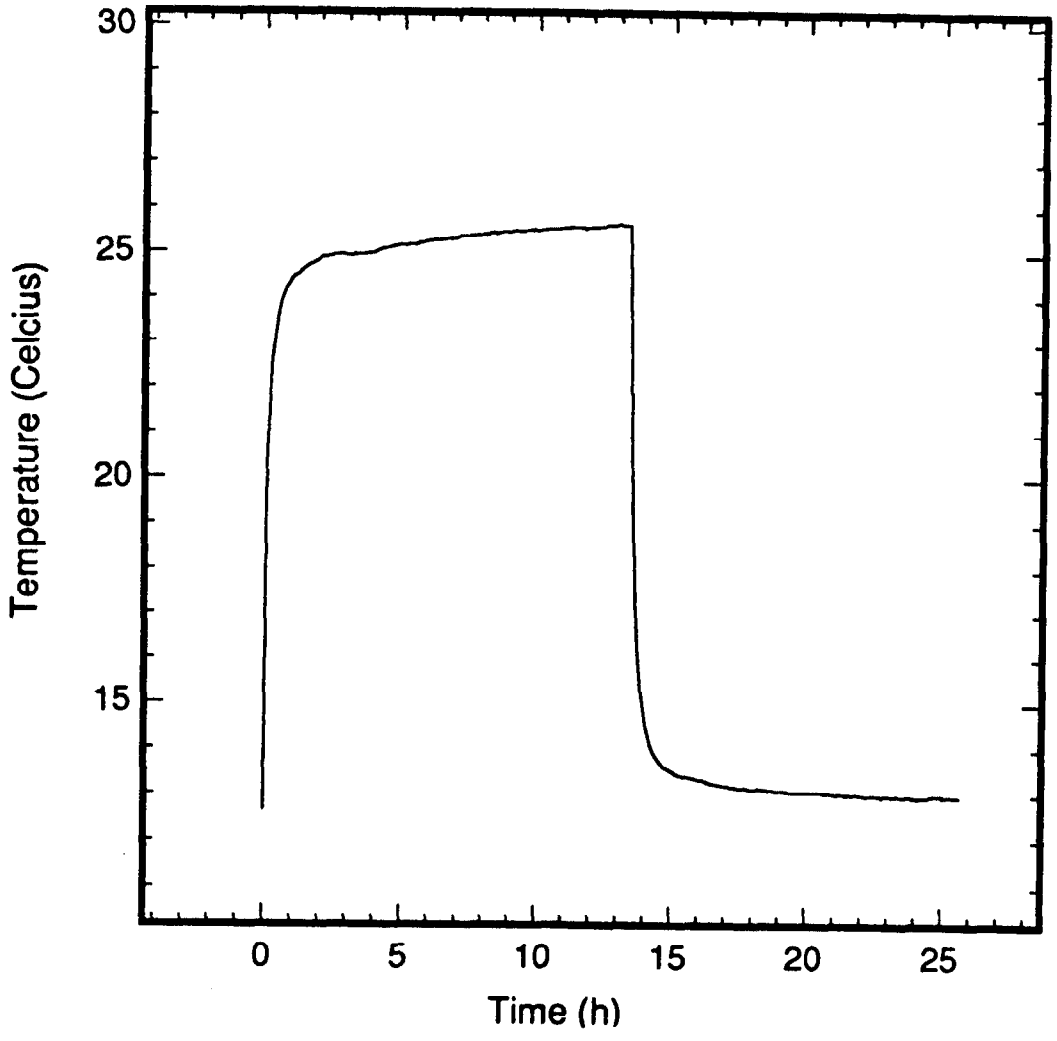

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FIG. 8 TYPICAL TEMPERATURE CURVE
HEATING AND COOLING PHASES

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The typical temperature profile in Figure 8 shows a rapid rise after the heating element is switched on, due to the thermal resistance of the plastic liner which is interposed between the probe and the dump material. The slower temperature rise one to two hours after the start of heating is influenced predominantly by the thermal properties of the waste rock material itself. It is this section of the temperature curve that is used for the thermal conductivity determination during the heating phase. When the heater is switched off the temperature drops sharply initially, but the rate of cooling is much lower one to two hours afterwards. This flatter section of the temperature profile is used for the determination of thermal conductivity during cooling.

The thermal conductivity values obtained from the heating phase and those from the cooling phase should not be significantly different from each other and hence an average value can be obtained. Changes in the physical conditions within the pile during the course of a measurement, such as in moisture content, may result in different values being obtained.

Thermal conductivity values are readily converted to thermal diffusivity using established relationships between the bulk density and specific heat of the phase of the bulk materials. The typical values of specific heat are 870 J kg-1K-1 for waste rock solids (Harries and Ritchie 1981) and 4200 J kg-1K-1 for pore water, whereas the bulk densities of dump solids and water will clearly vary from site to site.

6. ACKNOWLEDGEMENTS

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APPENDIX I

PROBE INSTALLATION

boundary. Where groundwater is not present, the probe hole should extend from ground surface to below the base of the waste rock pile. In such cases, the probe holes should extend 1 to 2m into the underlying soils or bedrock in order to determine the continuity of the measured variables across the boundary, between waste rock and native material.

1.2. Air Diffusion, Air permeability and Thermal Conductivity Probes

Research to date has shown that bulk physical parameters such as air diffusion, air permeability and thermal conductivity are properties intrinsic to the waste rock pile. Consequently, the number of probe holes required to characterize a site can be less than for the oxygen and temperature measurements. For a typical waste rock site, it is recommended that the bulk physical parameters be measured at a minimum of three locations, evaluated to be representative of the site. At each test location, two probe holes, spaced 1.5 - 3.5 m apart are required. The criteria for the depth of the probe holes is the same as for the oxygen and temperature probes, namely to below the lowest anticipated groundwater interface or the base of the waste rock pile. Where bulk physical parameters are to be measured, it is recommended that at least one of the two probes at each monitoring location be installed so that subsequent temperature and oxygen measurements can be recorded.

Convection is another consideration for the depth of probe holes for the measurement of bulk physical parameters. If convection is expected or suspected, it is recommended that the probe holes be drilled through the entire thickness of the pile in order to establish complete profiles. If convection is not suspected within the pile, the probe holes should be put down to 7 to 8 metres below the top surface of the dump. Generally, the older the material in the waste rock pile, the deeper the probe hole must be drilled in order to obtain representative results.

The location and depth of the probe holes are also influenced by both waste rock pile location and geometry as well as site construction characteristics. Depending upon the geometry of a waste rock dump, there may be some advantages to drilling across the pile in a transect in order to allow the construction of two-dimensional profiles of important physical parameters. If there are several different generations or types of materials within the pile, the probe holes should be located to intercept each of these areas.

1. SITE ASSESSMENT

The measurement of the key bulk physical parameters related to gas transfer in waste rock piles requires the drilling of several probe holes and the subsequent installation of monitoring equipment in these holes. The location, number, depth and configuration of the probe holes are very site specific and depend on site conditions and monitoring objectives.

1.1. Temperature and Oxygen Probes

For monitoring the rate of oxidation through change in temperature and oxygen concentration measurements, the initial decision to be made is the location of probe holes. These will differ from holes used to measure the bulk physical parameters. The goals of any monitoring program relating to gas transfer mechanisms must be clearly stated and understood prior to making decisions with respect to the type, number, and location of probes. The location of the probes for measuring temperature and oxygen should take into consideration:

- age of waste rock
- composition of waste rock
- site hydrogeology
- volume of waste rock
- budget
- regulatory requirements

A phased approach is recommended when identifying the requirements for probe hole installations. The initial phase involves a global approach whereby sufficient monitoring probes are located so as to provide the necessary data for site characterization. It is recommended that no fewer than three probe holes be installed at strategic locations within a waste rock pile. Additional probe holes can be added to address specific site conditions or to provide a wider coverage of the area.

The depth of the probe hole is dependent on site conditions. Where groundwater is present, the probe should be installed from the pile surface into the lowest anticipated annual groundwater elevation, to provide temperature measurements at this important

2. DRILLING IN WASTE ROCK PILES

Air rotary percussion hammer drill is recommended for drilling and installing probe holes within a waste rock pile or dump. With this technique, air is the primary drilling fluid. Compressed air is forced down the drill stem and escapes through small ports at the bottom of the drill bit thereby lifting the cuttings and cooling the cutting bit. The cuttings are blown out the top of the hole and collect at the surface around the borehole. Air rotary is favored over other drilling techniques because it does not require the use of water or water-based drilling fluids.

The diameter of the drilled probe hole should be approximately 150 mm. This allows a sufficient annulus for the installation of the backfill materials while limiting bridging problems. If the diameter of the hole is much larger than 150 mm, the interpretation of some of the in situ measurements is affected, in particular the thermal conductivity. The probe holes should, where possible, be drilled uncased. However, the main difficulty that may arise from drilling an uncased hole is the temporary loss of air circulation when porous sections of the waste rock are encountered during drilling. The loss of circulation will inhibit the return of drill cuttings to surface and may cause the drill stem to jam in the probe hole. In this situation it is recommended that drilling proceed slowly with the drill stem moved frequently up and down in the hole as the bit advances. This approach will reduce the potential for jamming.

Compressed air is the only drilling fluid recommended for drilling in waste rock material. The use of any other drilling fluid such as water, or polymer mud is not recommended due to the potential for these materials to alter the physical and chemical characteristics of the formation in the vicinity of the probe hole. Samples of drill cuttings, roughly 500g per hole, should be recovered at one metre intervals throughout the drilling. The samples may subsequently be analyzed for sulphur, which is an indicator of pyritic content, and tested for their acid generation and acid consumption potential of the waste rock material.

3. PROBE INSTALLATIONS

3.1. Material

A complete list of materials required to complete a probe hole installation is provided below. Various sized fittings may be substituted for those noted below, provided they form a gas tight seal. The length and quantity of materials such as the PVC liner piping and the gas sampling tubing is ultimately dependant on the thickness of the waste rock pile. Therefore, it is recommended that an accurate estimate of the pile thickness be obtained prior to the start of drilling operations. When estimating the materials required for backfilling, a large margin of safety is recommended. A factor of up to two times the estimated volume is not unreasonable.

- PVC piping, 40 mm inside diameter, 47 mm outside diameter
- 2 PVC friction caps
- nylon pressure tubing, 5 mm diameter
- Schraeder tank valves, two required for each metre of borehole length
- nylon straight connectors (to connect Schraeder valves and nylon tubing) one per valve
- mounting plate (similar to design indicated in this document)
- pipe clamps (to secure mounting plate to PVC liner)
- adhesive tape (one roll per borehole)
- PVC pipe cement
- 5 to 7 mm gravel
- dry silica sand
- bentonite chips/pellets

3.2. Procedure

The subsequent field measurements of temperature and oxygen concentrations, and/or bulk physical parameters, require the installation of a standard PVC liner throughout the entire depth of drilled hole. The PVC liner should consist of 40 mm inside diameter sections, 3.1 m in length, glued together and cut to the required length. Approximately 1.5 m of PVC liner should be left protruding above the ground surface. Water tight friction caps should be placed on each end of the PVC liner. The PVC liner should be installed in the drilled hole prior to moving the drill rig off the hole. This is particularly important in unconsolidated deposits where sections of the hole may collapse after the drill stem has been removed, blocking the subsequent installation of the PVC

liner. If the drill rig is kept on the hole until the installation is complete, the hole can be redrilled if blockages occur.

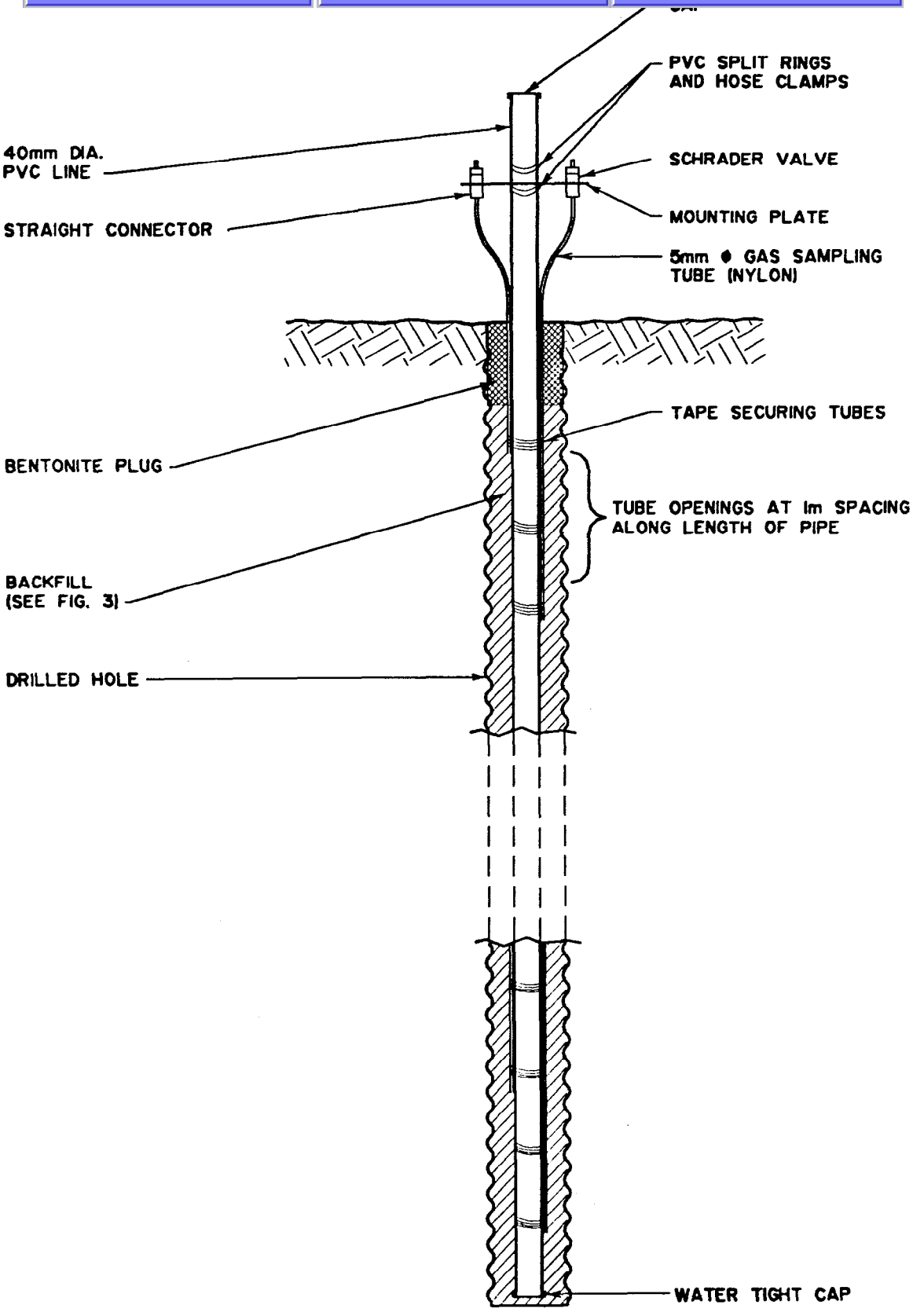
The PVC liner is the conduit by which instrumentation for temperature, oxygen and the bulk physical parameters are installed. Temperature measurements within a waste rock pile can be carried out either with a series of thermocouples or thermistors. However, it is recommended that the temperature measuring devices used at one site be all the same type. Thermocouples and the thermistors should be acid resistant and designed for burial in contact with water. Prior to inserting PVC liner in the drilled hole, thermocouples or thermistors are attached to the exterior of the liner at the depths where measurements are required. Spacing of the thermocouples or thermistors is dependent on a number of factors including the total depth of waste rock and the coverage of temperature profile data required. There are also physical considerations such as the number of thermocouples or thermistors that can be physically attached to the exterior of the liner and how the thermocouples or the thermistors will be read. For instance, for manual measurement, it would be prudent to limit the number of thermocouples or thermistors to 5 or 6 per liner to avoid possible confusion in identifying each thermocouple by field staff. On the other hand, should an automatic data logger be used, the number of thermocouples or thermsitors is limited only by the capacity of the data logger.

Gas measurements, such as oxygen or sulphur hexafluouride, require a series of 3 mm diameter nylon tubing secured to the exterior of the PVC liner. For measurement of oxygen concentrations, one port at each depth within the probe hole is required. However, for the measurement of gas diffusion and gas permeability, two ports are required at each depth, attached on opposite sides of the liner, starting at the base of the probe hole. The spacing of ports for gas measurement is dependent on a number of variables, the most important of which is the depth of the waste rock. To ensure that the probes are installed and backfilled properly, it is recommended that a minimum spacing of 1 m be provided between the probes.

Backfilling around the completed monitoring probe should provide a high permeability chamber around the openings of each of the gas sampling tubes, while at the same time isolating the chambers from each another. A schematic of the recommended backfilling scheme is shown on Figures 1 and 2. In summary, for each sampling port, a 500 mm gravel pack is installed in the borehole annulus, with the sampling port located at mid depth of the gravel. A clean sand pack is placed above and below the gravel pack

with a 50 mm bentonite seal placed above and below the sand. The thickness of the sand pack is a function of the spacing of the sampling ports. For port spacing of 1 m, a 450 mm total sand pack is required while a 1.5 m spacing requires a 950 mm sand pack.

During backfilling operations, a detailed record should be maintained of the levels of backfill placed within the probe hole and the overall volumes of backfill materials placed. This data is necessary to determine the effective radius of the outer boundary of the backfilled chambers, which is required for the analysis of air permeability measurements. Each probe hole should be sealed with 300 to 400 mm of bentonite at the surface in order to prevent surface water infiltration and reduce inflow of air.



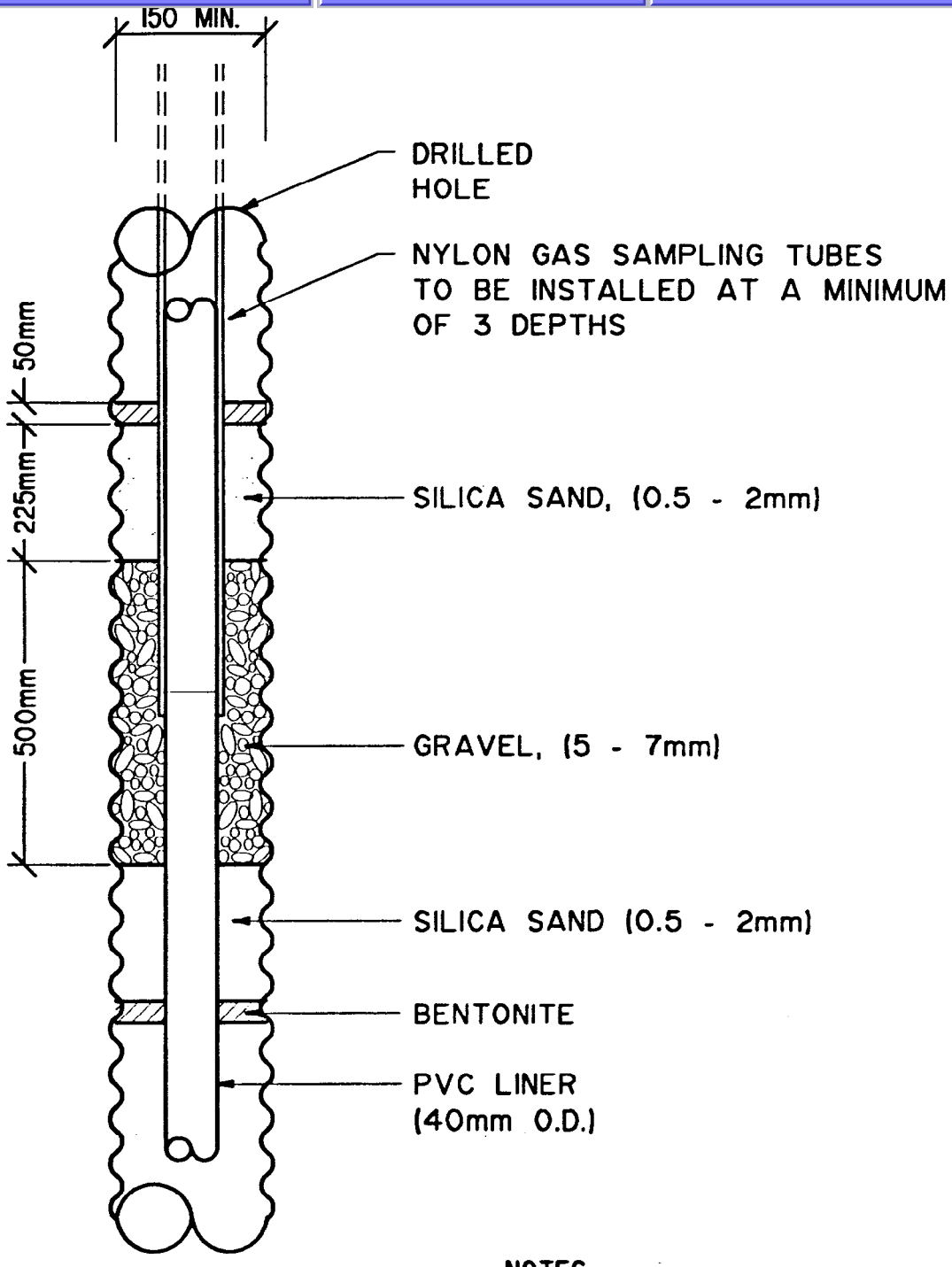
NOLAN, DAVIS & ASSOCIATES

FIG. 1 - PROBE HOLE LINER SCHEMATIC

GAS TRANSFER MONITORING
HEATH STEELE MINES
NEWCASTLE, N.B.

F92-081

05/93



NOTES:

1. ONE TUBE ONLY REQUIRED AT EACH LEVEL FOR OXYGEN CONCENTRATION MEASUREMENTS.
2. TWO TUBES REQUIRED AT EACH LEVEL FOR AIR PERMEABILITY MEASUREMENTS.

NOLAN, DAVIS & ASSOCIATES

FIG. 2 - TYPICAL BACKFILL OXYGEN / TEMPERATURE MONITORING PROBES

WASTE ROCK STUDY
HEATH STEELE, NEWCASTLE, NB

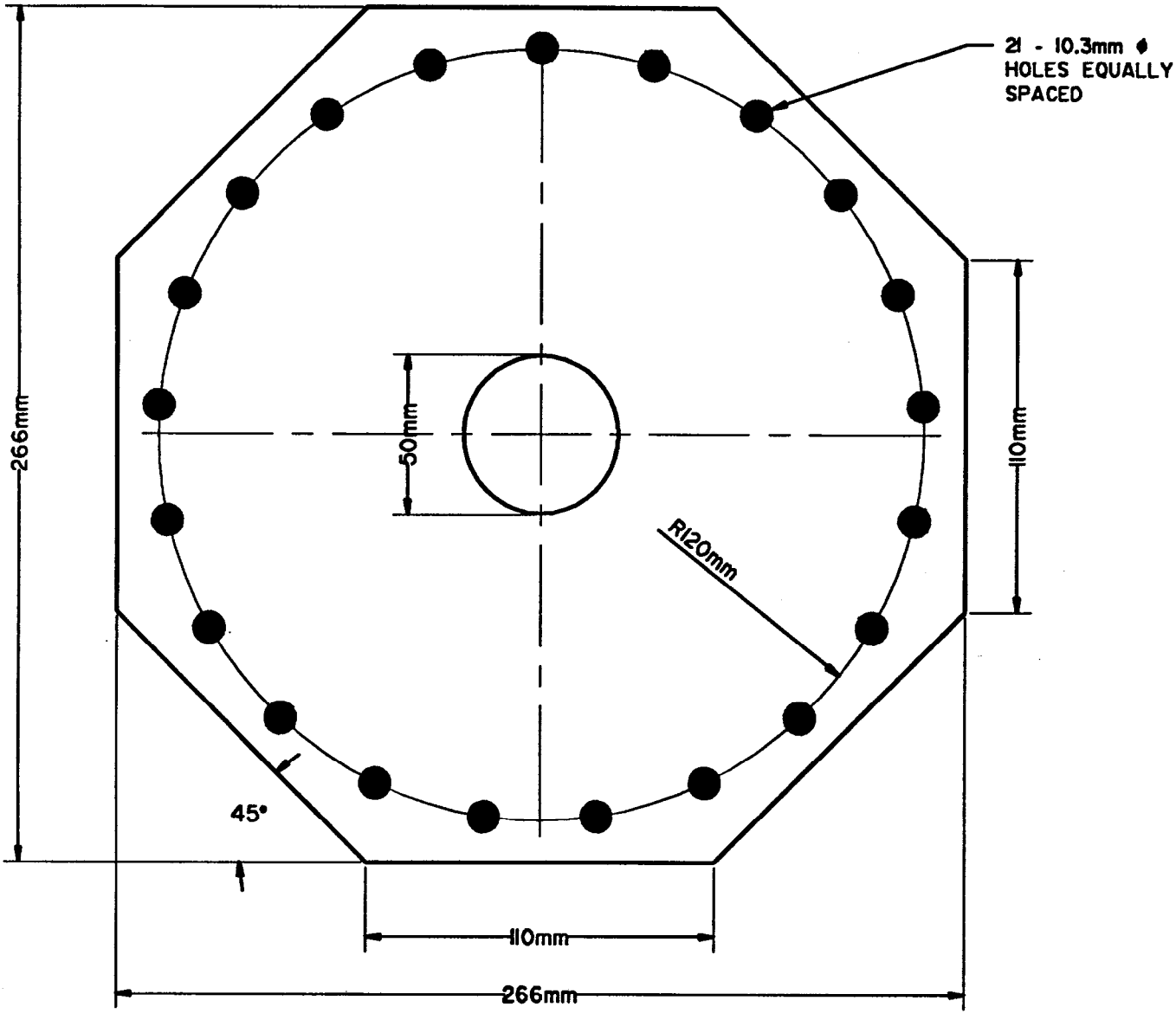
F92-08 05/93

4. VALVE ASSEMBLY

A durable plate is required for mounting of the sampling valve assembly at the top of the PVC liner. The plate should be at least 1 mm thick in order to secure the Schraeder valves tightly to the straight connectors, through the plate. The mounting plate should be constructed from a material that is rigid and will not degrade from long term exposure to the environment. Materials such as brass, stainless steel or PVC are recommended. A schematic of a typical mounting plate is shown in Figure 3.

Each of the nylon gas sampling tubes attached to the exterior of the PVC liner is terminated with a Schraeder valve. The following assembly is recommended: Schraeder tank valves, 3 mm BSP tapered thread, and nylon straight connectors that fit both the 5 mm nylon pressure tubing and the valves. The actual sizes of all the components are not critical, provided that the completed assembly forms a gas tight seal. Teflon tape is recommended during the assembly of all threaded pieces. The diameter of the holes in the mounting plate must suit the valves. In the final valve assembly, the valves sit above the mounting plate with the straight connectors mounted below.

The mounting plate should be permanently labelled or stamped with the number of the probe hole and the depth from the top lip of the liner to the bottom. At the completion of the installation of the valves, a watertight PVC friction cap should be placed on top of the PVC liner to prevent moisture from entering.



MATERIAL: WEATHER RESISTANT PLATE (1mm THICK)

TOLERANCE± 0.5

NOTE: THE CENTRAL HOLE NEEDS TO BE SLIGHTLY LARGER THAN THE OUTER DIAMETER OF THE PVC LINER & THE OTHER ONES NEED TO SUIT THE SIZE OF THE SCHRADER VALVES.

NOLAN, DAVIS & ASSOCIATES

FIG. 3 - MOUNTING PLATE SCHEMATIC

HEATH STEELE MINES
NEWCASTLE, N.B.

F92-081

02/93

APPENDIX II

OXYGEN/TEMPERATURE

ANSTO/C316

ansto

A Report to
Nolan, Davis & Associates (NB) Ltd
for the **MEND** Project on

GAS TRANSFER IN WASTE ROCK DUMPS
AT THE HEATH STEELE MINE

FIELD PROCEDURES MANUAL

MEASUREMENT OF OXYGEN AND TEMPERATURE PROFILES

by

J.W. Bennett
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Prepared within the Environmental Science Program
of the Australian Nuclear Science and Technology Organisation
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APRIL 1993

1. Introduction

The oxidation of iron pyrite (FeS_2) is central to the generation of acid drainage from pyritic mine wastes. The process leads directly to the generation of acid and is responsible for the conversion of largely insoluble metal sulphides to metal sulphates which are much more soluble, particularly under acid conditions. The oxidation of iron pyrite requires oxygen and water and, being exothermic, generates heat as well as acid.

Even without a quantitative knowledge of the gas and heat transport properties of the waste dump, measurements of the oxygen and temperature profiles can be interpreted qualitatively to provide insight into the oxidation and, hence the pollution generation properties of waste dump. For example, relatively high levels of oxygen in the dump pore space could indicate either a low oxygen consumption rate (low intrinsic oxidation rate) for the dump material or ready access of air to the dump interior. In the latter case high temperatures will indicate the high overall oxidation rate consequent on a high intrinsic oxidation rate and ready access to oxygen. Similarly a judgement can be made that the gas transport processes are essentially one-dimensional or multi-dimensional, so aiding plans for further measurements or plans for predictive modelling.

The techniques for measuring temperature and oxygen profiles in probe holes in waste rock piles are described below. The required probe holes consist of a central plastic liner pipe with an internal diameter of approximately 40 mm in a backfilled drilled hole. A nylon pneumatic tube, about 3 mm internal diameter, runs to each metre depth in the backfill. Each of the nylon tubes is terminated above the surface of the pile by a Schrader valve. The liner can be used to lower a temperature probe to any depth within the pile and the nylon tubes are used to withdraw pore gas samples for on-line oxygen analysis. In some installations, thermocouples are buried at fixed depths in the probe hole backfill for temperature measurement.

All of the measurement and analysis techniques described in this document have been developed by **Ansto**. Equally, all the instruments described here have been designed and constructed by **Ansto**, except where other suppliers are noted, and some commercially available equipment have been modified and calibrated.

2. Measurement Methods

Pore gas oxygen concentrations can be measured by drawing gas samples from gas-filled pores of the waste rock pile and analysing them using a field-portable oxygen analyser. A simple system such as this has the advantages of being relatively cheap, easily portable and able to provide accurate data at the time of measurement.

Two different methods have been used for measuring temperatures in waste rock piles. One involves installing thermocouples in the probe holes as fixed installations and the other uses a single thermistor which is lowered down the probe hole liners. The instrumentation for reading the temperatures is simple in both cases, being either a device to read the temperature of the thermocouple directly, or one to measure the resistance of the thermistor which can then be converted to temperature using a

measured calibration relationship. Using buried thermocouples has the advantage of speed of data collection but lacks the spatial resolution which can be obtained using a thermistor, given that a thermistor can be lowered in any series of depth increments.

The extraction of oxidation rates from measured temperature distributions in waste rock piles requires the field data to have a high degree of accuracy. Experience has shown that such accuracy can be achieved with thermistors and this is the technique which will be described below.

Data collected using buried thermocouples is likely to be more suitable for providing a qualitative description of processes occurring within an oxidising waste rock pile rather than for quantitative analysis. Thermocouples installed in backfill have the particular disadvantage that any failure within a pile is unlikely to be repairable.

Harries and Ritchie (1981) have described the measurement and interpretation of temperature profiles using thermistors. The method measures the temperature of the air column in a probe hole liner and therefore requires the air in the liner to be in thermal equilibrium with the surrounding pile material. They show that the air column in a liner of about 40 mm diameter can support a temperature gradient of at least +4°C per metre depth without any convective air movement in the liner. Hence in most practical cases the air in the liner is in thermal equilibrium with the surrounding pile material.

3. Instrumentation

3.1 Oxygen Measurement

The pore gas oxygen concentration measurement system is based around a commercially available portable oxygen analyser made by Teledyne Analytical Instruments, City of Industry, California, USA, model 320B. In this instrument oxygen is sensed in a micro-fuel cell, which consumes oxygen from the gas sample and generates a proportional electric current or voltage.

A schematic diagram of the measurement system is shown in Figure 1. Pore gas samples are collected from the nylon tubes installed in the probe holes using a vacuum hand pump and are passed over the Teledyne fuel cell. The oxygen concentration is read directly from the instrument.

Figure 1 shows a small disposable filter which is placed in the gas sample inlet line. The filter is a Minisart single use filter unit, 5.0 µm, model SM17594, made by Sartorius GmbH, Göttingen, Germany. The filter is to protect the hand-pump and fuel cell from damage which may be caused by dust or moisture. Dust is most likely to be a problem soon after installation, before the dry backfill materials have reached hydraulic equilibrium with the pile. The filter is easily replaced if it becomes wet or clogged.

The vacuum hand-pump, Nalgene model 6130-0010, manufactured by Nalge Company, a subsidiary of Sybron Corp., New York, USA, is made of plastic and has a stroke of 15 mL.

The tubing used to connect all the components of the system is Masterflex C-flex

tubing, size 16, model 06424-16, made by Cole-Parmer Instrument Company, Chicago, USA. It has the particular advantage of being highly elastic so that it can provide a good gas tight seal when pushed onto the various sizes of connection nipples and barbs, without the need for hose clamps or sealants. The connections can also be broken and re-made many times without altering the properties of the tubing.

Ansto has modified all of its analysers to incorporate a digital display of the oxygen concentration. The reasons for this are that it is easier to read in the field than the analogue display supplied by the manufacturer and, more importantly, greater precision is possible since the resolution of the LCD display used is 0.01 percent oxygen concentration. (Teledyne does supply a model with an LCD display, but only with a resolution of 0.1 percent oxygen.) The measured reproducibility of values in the field have frequently demonstrated that the higher degree of precision is warranted in this system.

A further modification of the Teledyne oxygen analyser has been to incorporate an 'offset' button which short-circuits the input voltage to the amplifier stages. The digital display then indicates the effective zero oxygen reading of the instrument.

Attachment I describes an automatic oxygen analyser which was designed and built specifically for use with the type of probe hole installations described here. The analyser is based on the same principle of operation as the Teledyne instrument, is software controlled and allows up to 21 gas ports to be sampled and analysed automatically.

3.2 Temperature Measurement

The temperature probe consists of a single thermistor soldered to a twisted-pair of wires which can be connected to a digital Ohm-metre. The long length of wire, typically 25 metres, is wrapped around a plastic fishing hand-reel. The reel incorporates a series of six standard resistors which span the range over which the thermistor has been calibrated (described below). These resistors can be switched to the Ohm-meter to check the operation of the system. The mounting of the thermistor in the probe has been described by Harries and Ritchie (*ibid.*).

The precision thermistors, model YSI 44030, used in the temperature probes are made by Yellow Springs Instrument Co, Yellow Springs, Ohio, USA. Each thermistor was calibrated to obtain the temperature versus resistance relationship using a temperature calibrator, model D55SE, made by Jofra Instruments AS, Farum, Denmark. In order to maximise the accuracy of a particular probe, the thermistor is calibrated over the temperature range which is expected to be encountered at a specific site; a wider range is required in the Arctic than in the tropics. Attachment II gives an example of a calibration sheet where the estimated standard deviation over the range from 0 to 65 ^{o}C was $\pm$0.04 ^{o}C.

An automatic temperature logger has been developed to measure temperature profiles in probe holes. The instrument is software controlled and mechanically lowers a thermistor string down the installed liner, logging the temperature at each metre depth. The specifications of the logger are included in Attachment III.

4. Field Measurement Procedures

4.1 Pore Gas Oxygen Concentration

1. Record all background information on the log sheet (Attachment IV).
2. Turn on the Teledyne oxygen analyser 15 minutes before the first measurement, by turning the range knob to 'medium', pressing the red button on the side and removing the cell holder cover cap. Do not switch off between measurements.
3. Test the battery using the range knob (if the absolute value of the reading of the digital meter is less than 105, replace the batteries) and then turn the range knob back to 'medium'.
4. Press the 'offset' button to check that the reading of the digital meter is between 0.00 and 0.02.
5. Wait for 2 to 3 minutes for the analyser to re-stabilise.
6. Calibrate the analyser by pumping fresh air over the fuel cell and adjusting the reading of the digital meter to 20.95 per cent using the span knob. Lock the knob afterwards.
7. Remove the caps from one of each pair of schrader valves.
8. Connect the hand pump to port number 1, the first Schrader valve, pump 10 times to obtain approximately 150 mL of pore gas, wait for the reading to stabilise and record the reading. Pump another 10 times and record the reading. If the difference between the two recorded values is less than 0.05, move to the next schrader valve for measurement. If not, pump 10 more times and record the reading and move to the next port. If the port is blocked (indicated by the pressure gauge on the hand pump), try the other Schrader valve of the pair. If both are blocked record this information on the log sheet.
9. Check the calibration after half of the ports in one hole have been measured and reset if the value is less than 20.90 or more than 21.00.
10. Check and record the calibration and offset reading at the end of measurements.
11. Leave the meter switched on when moving between holes. Switch it off at the end of a series of measurements or when it will not be used for more than, say, half an hour. Remember to switch the range knob to 'off', switch off the digital display and replace the cell holder cap. If the digital display is accidentally left on, and the 9V battery goes flat, it can be accessed by removing the front of the analyser.

4.2 Temperature

1. Record all background information on the log sheet (Attachment V).
2. Connect the temperature reel to the digital Ohm-meter and check the Ohm-meter against the standard resistors on the temperature reel using the selector switch.
3. Lower the thermistor to the first metre mark and fix it in place with a suitably sized stopper. Do not bend or squash the cable.

4. Record the Ohm-meter reading after the first 30 seconds and then every minute thereafter until the difference between two successive readings is equal to or less than 3 ohms.
5. Lower the thermistor to the next metre mark and repeat step 4 (securing the cable each time). Care should be taken not to lower the thermistor into any water in the bottom of the liner. If it does get wet (indicated by erratic resistance readings), remove it from the hole and dry it before proceeding.
6. Make one repeat measurement approximately halfway up the liner before removing the thermistor.
7. Extrapolate the resistance by the difference between the last two values recorded at each depth and write it in the 'R_{inf}' column, e.g., 2077, 2074, R_{inf}=2071.
8. Calculate the temperature at each depth using R_{inf} in the calibration curve which relates temperature to thermistor resistance.

5. Acknowledgements

The contribution of Mr Alan Boyd, Mr Warren Hart and Mr Viphakone Sisoutham to the design, construction and calibration of the instruments described here is greatly acknowledged.

6. Reference

Harries, J.R. and A.I.M. Ritchie. 1981. The use of temperature profiles to estimate the pyritic oxidation rate in a waste rock dump from an opencut mine. *Water, Air and Soil Pollution*. 15:405-423.

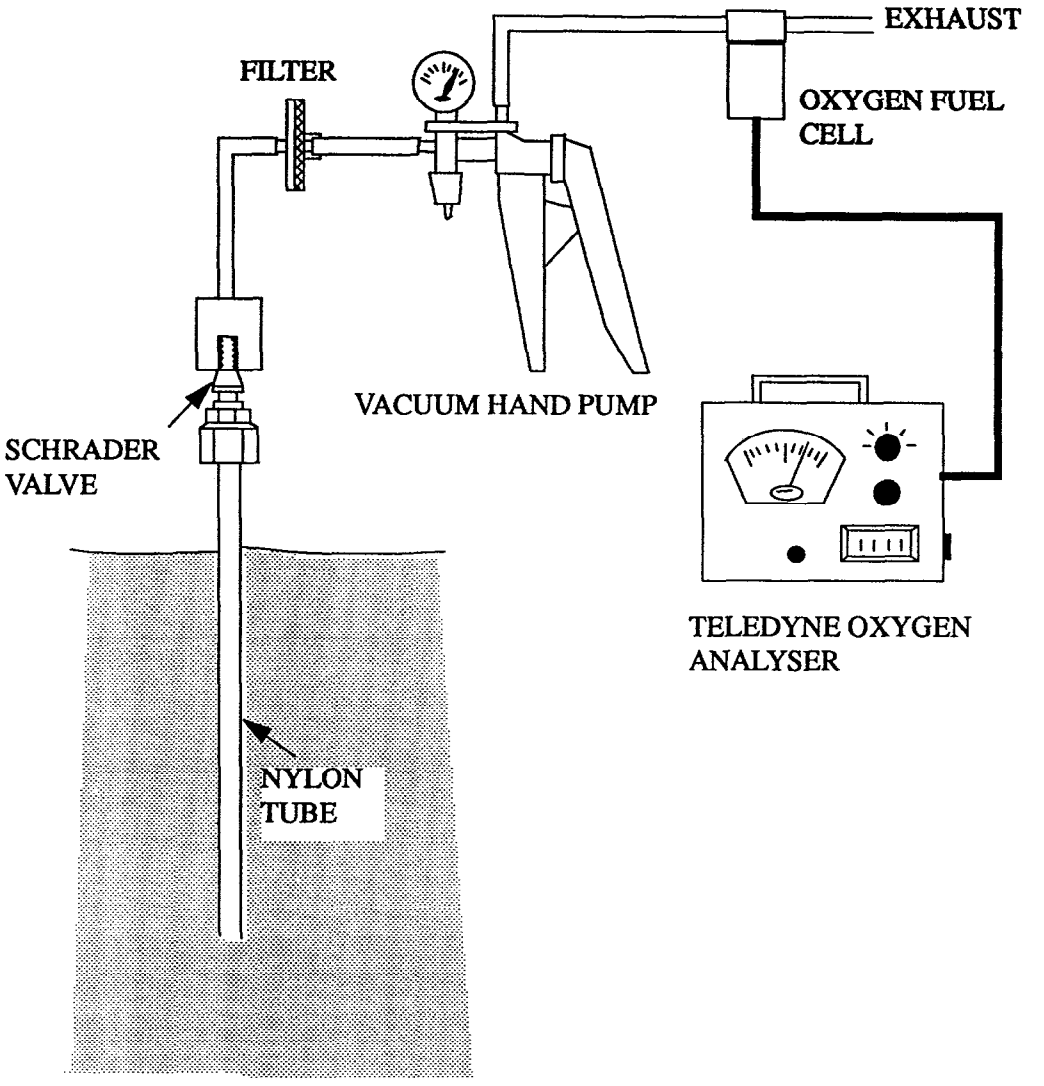


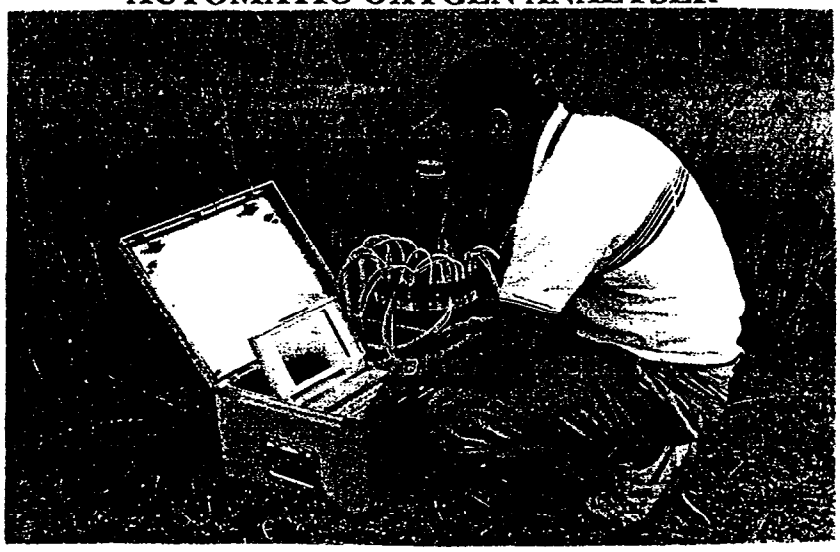
Figure 1. Schematic diagram showing the system for measuring pore gas oxygen concentration.

Attachment I.

The specifications of the automatic oxygen analyser.

Australian Nuclear Science and Technology Organisation

AUTOMATIC OXYGEN ANALYSER



Monitoring of oxygen levels in gas samples in the field, has previously required the use of instrumentation which use only a single sensor. These units require manual operation and are time consuming. The use of single sensor instruments in monitoring of large or remote sites is consequently labour expensive and may effect the quality of results due to varying sampling conditions or sampling techniques. High labour costs relate both to the set up time at the site and also to the recording and analysis of results. In response to these deficiencies, Ansto has developed the Automatic Oxygen Analyser.

The **Ansto Automatic Oxygen Analyser** is a **portable** system contained within a **shock resistant carry case**, for the measurement of oxygen concentration in a gas sample. The analyser collects gas samples form **1 to 21 different locations** sequentially, with the complete measurement of 21 sites taking only about 30 minutes. **Result uniformity is enhanced** through the software monitoring of system functions.

The unit is **battery powered** (mains power connection is provided) with the **on-board computer** recording data related to operator name, sensor identification, date, time, calibration data, oxygen concentrations, ambient air pressure and instrument temperature. The unit has a **automatic restart facility** which enables a series of measurements to be made by the unattended analyser at pre-set time intervals.

The system has a **wide range of applications** both in the environmental and industrial fields where on-line and/or continuous oxygen monitoring in gas samples is required.

For further information, contact:

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Environmental Science Program
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Australia

Phone: +61 2 717 3743

Fax: +61 2 717 9260

TECHNICAL SPECIFICATIONS

Operating temperature:	0 - 50°C
Oxygen analyser range:	0 - 20.95%
Resolution:	0.03% oxygen
Accuracy:	± 0.10% oxygen
Micro-fuel cell:	Teledyne Class B-1. Life is dependent on duty cycle (e.g. 2.5 years, assuming 10% duty cycle in air; continuous duty in air, 6 months)
Response time:	90% in less than 7 seconds
Running time on full charge:	15 hours
Battery:	6 x 2 Volt cells, rechargeable Rating : 5 A.H Sealed lead acid
Solenoid Valves:	22 x 12 Volt D.C. 2-way normally closed Current approximately 120 ma
In-line Filters:	Commercially available Pore size : 5 u m
Tubing:	C-Flex thermoplastic elastomer (tubing can be selected for suitability)
Tube terminators:	Quick-release plastic shrader valve connectors
Pump:	12 Volt D.C. commutator type Diaphragm pump
Barometric Pressure	Absolute pressure transducer Range 950-1050 mb Accuracy ± 1.0 mb Resolution ± 0.05 mb
Vacuum Transducer:	Absolute pressure transducer Linearity, hysterisis : 0.1% FS
Instrument Size:	530 x 420 x 230 mm
Instrument Weight:	13 kg (approximately)
Instrument Case:	Polycarbonate
Computer Interface Card:	16 digital outputs 8 digital inputs 3 counters 8 analogue channels 2 D-A outputs

Attachment II.

An example of a thermistor calibration sheet.

A N S T O

ENVIRONMENTAL SCIENCE PROGRAM

Thermistor Calibration Report

30 March 1992

To: Acid Mine Drainage and Leaching Group
Environmental Physics

Attention:

Thermistor number 1 which will be incorporated into the newly constructed thermal conductivity probe has been calibrated to find the functional relationship between the temperature of the thermistor and its measured resistance, using a Jofra brand temperature calibrator, model D55SE, serial number 912296. The system was calibrated between 0 and 65°C.

The manufacturer of the thermistor gives the form of the function as:

$$T = \frac{1}{A + B\,(lnR) + C\,(lnR)^3} - 273.15$$

where T is the temperature (°C) and R is the resistance (Ω).

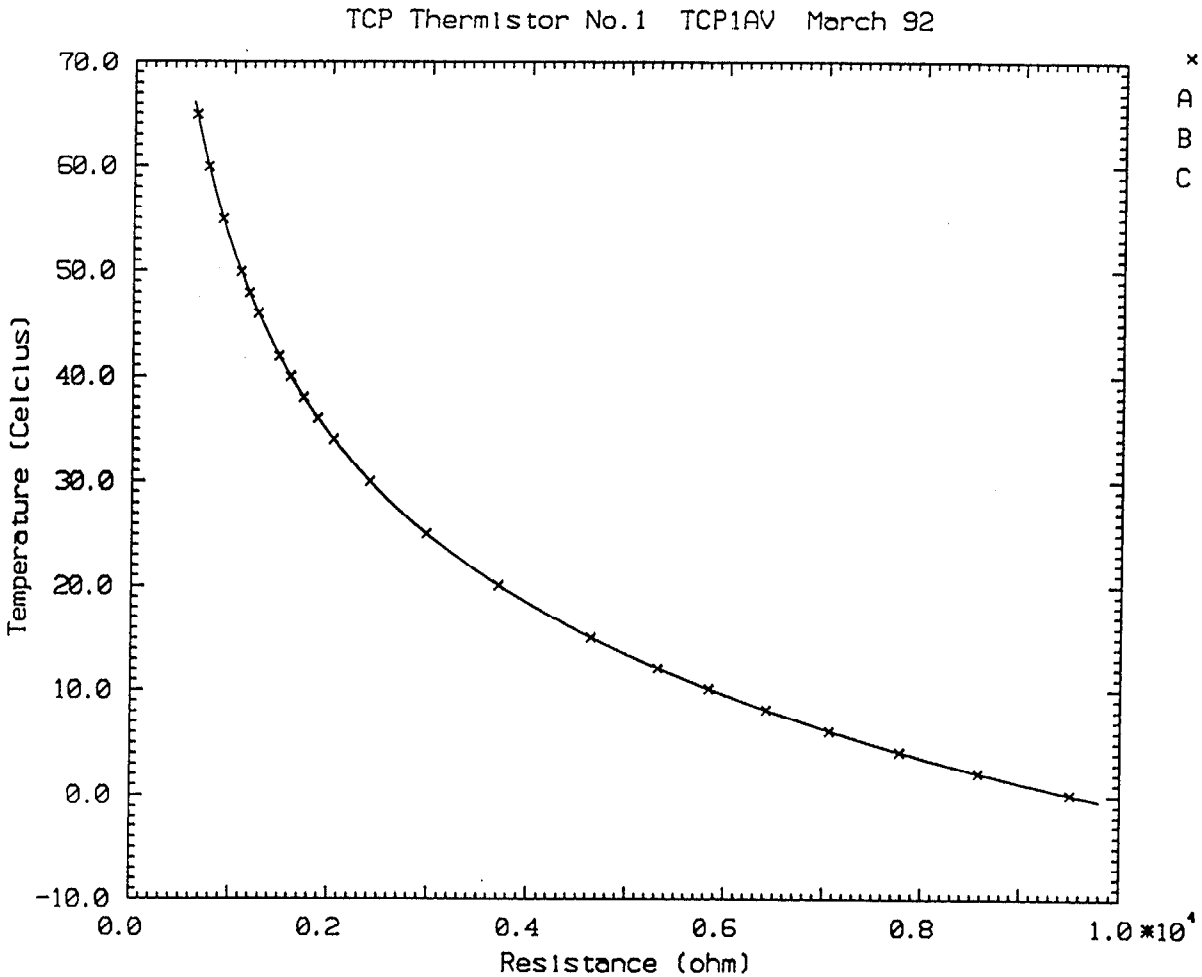
The function was fitted to the measured data points using a least squares fitting program to obtain the following values of the coefficients:

$$A = 1.4266 \times 10^{-3}$$
$$B = 2.3201 \times 10^{-4}$$
$$C = 1.4084 \times 10^{-7}$$

A graph of the data points and the fitted curve is attached.

The estimated standard deviation on temperatures obtained using this curve over the range 0 to 65°C is ±0.04°C.

PMB 1
MENAI NSW 2234
AUSTRALIA



× shows data points

A = +1.42662e-03

B = +2.32010e-04

C = +1.40836e-07

Weighted sum of squared errors=6.51e-03

Attachment III.

The specifications of the automatic temperature logger.

Australian Nuclear Science and Technology Organisation

AUTOMATIC TEMPERATURE LOGGER

Monitoring of temperature profiles within waste rock dumps has previously required manual operation of field equipment and data storage. These manual tests also require laborious 'in house' data manipulation to convert the field data to a usable format for analysis and display. **Ansto** has developed an **Automatic Temperature Logger** in response to these perceived needs.

The **Ansto Automatic Temperature Logger** is a portable system consisting of two units. A polycarbonate water and shock resistant case houses a Sharp 3100 palmtop computer, battery supply, control electronics, and accessories. The second unit which is fixed to the top of the probe hole liners contains the temperature measuring cable, electronics and mechanics.

The analyser is easily programmed using the on-board computer to measure temperatures down to a depth of 46 metres. Two calibrated precision thermistors spaced one metre apart ensure quick data collection. Automatic calibration tests before each temperature measurement ensure accuracy of the data. The software menu allows the user to view the data as either resistance, temperature in °C, or in graphical form. The instrument has an automatic restart facility which enables a series of measurements to be made by the unattended analyser at pre-set time intervals.

Information recorded on disk or sram includes: operator's name, instrument identification, hole identification, date, time, calibration data, temperature data and battery voltage.

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Fax: +61 2 717 9260

TECHNICAL SPECIFICATIONS

Operating temperature:		0-50°C
Temperature measurement range:		-30°C to +100°C
Accuracy:		Better than ±0.05°C over the range 0 to 50°C
Resolution:		Varies from a minimum of 0.01°C at 20°C to 0.33°C at the upper range limit of 100°C.
Thermistors:	**Interchangeability**	±0.1°C
	Type	NTC
	Resistance	3000 ohms @ 25°C
Running time on full charge:		12 hours
Battery:		6 x 2 volt cells, rechargeable Rating: 5 A.H. Sealed lead acid
Unit 1	**size:**	420 x 320 x 180 mm
	weight:	10 kg (approximately)
	casing:	Polycarbonate
Unit 2	**size:**	375 x 200 x 200 mm
	weight:	6 kg (approximately)
	casing:	Painted aluminium
Computer interface card:		16 digital outputs 8 digital inputs 3 counter/timers 8 analogue channels 2 D-A outputs

Attachment IV.

An example of the field log sheet used for recording oxygen data.

HOLE :

BOREHOLE OXYGEN ANALYSIS LOG SHEET

Date: .... Experimenter: ....

Weather: .... Oxygen Meter No: .... Battery Test: ....

Zero Test: .... Leak Test: ....

Start: Time: .... Temperature: ....

End: Time: .... Temperature: ....

Port	Oxygen Reading after pumping				Atmospheric Calibration after pumping			Oxygen Concentration (%)
	10	20	30	40	10	20	30	

Attachment V.

An example of the field log sheet used for recording temperature data.

HOLE:

REEL:

TEMPERATURE PROBE LOG SHEET

Experimenter: .....

Date: ..... Start Time: ..... Finish: .....

Air Temp (Shade): ..... Weather: .....

Resistance calibration check:

R1 ..... R2 ..... R3 ..... R4 ..... R5 .....

Depth (m)	Resistance (ohm)						Temperature (°C)
	0.5 Min	1.5 Min	2.5 Min	3.5 Min	4.5 Min	R_{infin}	
Repeat Measurement							

APPENDIX III

AIR PERMEABILITY

ANSTO/C317

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A Report to
Nolan, Davis & Associates (NB) Ltd
for the **MEND** Project on

GAS TRANSFER IN WASTE ROCK DUMPS
AT THE HEATH STEELE MINE

FIELD PROCEDURES MANUAL
MEASUREMENT OF GAS PERMEABILITY

by

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1. Introduction

The oxidation of iron pyrite (FeS_2) is central to the generation of acid drainage from pyritic mine wastes. The process leads directly to the generation of acid and is responsible for the conversion of largely insoluble metal sulphides to metal sulphates which are much more soluble, particularly under acid conditions. The oxidation of iron pyrite requires oxygen and water and, being exothermic, generates heat as well as acid.

For a typical mass of pyritic mine waste the mass of oxygen required to oxidise all the pyritic material is about a thousand times greater than the oxygen initially available in the pore space of the pile while the water required is only about a tenth of that available in the pore space. This means that, if oxidation of pyrite in the wastes is to proceed to completion, oxygen needs to flow from the surface of the wastes, where it is available in air, to oxidation sites within the wastes. It also means that a slow rate of oxygen supply from the surface will lead to a low oxidation rate and hence a low rate of pollution generation within the wastes.

To reach oxidation sites within the wastes, oxygen must flow through the pore space of the wastes. There is a flux of oxygen into the waste pile consequent on oxygen dissolved in water infiltrating the surface of the pile but this flux is typically a thousand times lower than the oxygen flux through the gas filled pore space. There are two mechanisms which lead to oxygen flow through the gas filled pore space. The first is diffusion where the flux results from the oxygen gradient consequent on oxygen consumed in the oxidation process. The second is advection where the flux results from a pressure gradient set up in the waste pile. A pressure gradient can result from temperature gradients in the waste dump consequent on heat released in the oxidation process. This form of advection is usually termed convection and has been observed in a number of waste rock dumps (Harries and Ritchie 1981, Firlotte *et al* 1991). In principle, pressure gradients consequent on wind driven air flow over the dump surface should be high enough to generate significant advective gas fluxes within the dump. In practice, there has been no quantitative evidence to date to show that such a process occurs.

The *gas permeability*, K (m^2), of a porous medium such as a waste rock pile is a coefficient which relates the gas convective velocity, v ($m\ s^{-1}$), to an applied pressure gradient and can be described by Darcy's Law which in one dimension can be written as

$$v = -\frac{K}{\mu_a}\left(\frac{\partial p}{\partial z} + \rho g\right) \qquad (1)$$

where ρ, μ_a, and p are the density ($kg\ m^{-3}$), absolute viscosity ($kg\ m^{-1}\ s^{-1}$) and pressure (Pa) of the gas respectively, and g is the acceleration due to gravity. If μ_a is replaced with μ, the kinematic viscosity of the gas ($m^2\ s^{-1}$), then v in Equation (1) becomes q, the mass flux of gas ($kg\ m^{-2}\ s^{-1}$). This latter form of Darcy's Law is presented in **Figure 4** which will be referred to in **Section 4.2**.

Gas permeability depends on the percentage, continuity and size of the gas-filled pore space in the pile. The size distribution of the pores is relevant because the flow

rate depends on the dynamic viscosity of the gas. As a consequence, for a given pressure difference, there will be a disproportionately higher mass flux through larger pores compared with the smaller capillaries where wall effects have a greater influence. In the process of diffusion all gas-filled pore spaces participate equally, irrespective of pore size. As a consequence, the dependence of gas permeability on the gas-filled porosity is much stronger than is the dependence of the gas diffusion coefficient.

The relations between gas-filled porosity, permeability and diffusion are well summarised by Hillel (1980):

> There is a fundamental difference between the functional dependence of a soils permeability (or conductivity) upon pore geometry and the corresponding function for diffusion coefficient. As the permeability pertains to pressure-induced convective-viscous flow, it obeys Poiseuille's law which states that the flow varies as the fourth power of the pore radius. Hence the permeability is strongly dependent on pore size distribution. Diffusion, on the other hand, depends primarily on the total volume and tortuosity of continuous pores available for diffusion. The reason that diffusion does not depend on pore size distribution is that the mean free path of molecules is of the order $1 - 5 \times 10^{-7}$ m, which is much less than the radii of the pores which generally account for most of the soils air filled porosity.

The technique developed by **Ansto** to measure gas permeability involves injecting gas into a waste rock pile at a known flow rate and measuring the resulting gas pressure rise in the material in that region; the lower the gas permeability of the material in the pile, the higher the pressure measured for a given flow rate.

2. Instrumentation

Figure 1 shows the schematic arrangement used for the measurement of gas permeability and includes a simplified representation of the special backfill installation.

Figure 2 shows the backfilling scheme which the authors recommend for use in probe holes which are to be used for gas permeability measurements. The aim of the backfill is to provide a high permeability chamber around the openings of the gas sampling tubes, and to isolate these chambers from each other by the lower permeability materials, sand and bentonite.

The gas tubes should be stiff nylon pressure tubing, about 3 mm internal diameter, such as is used in pneumatic systems. Two tubes are fixed diametrically opposite each other at each metre depth along the central PVC liner. The tubes are left open in the backfill and capped with Schrader valves above the surface of the waste rock.

The cylinder of compressed gas shown in **Figure 1** can be either air or nitrogen since they have the same viscosity. The measured parameter is then termed the *air permeability*. An advantage of using nitrogen is that it does not promote oxidation in the waste rock system.

The gas is introduced into the pile through the Schrader valve connectors on the nylon gas tubes and the flow rates are measured using an electronic flowmeter. The measurement system incorporates a mass flow meter which has been calibrated for flows from 2 to 100 L/min, model F-112C-HA, manufactured by Bronkhorst Hi-Tec BV, Ruurlo, The Netherlands.

The pressure rise in the vicinity of the injection point is measured by connecting the nylon tube adjacent to the injection port to a sensitive differential pressure transducer. To check for air flow 'short-circuiting' along the liner through the backfill and past the bentonite plugs, gas pressures should also be monitored at the ports one metre above and below the injection port. The differential pressure transducers used in the system are made by Modus Instruments Inc. (Northborough, MA, USA), model T10, with a pressure range of ±1.0" water column (254 Pa). The pressure transducers should be calibrated once they have been installed in the measurement system.

The data acquisition system links the electronic transducers to a portable DOS-based computer with floppy disk drive through an analogue-to-digital interface card. In normal operation the output of the flowmeter and pressure transducers are scanned and logged once per second. The logger software causes a beeper to sound after every scan, to give the operator an indication of elapsed time without needing to watch a clock display. The computer screen displays the gas flow rate and the voltage output of the three pressure transducers.

The equipment can be powered by an external 12 volt power supply; a car battery is sufficient for continuous operation during a day.

3. Field Measurement and Interpretation

At the commencement of a measurement, data is logged for at least ten seconds with no flow, to establish the zero levels on the flowmeter and transducers. To be certain that there is no flow, this is usually carried out with the gas inlet line to the flowmeter disconnected. Following this, the gas regulator shown in Figure 1 is used to adjust the air or nitrogen flow down the required gas port.

During the course of a measurement, the flow rate should be increased in about five increments over the maximum range, bearing in mind that this range is imposed by either the flowmeter or the differential pressure transducer, depending on the air permeability in the region of the measurement. Once a steady flow rate is established it should be maintained for at least fifteen seconds to ensure that steady-state physical and instrumental conditions are achieved. After the measurement at the highest flow rate has been completed, further measurements should be made as the flow is stepped back down through the range, again logging the data for at least fifteen seconds at each step. Finally, the gas flow should be turned off and the data from the transducers logged until steady readings are observed, to re-check the zero values of the system.

The data collected during this measurement cycle, from zero flow, stepping the flow in increments to a maximum and stepping back to zero, constitutes a complete set for the determination of the air permeability of the waste rock pile in the vicinity of the injection port.

At the commencement of a new measurement, it is particularly important to pay close attention to both the flow rate and the consequent pressure rise because the sensitive pressure transducers can be easily damaged by over-pressure. It needs to be recognised that the maximum allowable pressure can be reached rapidly, even at low flow, if the waste rock material has a particularly low permeability or if the probe hole in that section has been drilled and backfilled through a boulder.

Another situation which may be encountered is where no pressure rise is measured, irrespective of the gas flow rate. This can be due to the liner having passed through a void in the waste rock pile, resulting in a poorly backfilled section.

Care should be taken when measurements are made in ports near the base of a pile. Ports lying in a saturated zone may be blocked, with the result that there is no flow when the gas regulator is opened. This could lead to the electronic flowmeter being damaged due to over-pressure, or even to a potentially dangerous situation arising due to gas pressurising the tubing on the outlet side of the flowmeter. Along the same lines, it is possible that gas can flow into the aquifer and that the increased pressure can force water into one of the pressure monitoring ports, or conceivably water could be pulled out. If water in the nylon tube rises or falls much more than 25 mm, the differential pressure transducer can be damaged, due to over-pressure.

4. Data Analysis

4.1 Data Validation

The logged data from the flowmeter and three pressure transducers are recorded as ASCII files during the field measurements. For ease of handling and analysis, these files should be read into a spreadsheet software package which has statistical and scientific formulae capabilities, such as *Wingz* (Informix Software Inc, Lenexa, Kansas, USA).

Before detailed analysis, each set of measured data should be inspected to check that there was no significant flow of gas from the central gravel chamber containing the injection gas port, through the bentonite plugs, to the adjacent chambers above and below. This is most easily done by plotting the voltage output from the three differential pressure transducers versus scan number.

Figure 3 shows an example of such a plot produced by *Wingz*. The plot is made up of three histograms, each one showing the measured pressure in a port as a function of time, over the course of an air permeability measurement. The axis labelled 'Relative Pressure Rise' represents the output of the differential pressure transducers in milliVolts. The central port, labelled '2', shows the pressure which was monitored in the air flow chamber, and the other two show the consequent pressure rise in the adjacent gravel chambers. The plot shows that there is no significant leakage from port 2 to port 1, but the pressure rise in port 3 is about 80 percent of that in port 2, representing an unacceptably high flow of gas from chamber 2 to chamber 3. As it stands, this plot indicates that the conditions for a valid air permeability measurement have not been met and consequently the data must be rejected. If on the other hand the pressure rise in port 3 had been similar to that in port 1, the data would be accepted for the next stage of analysis, where air permeability values are calculated according to the method discussed below.

4.2 Air Permeability Equation

Air permeability values can be obtained by comparing the field measurements with the results of a numerical model of the system. The modelling was done using the computer code *PDE/PROTRAN* (released by IMSL), which is a system for the solution of partial differential equations whereby spatial discretisation is performed by the finite element (Galerkin) method, using triangular elements. **Figure 4** summarises

the general equations of flow in porous media and presents the equation solved by *PDE/PROTRAN* for this work.

One of the assumptions made in the modelling was that the air can be treated as an incompressible fluid. Whilst this is clearly not strictly true, the maximum pressure that can be tolerated by the measurement system is only 250 Pa above the atmospheric pressure of 101.3 kPa. At these very low pressures, gas compression is considered to have an insignificant effect on the behaviour of the dynamic system.

The geometry of the waste rock pile was modelled as being spherical, having a large radius of 10 m, which may be considered to be effectively infinite, with a probe hole and liner through the vertical diameter. The liner tube was represented as having a diameter of 60 mm in a drilled hole of 200 mm (7.9") diameter. Three backfilled sections were included, with air being injected into the central gravel chamber at a flow of 20 L min^{-1}. The modelled geometry is shown in **Figure 5**. The air permeability of the backfill materials were chosen on the basis of laboratory measurements to be 2.2×10^{-8}, 4.4×10^{-10} and 2.2×10^{-11} m^2 for the gravel, sand and bentonite respectively.

The output of the model gave gas pressure as a function of space throughout the system. By processing a large number of runs over a range of values for the air permeability of the waste rock, a relationship was established between the pressure rise in the air injection chamber and the air permeability. The relationship can be written as

$$K = e^{\frac{lnP_{20} + 14.5644}{-0.81026}} \qquad (2)$$

where K is the air permeability (m^2) and P_{20} is the gas pressure rise (Pa) measured at the port adjacent to the air flow port, resulting from an injected air flow of 20 L min^{-1}. In practice, the value of P_{20} is obtained by dividing the measured pressure rise P_m (Pa) by the flow producing it F (L min^{-1}) as a fraction of 20 L min^{-1}, such that

$$P_{20} = \frac{P_m \times 20}{F} \qquad (3)$$

The relationship given by Equation (2) is graphed in **Figure 6**. The upper limit on the air permeability of waste rock which can be measured seems to be related to the permeability of the gravel backfill surrounding the gas ports.

It should be noted that Equation (2) is only applicable to sites where the probe hole installations match the modelled parameters of the drilled hole and liner diameters, backfill material permeabilities and backfilled section lengths. If these are varied significantly, the new system should be modelled to establish the appropriate relationship.

4.3 Data Processing

Having checked that there has been no significant gas leakage between the gravel chambers, as described in **Section 4.1**, the field data in the spreadsheet should be further processed to obtain values of air permeability.

As has been seen above, the data required for the calculation of air permeability are the air flow and gas pressure rise adjacent to the air flow port. The data collected during the initial 'no flow' period can be used to establish zero reference levels for the flowmeter and pressure transducer.

Using the capabilities of the spreadsheet package, a value for air permeability can be calculated for each individual scan during the course of a measurement. A graph can then be produced showing both the air permeability and the air flow rate as a function of scan number such as that shown in **Figure 7**. An overall value for the air permeability of the waste rock pile at the position of the particular gas flow port can be read from the graph, making appropriate allowances for spikes which may appear. Such spikes occur mainly because of the differing response times of the transducers when the air flow rate is changed. This is why a steady gas flow should be maintained for at least fifteen seconds before it is altered. The general variation of the curve about the mean can be used to estimate the standard deviation on the air permeability. The standard deviation is usually less than about 15 percent on individual measurements. This analysis is unable however to provide any indication of systematic errors arising from differences between the modelled and field systems, as referred to in **Section 4.2**.

The graph presented in **Figure 8** shows an example where the air permeability curve closely tracks the air flow rate. This indicates that the assumption that the pressure rise is proportional to the air flow is not valid in this case and therefore the measurement must be disregarded. Such a curve may result from a situation where the pressure remains relatively constant as the air flow is increased, due to a poorly backfilled section, for example.

5. Acknowledgements

The assistance of Dr Garry Pantelis with the mathematical modelling study is gratefully acknowledged, as is the contribution of Mr Alan Boyd and Mr Warren Hart in the design and construction of the air permeability apparatus.

6. Reference

Hillel, D. 1980. *Fundamentals of Soil Physics*. Academic Press, New York.

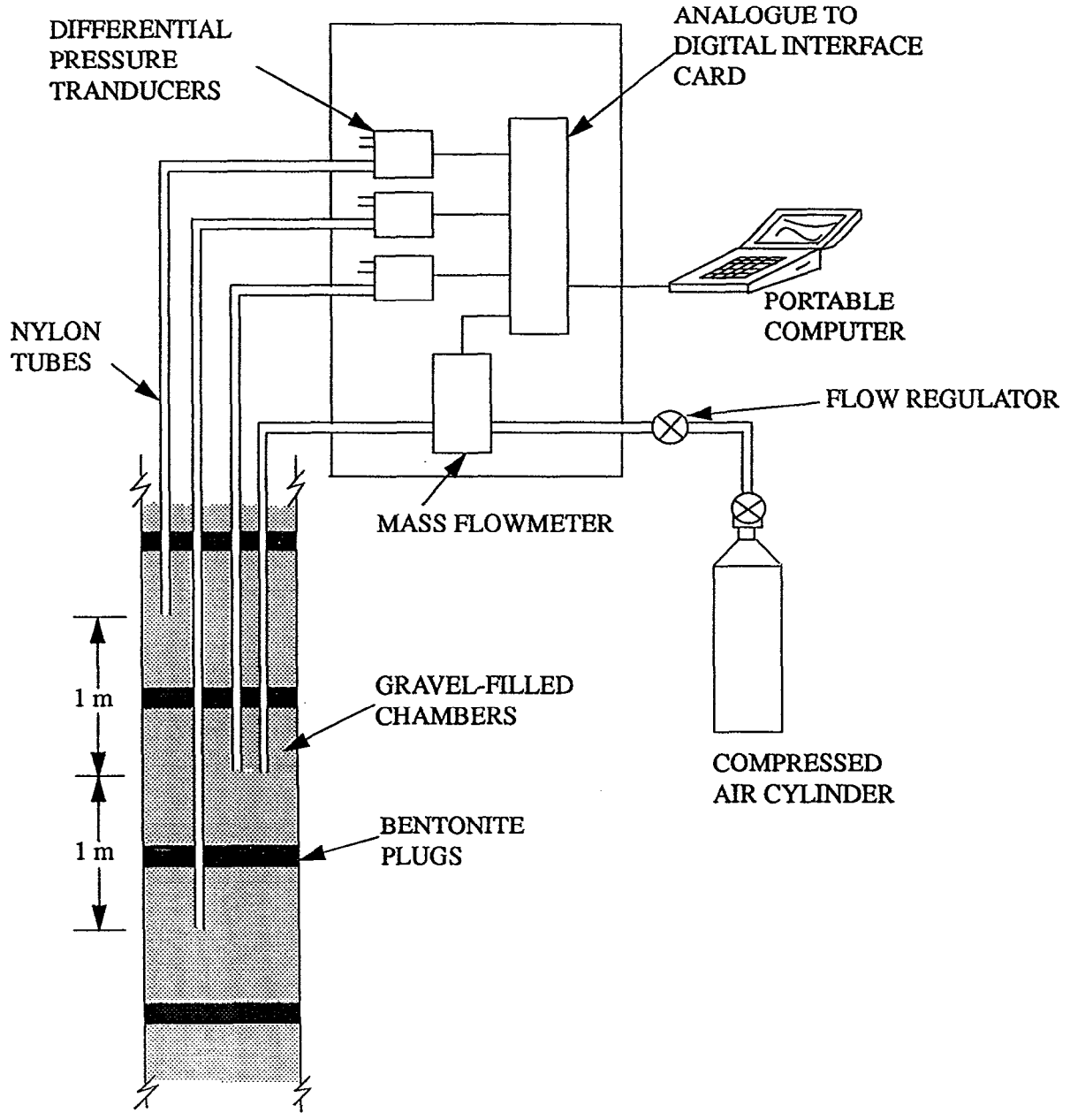

Figure 1. Schematic diagram of the apparatus for measuring air permeability showing three adjacent sections of the probe hole backfill (the sand-filled lengths are not included). A compressed nitrogen cylinder can be substituted for the one of air.

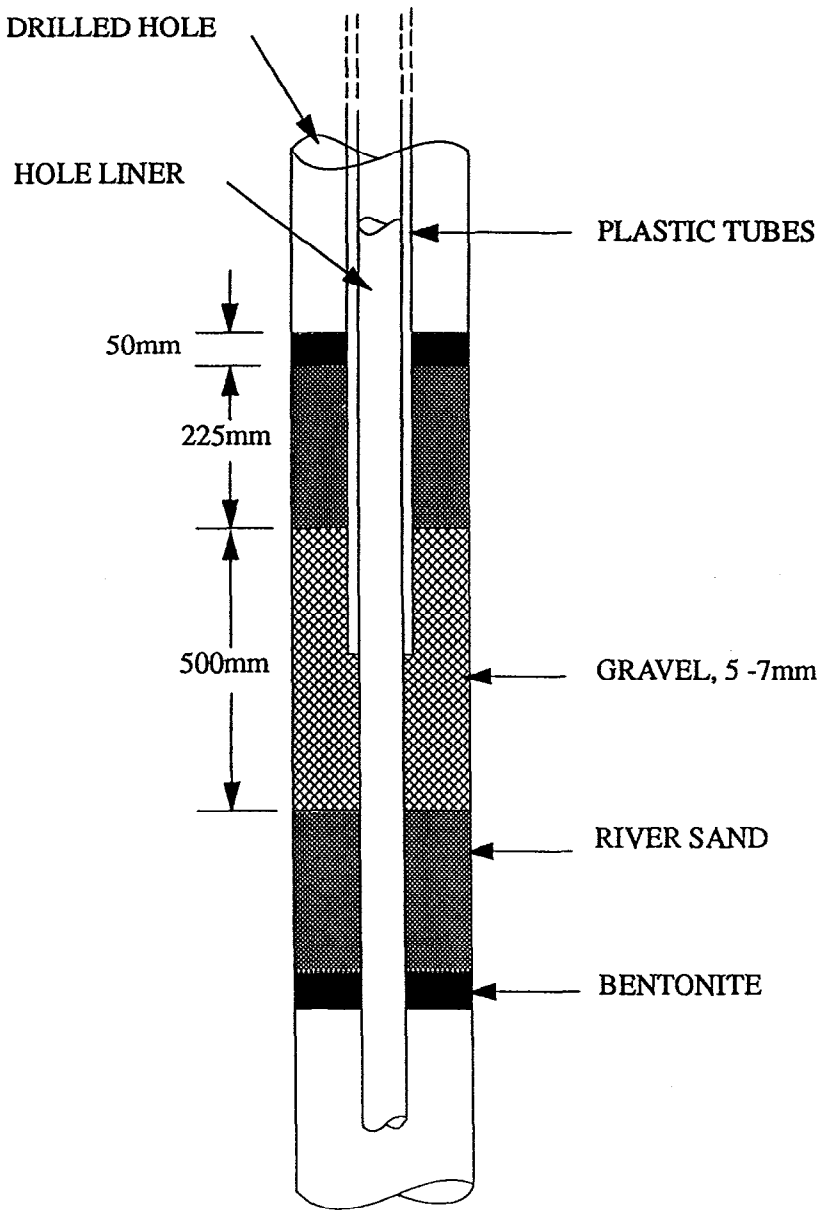

Figure 2. The backfilling scheme in probe holes to be used for gas permeability measurements.

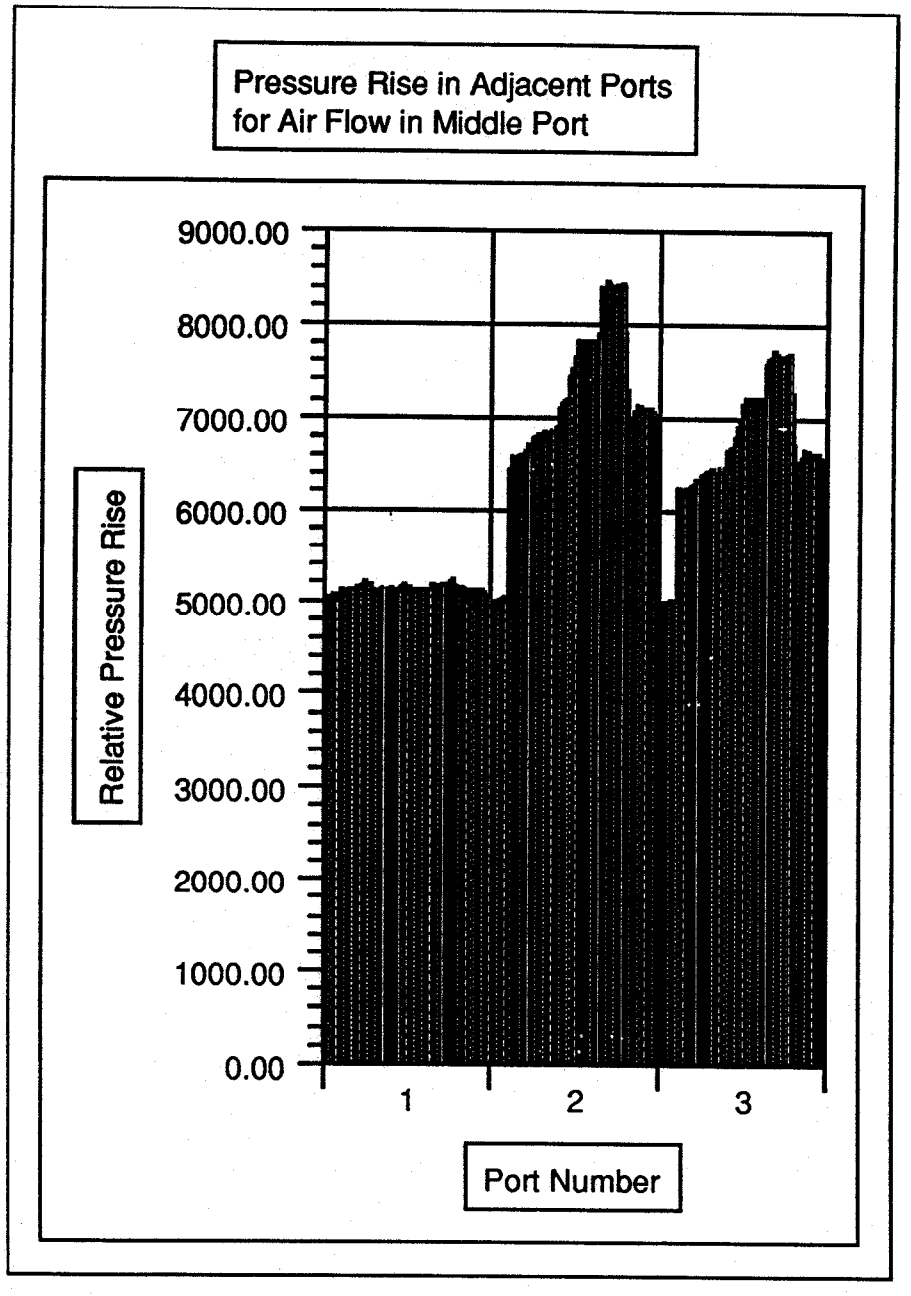

Figure 3. Voltage output from three adjacent pressure transducers, used to check for gas leakage between measurement pots.

Figure 4.

GENERAL EQUATIONS OF FLOW IN POROUS MEDIA

1. Continuity Equation, steady state

$$\nabla \cdot (\rho \underline{q}) = 0$$

2. Darcy's Law

$$\underline{q} = -\frac{k}{\mu}(\nabla p - \rho \underline{g})$$

Assume
- incompressible fluid
- gravity negligible
- k constant in each subdomain

3. Equation Solved by PROTRAN

$$-\left(\frac{k}{\mu}\right)\nabla^2 p = 0$$

where

• p	is fluid pressure	($N\ m^{-2}$)
• q	is mass flux of fluid	($kg\ m^{-2}\ s^{-1}$)
• k	is permeability of medium	(m^2)
• μ	is kinematic viscosity of fluid	($m^2\ s^{-1}$)
• ρ	is density of fluid	($kg\ m^{-3}$)

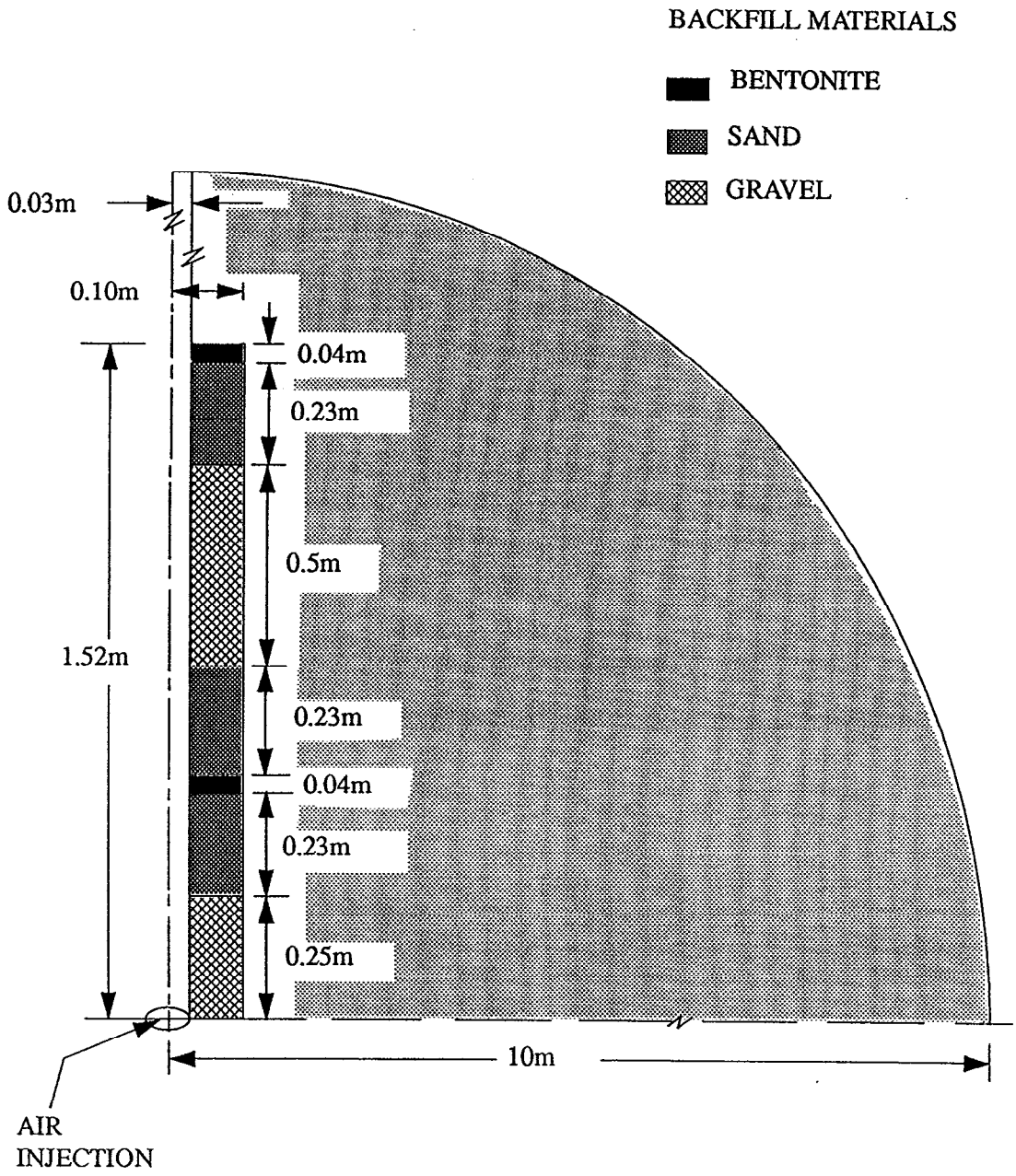

Figure 5. The dump and probe hole geometry modelled by PDE/PROTRAN.

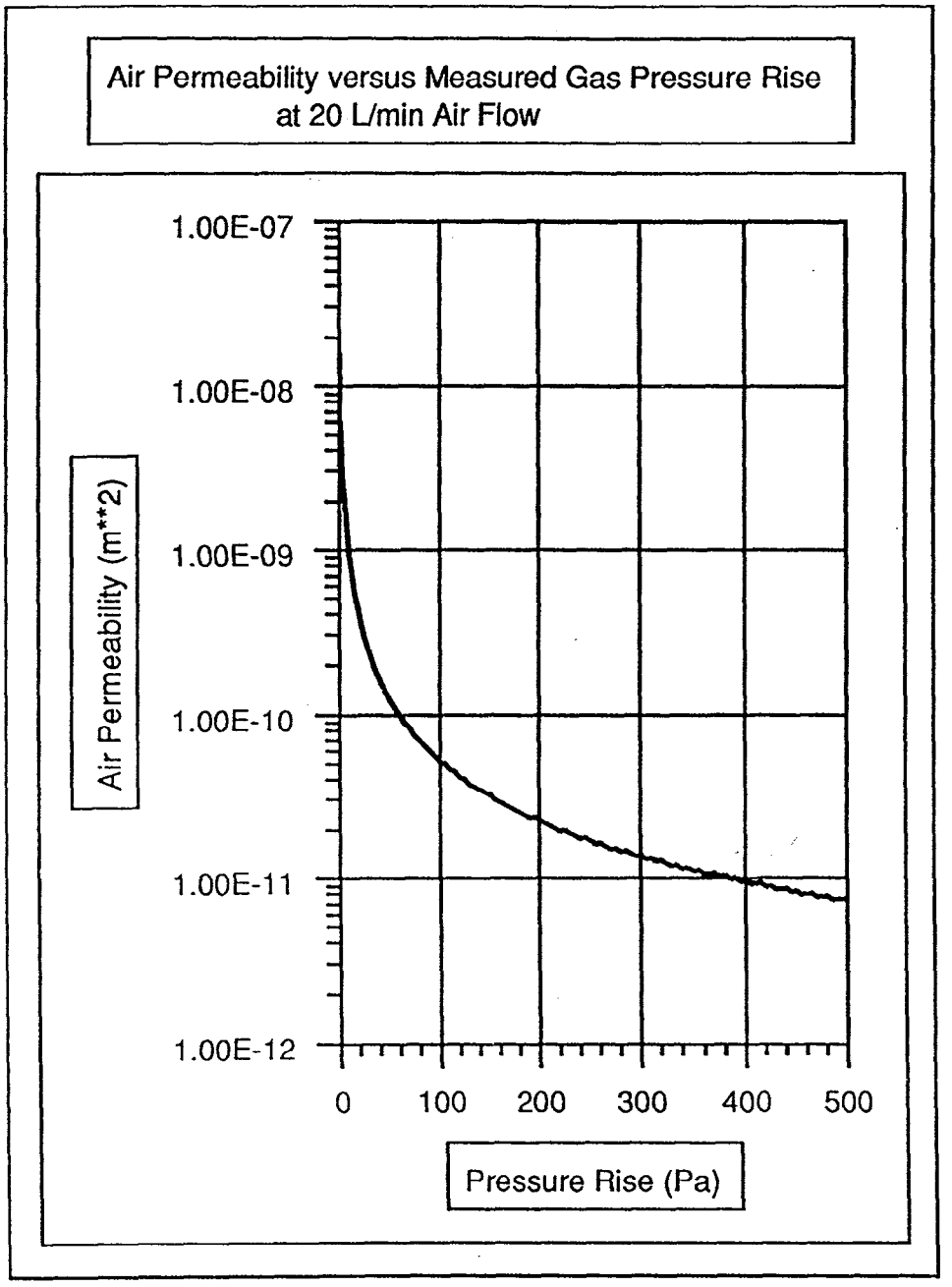

Figure 6. The relationship between the measured gas pressure rise in the vicinity of the gas flow injection point and the air permeability of the waste rock.

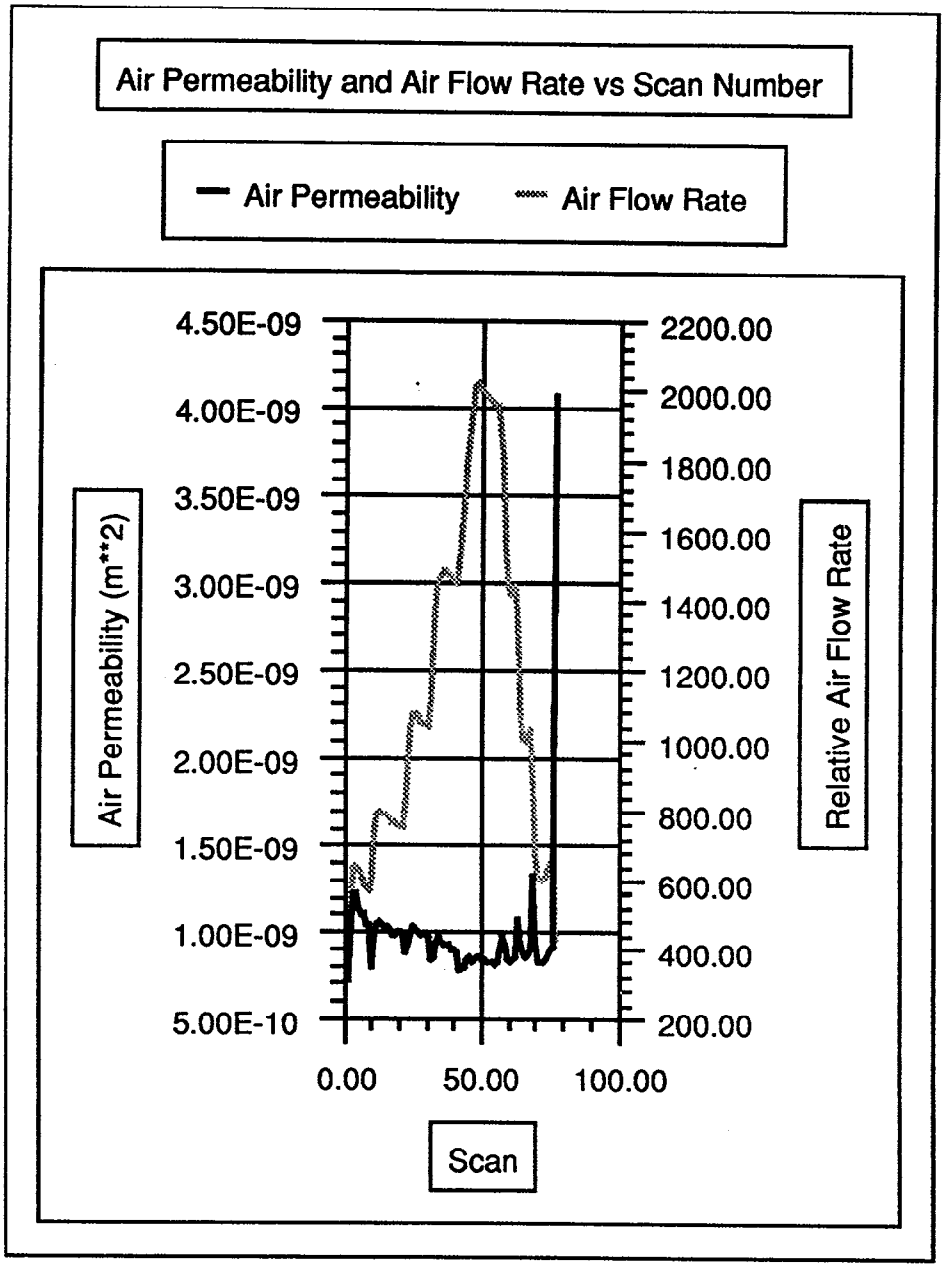

Figure 7. Air permeability and air flow rate as a function of scan number, used to check the validity of the measured data and to determine the overall value of air permeability and its standard deviation.

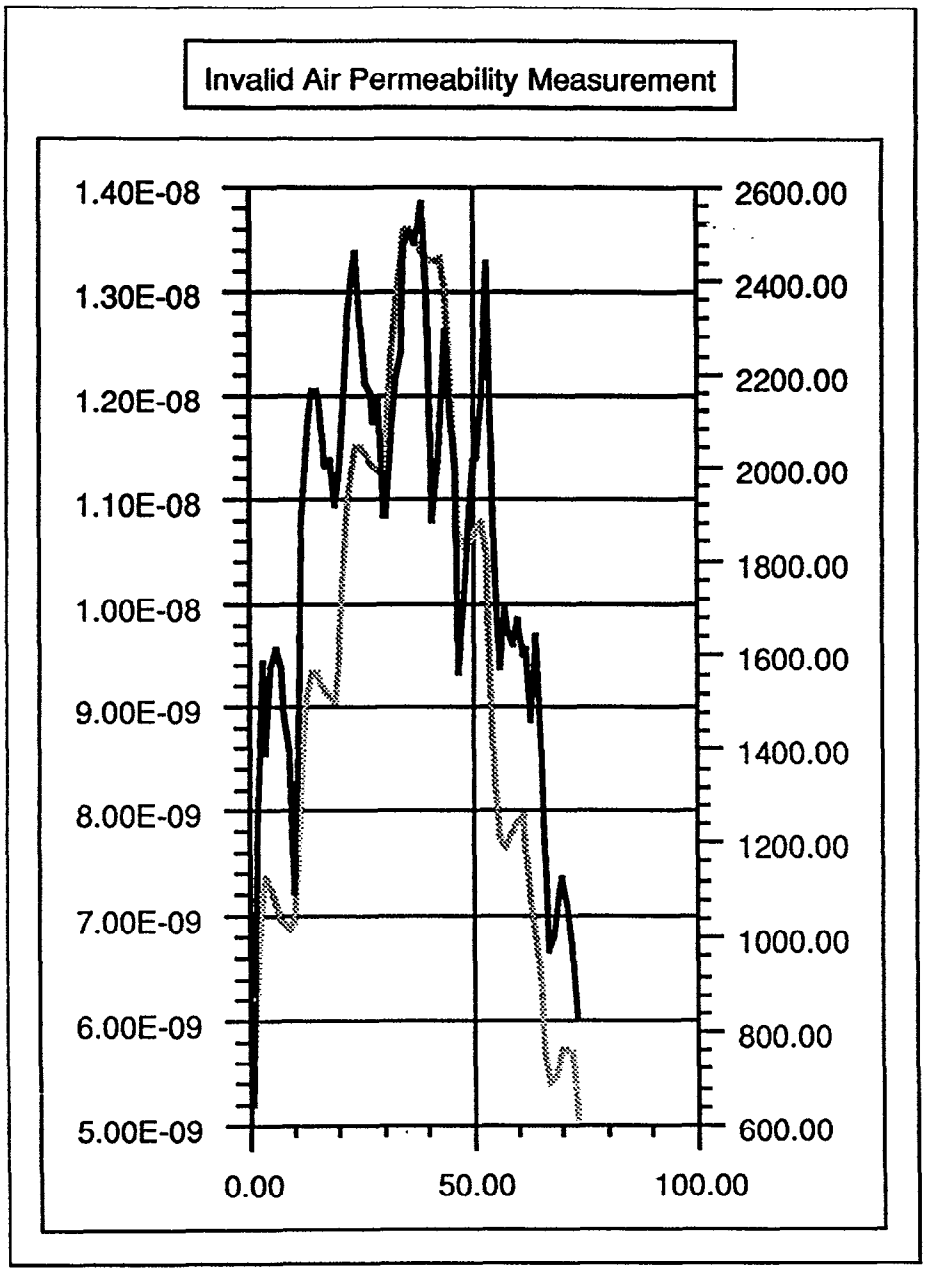

Figure 8. An example of an invalid set of data, where the air permeability closely tracks the air flow rate.

APPENDIX IV

GAS DIFFUSION

ANSTO/C318

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A Report to
Nolan, Davis & Associates (NB) Ltd
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GAS TRANSFER IN WASTE ROCK DUMPS
AT THE HEATH STEELE MINE

FIELD PROCEDURES MANUAL
MEASUREMENT OF GAS DIFFUSION COEFFICIENTS

by

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1. Introduction

The constant of proportionality relating oxygen flux to oxygen concentration gradient is termed the oxygen diffusion coefficient, D_{O2}. Direct determination of the diffusion coefficient of oxygen is made difficult because the oxygen is consumed by the pyritic oxidation reactions at rates which vary in both space and time. The difficulty arises in distinguishing between changes in oxygen concentrations caused by oxygen transport from those caused by oxygen consumption. Introducing an inert tracer gas simplifies the task by removing this ambiguity. In the method described here a volume of sulphur hexafluouride (SF_6) is injected into a waste rock pile as a tracer, establishing a concentration gradient, its diffusion coefficient in the waste rock pile is measured and the corresponding diffusion coefficient of oxygen is deduced.

Following the injection of a point source of a diffusing tracer gas, the concentration of the gas as a function of space and time, *c(r,t)*, can be described by the relationship

$$c(r,t) = \frac{(\Theta/\varepsilon)\, exp\,(-\frac{r^2}{4Dt})}{(4\pi Dt)^{3/2}} \qquad (1)$$

where Θ is the quantity of tracer injected (Θ is the number of molecules of SF_6), ε is the gas filled porosity, D is the diffusion coefficient of SF_6 in the pile material, r is the distance between injection and measurement points, and t is the time elapsed between injection and measurement. This relationship can be solved to obtain the diffusion coefficient, D, where Θ is known and *c(r,t)* is measured in the field.

2. Instrumentation

The determination of oxygen diffusion coefficients *in situ* is based on the measurement of the concentration of SF_6 tracer gas using a commercially available electron capture detector gas chromatograph (GC), optimised for SF_6 detection. There is an extensive literature describing gas chromatography (Ettre and Zlatkis, 1967 and Littlewood, 1970, for example).

Gas chromatography is a method of separating components of mixtures of volatile compounds. The principal component of the apparatus is the diffusion column. In the instrument modified by the authors, shown schematically in Figure 1, the column is a long stainless steel tube packed with a permeable adsorbent powder. A stream of inert gas such as argon, known as the carrier gas, flows continuously through the column. The sample of gas is injected into the column as a slug in the carrier gas stream by means of a multi-way valve. In a mixed sample, the gas constituents are free to behave independently, depending on the characteristics of each species. For a given carrier flow rate, each constituent gas moves at a different speed, depending on its interaction with the diffusion column, so that they arrive at the detector at different times. The electron capture detector at the exit of the column produces a roughly Gaussian response when an electronegative gas such as oxygen or sulphur hexafluouride is introduced. Thus, the system can distinguish between

electronegative gas components in a sample if the difference between the time of arrival of these gases at the detector is great enough for the response peaks to be resolved. In the instrument described here, the oxygen peak arrives first, followed by the SF_6 peak some five seconds later and the two are well resolved.

Data acquisition in the system is via an analog-to-digital data acquisition board (**Ansto** General Purpose Parallel Port Interface) and a portable DOS-based computer (Toshiba T1200). Purpose-written software produces plots of the chromatograph response after each measurement, providing an immediate indication of the relative SF_6 concentration.

3. Field Measurement and Interpretation

The technique developed by the authors to measure gas diffusion coefficients *in situ* in waste rock piles requires two vertical probe holes to be spaced at a distance of between 2.5 and 3.5 metres apart; the tracer gas is injected at a single depth in one of the holes, at least three metres below the pile surface, and its subsequent arrival at the second hole is monitored. Movement of SF_6 directly along the backfill surrounding the installed liners is avoided by including a layer of bentonite both above and below the injection port, as illustrated in Figure 7. The depth and position of injection and monitoring are chosen so as to minimise the effects of pile boundaries, where rapid changes in gas diffusion coefficients at, for example, a compacted cover, an underlying aquifer or the air boundary, may complicate the analysis of the field measurements. The separation between the injection and monitoring probe holes must be large enough that the gas diffuses through materials representative of the types and distribution found in the dump, but not so large that measurements have to be carried out for too long. For separations between 2.5 and 3.5 metres, measurements need to be made at intervals over 2 or 3 days.

The effects of advective and convective gas movement, known as mass flow, on the tracer concentration distribution can be complicated and difficult to separate from those of diffusion. To ensure that the tracer gas moves solely due to diffusion the measurements should be made in regions of a pile where the magnitude of mass flow is expected to be small. Regions away from the batters or under a capping with low air permeability are most likely to be suitable.

Sulphur hexafluouride concentration measurements are made in a pile as a function of space and time by means of gas sampling ports installed in probe holes. The ports consist of nylon pressure tubing, about 3 mm internal diameter, which are buried in the backfill of probe holes drilled in a waste rock pile. Each port is left open at the bottom and attached to a Schrader valve above the surface. There is a gas sampling port at each metre depth in a probe hole. Gas samples are drawn from the ports in the appropriate probe hole using a hand-held vacuum pump which is plumbed through the gas chromatograph. Samples are taken at several depths greater than 3 metres below the surface of the pile and at several times to ensure that the diffusion coefficients determined are representative of the dump bulk material rather than of a local anomaly. For example, it is possible for a drilled probe hole to pass through a boulder, with the consequence that any gas diffusion determinations made using data

from gas sampling ports lying within or near such a boulder are likely to be perturbed by its presence. It is recommended therefore that a record be kept in the drilling log when a probe hole passes through a boulder and any ports in its vicinity not be used for either tracer injection or sampling in subsequent determinations of gas diffusion coefficients. It should be noted that such localised effects on gas concentrations may only be observed because the technique described here involves the measurement of a transient system and is carried out over a relatively short time, usually a couple of days; the measurement of parameters such as pore gas oxygen concentration is unaffected by such inhomogeneities because those gases are in quasi-equilibrium.

In a typical measurement program, the SF_6 tracer would be injected 7 m below the heap surface in a heap greater than 14 m in height. Measurements of SF_6 concentration would be made at ports 4 to 10 m below the surface in a hole 2.5 m from the source at intervals of 3 hours.

The way that the gas chromatograph has been used to measure gas diffusion coefficients is described in detail in the sections below.

3.1 Calibration

The analysis of diffusion data from the field requires absolute rather than relative values of the measured sulphur hexafluouride concentrations. It is therefore essential that the measurement equipment is carefully calibrated. Calibration measurements should be made at SF_6 concentrations spanning several orders of magnitude, as appropriate for the particular GC being used. An example calibration curve for the instrument described here is presented in Figure 2.

3.2 Gas Injection

The amount of SF_6 injected is dependent on the operating range of the SF_6 detector, and the product of the diffusion coefficient and the maximum time over which measurements are taken. To determine Θ, the number of molecules of SF_6 to inject, estimates must be made of:

- R_m, the upper limit on the amount of SF_6 that the detector can measure, as a fraction of the total gas. That is, R_m is the maximum value of the quantity given by $[SF_6]/[\text{background gases}]$ which the detector can measure, where the square brackets designate concentration, *i.e.* the number of molecules per m^3, and background gases are all gases other than SF_6;
- r, the distance between the point of injection and the closest detection point; and
- D, the diffusion coefficient of the material in the pile.

In practice the ratio R_m is small and consequently SF_6 can be included as a background gas in the calculation of R_m.

Next, an estimate must be made of the maximum concentration of SF_6 per unit amount of SF_6 injected that will be measured at the sampling point in the time over which the data will be collected, *i.e.* $X = \{c(r,t)/\Theta\}_{max}$. This can be obtained by using

Equation (1) to plot a curve of $c(r,t)/\Theta$ as a function of time for a typical value of D, such as that shown in Figure 5, where $X \sim 1.6 \times 10^{-3}$ at the end of two days. The number of molecules of SF_6 to inject, Θ, is given then by

$$\Theta = (R_m/X)\ [background] \qquad (2)$$

where $[background] = 2.51 \times 10^{25}$ molecules m^{-3} at 20°C and 1.013×10^5 Nm^{-2} (1 atmosphere). The volume of pure SF_6 containing this number of molecules can readily be determined from the Gas Law, $PV = NkT$, where N is Avagadro's number (6.022×10^{23} m^{-3}) and k is the Boltzmann constant (1.38×10^{-23} $J K^{-1}$).

Considering an example to which Figure 2 applies, a conservatively chosen value of R_m is 2.0×10^{-7} and if the measurements are made up to 1.75×10^5 seconds after injection then, from Figure 5, $X \sim 1.6 \times 10^{-3}$ and from equation (2) the number of molecules of SF_6 to be injected is 3.14×10^{21}. Assuming the source of SF_6 is pure then the volume to be injected is given by

$$V = \frac{NkT}{P}$$

and is 125 mL. It should be noted that an improvement in the diffusion coefficient values may be obtained by measuring at later times. Notice, however, that the injected volume must be calculated from the maximum value of the concentration of SF_6 likely to be detected.

The required amount of SF_6, Θ, is diluted prior to injection in a volume of approximately 3 litres of nitrogen. This volume is sufficient to fill the pore space of the gravel section surrounding the injection port. A hose from the bag containing SF_6 is connected to the Shrader valve fitting (with the valve itself removed) of the selected gas port and the bag is then carefully compressed to inject the tracer gas into the pile.

3.3 GC Operation

A single SF_6 measurement is made by connecting the gas chromatograph inlet to the appropriate gas port and drawing in a sample of pore gas. A number of estimates of D can be made by sampling at each port at a number of times. This will allow estimates of both the variation of and error in the determined diffusion coefficients. The instrument has a motorised pump in series with the detector for this purpose (Figure 1). With the multi-way valve in the *flush* position, as shown in the figure, gas is drawn continuously from the sample port, through the sample loop and out through the exhaust line. Throughout this operation carrier gas continues to pass through the column and detector. Once the operator is satisfied that the gas being drawn through the sample port is actually from the pile pore space rather than from the connecting tubing, typically after 20 seconds pumping, the multi-way valve is rotated to the *inject* position for two seconds and returned. During this operation the gas route is switched from the *flush* route of Figure 1a to the *inject* route of Figure 1b,

and back again. The effect of this is that the fixed volume of sample gas in the sample loop is inserted as a slug in the carrier gas stream flowing to the column and electron capture detector (ECD). The output current of the detector is reduced by the presence of electronegative gases, in particular oxygen and SF_6. As has been described, the diffusion column separates the time of arrival of any oxygen and SF_6 at the detector.

3.4 Data acquisition Hardware

The current from the ECD is recorded on a DOS-based laptop (Toshiba T1200) after passing through an analog-to-digital converter. Purpose-written software produces plots of the chromatograph current after each sample is measured, providing an immediate indication of the SF_6 concentration and measurement reliability.

Figure 3 shows the relationship between detection equipment, power supplies, temperature measurement circuits and the data storage computer. A thermistor and associated I-V circuit shown in the figure allows the temperature in the SF_6 detector housing to be recorded. This is to confirm that the instrument is operating within its temperature limits and to allow for data correction if any temperature-dependent effects are subsequently identified.

3.5 GC Output

As well as the SF_6 tracer, oxygen may be present in pore gas samples withdrawn from waste rock piles. Although both these gases produce a response in the chromatograph, the column is able to adequately resolve them, as indicated in Figure 4. It is noted that the GC has not been found to respond to any other naturally occurring gases in waste rock piles, making gas identification straight-forward. An example of how the expected value of concentration per injected amount of SF_6, $c(r,t)/\Theta$, varies with time is presented in Figure 5.

3.6 Precautions

Care must be taken in the field that the GC performance does not fluctuate due to changing environmental conditions. Sampling atmospheric air periodically during the course of a series of measurements provides an easy and useful means of checking the calibration of the system. Because the oxygen concentration in air is a constant 20.95 percent, any changes in the area under the measured oxygen peak reflect changes in the sensitivity of the chromatograph. This information can be used as a correction factor in analysing the field data.

Other precautions include:

- making a few measurements of pore gas samples before any tracer gas is injected into the pile. This is to confirm that there are no electronegative gases in the pile which might interfere with the later determinations of SF_6.
- drawing enough gas from the sampling port so that the measured gas sample is actually from the pile pore gas rather than the tubing,
- avoiding sampling gas which is likely to have an SF_6 concentration higher than

the upper measurement range of the instrument, as this may result in contamination of the GC column, interfering with subsequent measurements,

- avoiding column contamination with water vapour. Experience has shown that the natural humidity of pore gas samples does not cause a problem, but care should be taken to remove any condensation in the top of the sampling port or in the Schrader valve.

4. Data Analysis

Following the injection of a point source of a diffusing tracer gas, the concentration of the gas as a function of space and time, $c(r,t)$, can be described by the relationship

$$c(r,t) = \frac{(\Theta/\varepsilon)\, exp\,(-\frac{r^2}{4Dt})}{(4\pi Dt)^{3/2}} \qquad (3)$$

where Θ is the quantity of tracer injected (Θ is the number of molecules of SF_6), D is the diffusion coefficient of SF_6 in the pile material, r the distance between injection and measurement points, and t is the time elapsed between injection and measurement. Figure 5 is an example of how the quantity $c(r,t)/\Theta$ varies with time at a distance $r = 3.77$ m, and for a diffusion coefficient $D = 5.0 \times 10^{-6}$ m^2s^{-1}.

The area under the measured SF_6 peak is determined and the corresponding SF_6 concentration inferred from the GC calibration curve. A value of the diffusion coefficient is then obtained by rearranging Equation (3) to give Equation (4) and solving for D. This is readily done by graphing both the left and right hand sides of the equation as a function of D; the solution is read from the intercept as shown in Figure 6. Alternatively, the transcendental equation may be solved numerically with the aid of an appropriate code such as the mathematical applications software package *Mathematica*, Wolfram Research Inc., Champaign, Illinois, USA.

$$c(r,t) \times D^{3/2} = \frac{(\Theta/\varepsilon)\, exp\,(-\frac{r^2}{4Dt})}{(4\pi t)^{3/2}} \qquad (4)$$

A first order correction is made to the measured SF_6 diffusion coefficient to give the oxygen diffusion coefficient on the basis that both gases diffuse through a background gas which can be approximated as air:

$$D_{O2} = (D_{O2_a}/D_{SF6_a}) \times D_{SF6} \qquad (5)$$

Literature values of D_{O2a} and D_{SF6a} at 22 °C and 1 atmosphere pressure are 2.04×10^{-5} and 1.09×10^{-5} m^2s^{-1} respectively, so Equation (5) becomes

$$(D_{O2})_T = (2.04/1.09) \times (D_{SF6})_T \qquad (6)$$

D is dependent on both temperature T and pressure p (Washburn, 1929), such that:

$$D = D_0 (T/T_0)^x p_0/p \quad (7)$$

where D_0 is the value of D at T_0 (= 273 K) and p_0 (= 1 atm.), x is a constant which theoretically lies between 1.5 and 2.0 and practically may be taken as 1.75 for these gases. Equation (7) can be used to obtain diffusion coefficients for oxygen at temperatures other than that at which measurements were performed.

Based on data collected by the authors at a number of mine sites, from the tropics to the Arctic, measured values of the oxygen diffusion coefficient in waste rock piles can be expected to range from 2×10^{-6} to 6×10^{-6} m^2s^{-1}, with random error of less than ± 30 percent.

5. Measurement and Analysis Summary

The following is a step by step list of operations required to measure the diffusion coefficient.

1. Check the pore gas for gases that cause a response in the detector,
2. Determine the amount of SF_6 to be injected,
3. Increase the volume of gas by adding N_2,
4. Inject gas,
5. Check the equipment calibration using the oxygen peak from a sample of atmospheric air,
6. Make measurements at intervals of 2.5 hours for 48 hours or until the concentrations outside the equipment detection range,
7. Determine the area under the chromatograph peak,
8. From the chromatograph calibration determine the concentration of SF_6,
9. Substitute known parameter values into Equation (4) and graphically solve for D,
10. From the diffusion coefficient for SF_6 and Equation (6) determine the diffusion coefficient of oxygen.

6. References

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Washburn, E.W. 1929, *International Critical Tables of Numerical Data, Physics, Chemistry, and Technology* prepared by the National Research Council of the USA.

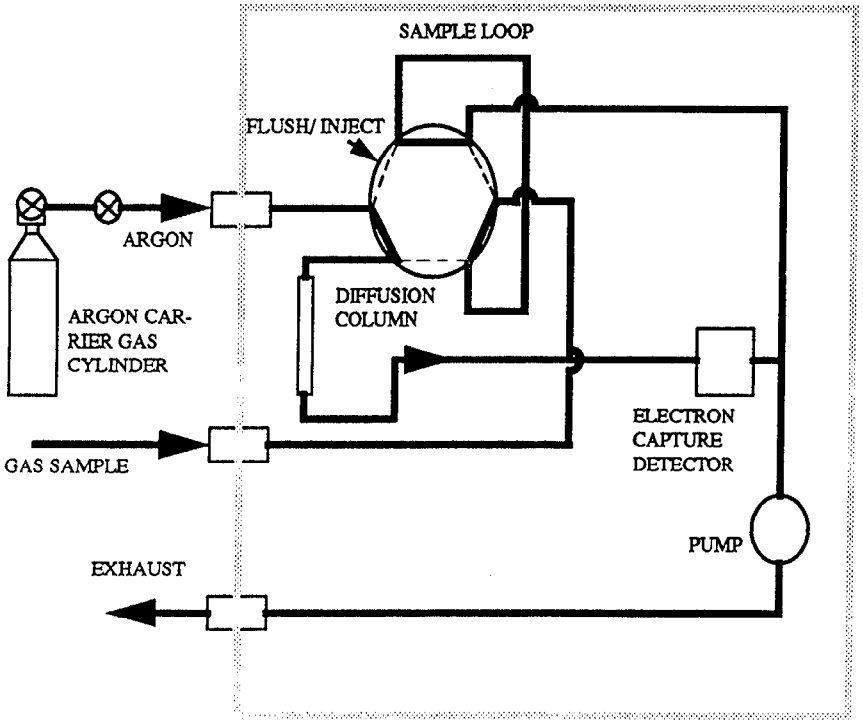

Figure 1a. Schematic diagram of electron capture detector gas chromatograph when in the *flush* position.

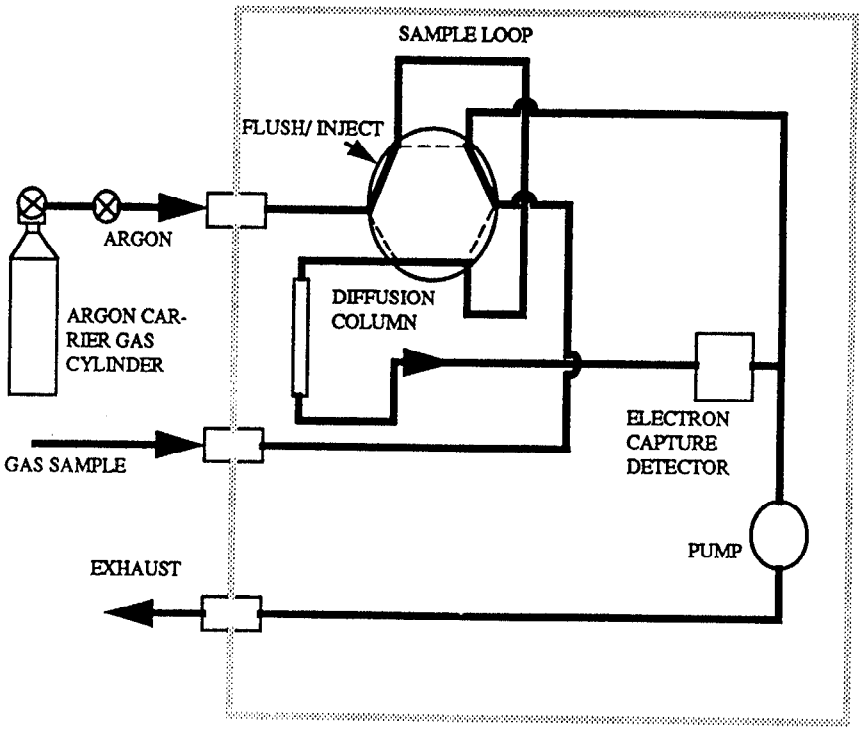

Figure 1b. Schematic diagram of electron capture detector gas chromatograph when in the *inject* position.

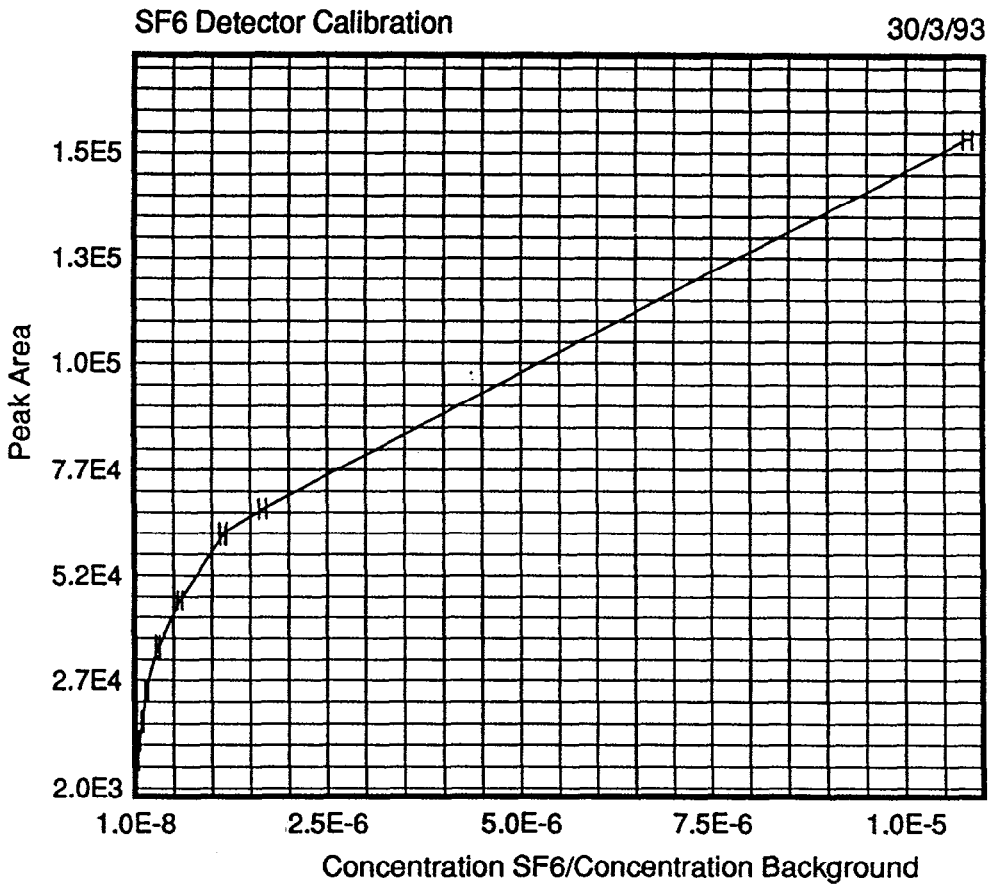

Figure 2. Calibration curve for the gas chromatograph.

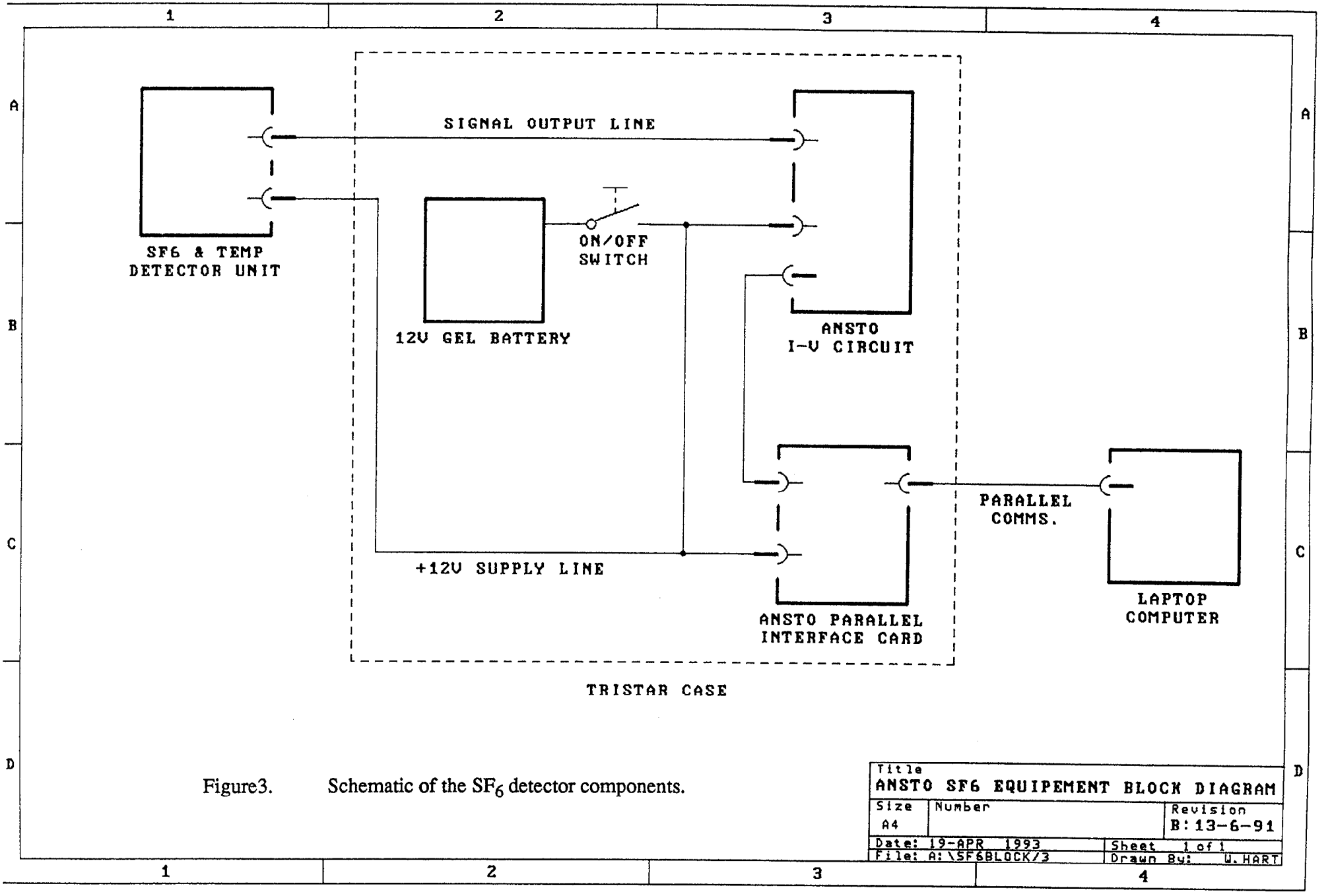

Figure3. Schematic of the SF_6 detector components.

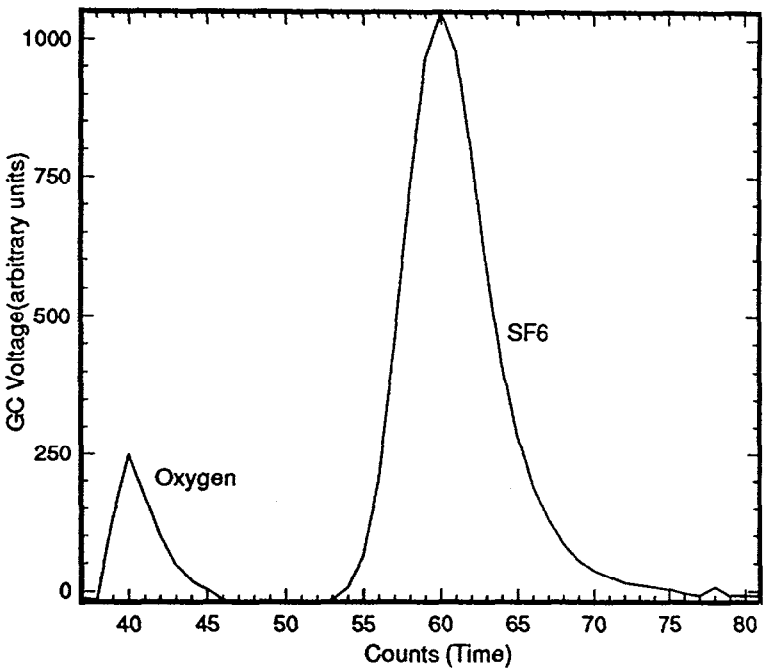

Figure 4. An example gas chromatograph from the GC showing good separation of O_2 and SF_6 peaks.

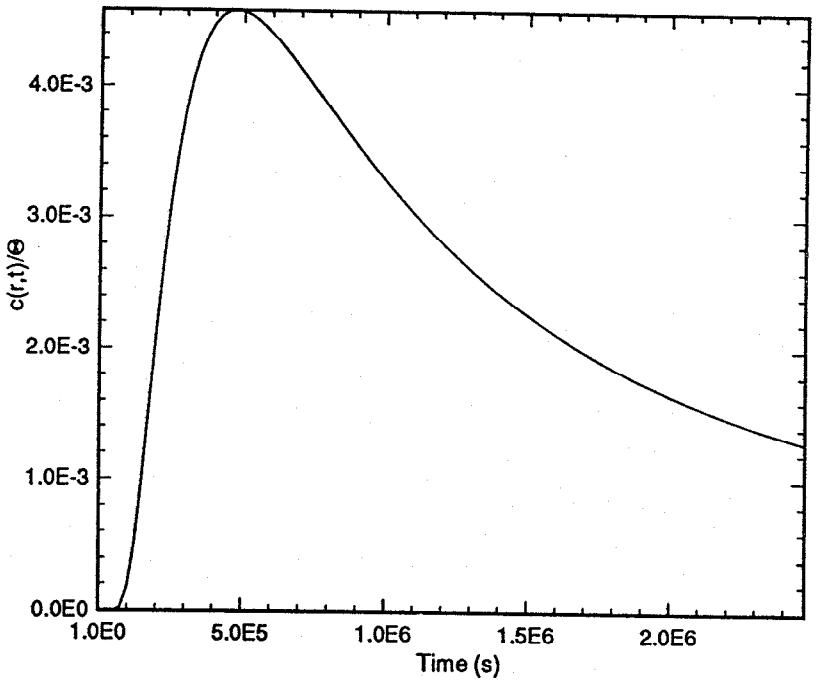

Figure 5. Concentration of tracer SF_6 in a pile per unit amount injected, $c(r,t)/\Theta$, for the point source model, at radius $r = 3.77$ m and $D = 5.0 \times 10\text{-}6$ m^2s^{-1}.

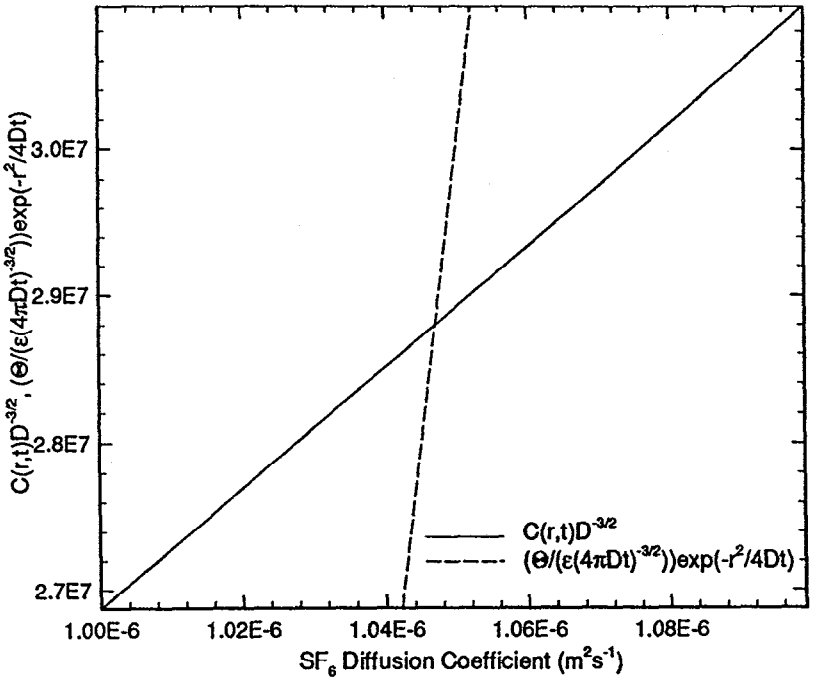

Figure 6. Graphical determination of the diffusion coefficient by plotting terms in the transcendental equation, equation (4), versus the diffusion coefficient, *D*.

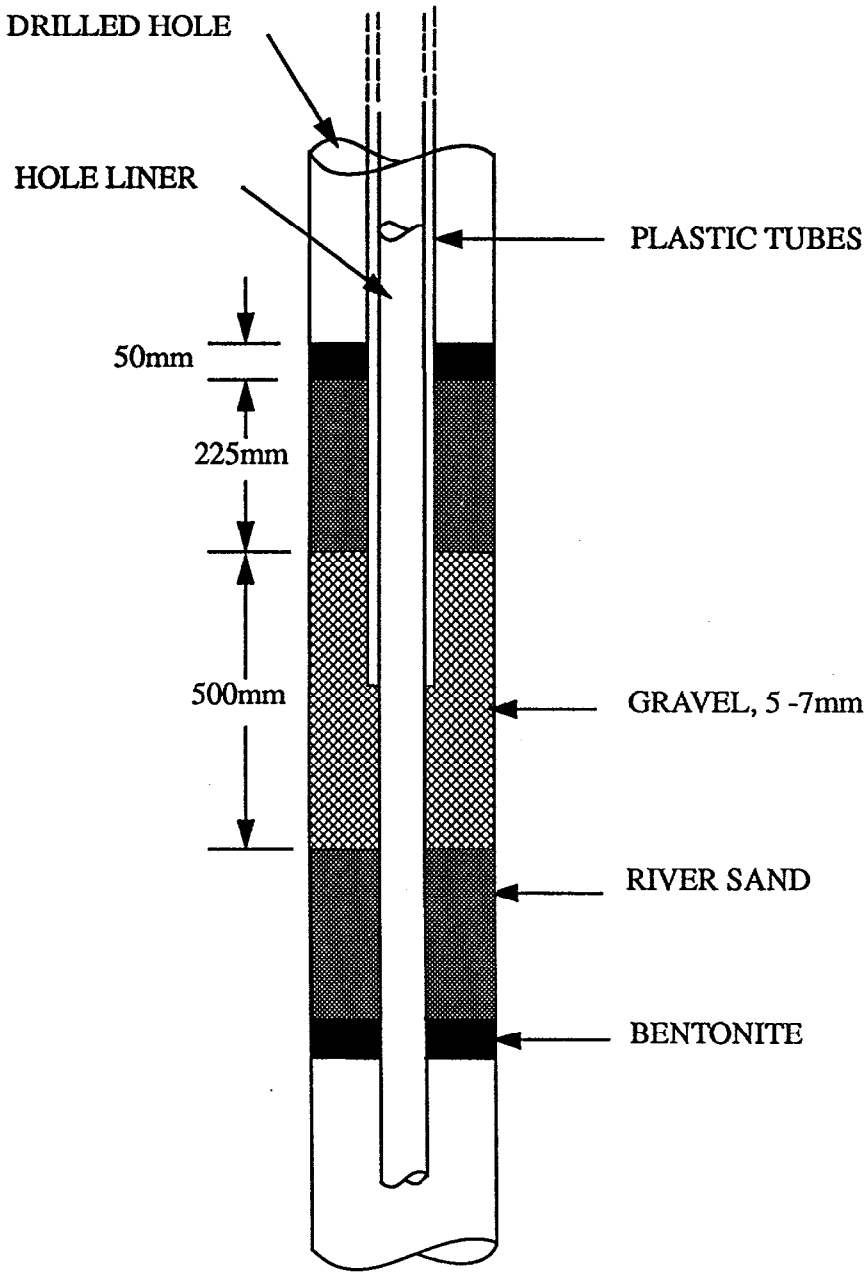

Figure 7. Backfill around a port used for injection of SF_6.

APPENDIX V

THERMAL DIFFUSION

ANSTO/C319

ansto

A Report to
Nolan, Davis & Associates (NB) Ltd
for the **MEND** Project on

GAS TRANSFER IN WASTE ROCK DUMPS
AT THE HEATH STEELE MINE

FIELD PROCEDURES MANUAL
MEASUREMENT OF THERMAL CONDUCTIVITY

by

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1. Introduction

Thermal conductivity is one of the physical parameters needed to describe the processes governing pyritic oxidation in waste rock piles. The oxidation reaction, being exothermic, leads to a temperature rise which is related to the thermal conductivity of the bulk material. Measurement of thermal conductivities therefore provides a means for determining oxidation rates from measured temperature distributions. Furthermore, temperature gradients in a pile cause gas density gradients which may in turn drive gas transport by convection, depending on other physical parameters such as gas permeability.

The transport of heat in a waste rock pile can be described by the heat conduction equation:

$$-\frac{1}{\kappa}\frac{\partial T}{\partial t} + \nabla^2 T = -\frac{Q}{\lambda} \tag{1}$$

where κ is the thermal diffusivity, Q is the rate of supply of heat, and λ is the thermal conductivity. Here, thermal diffusivity and thermal conductivity are related by the density (ρ_i) and specific heat (C_i) of the *i*th constituent phase (solid, liquid and gas) of the bulk materials by the expression:

$$\kappa = \lambda / (\sum_i (\rho_i C_i)) \tag{2}$$

Various methods have been developed for the measurement of the thermal conductivity of soils, rocks and insulating materials. In general, the methods involve emitting heat from a line source at a constant rate and monitoring the resulting temperature rise and the subsequent temperature decrease after the heater is switched off (Blackwell 1954, Boggs *et al* 1980).

The heat conduction equation, Equation (1), can be readily solved for a line source of heat to give the temperature distribution as a function of time. For a homogeneous porous medium and a continuous constant line source of heat (parallel to the z-axis passing through the point (x_1,y_1)), the solution to the heat conduction equation is given by

$$T(r,t) = T_o - \frac{Q}{4\pi\lambda} E_i(-\frac{r^2}{4\kappa t}) \tag{3}$$

where T is the temperature at time t, T_0 is the initial temperature, κ is the thermal diffusivity, Q is the constant heat supply rate from the line source per metre of heating element, λ is the thermal conductivity, and the radius r is given by $r = ((x-x_1)^2+(y-y_1)^2)^{1/2}$. The exponential integral E_i is defined as

$$-E_i(-\chi) = \int_{\chi}^{\infty} \frac{e^{-u}}{u} du \qquad (4)$$

For large values of t, such that $t >> r^2/4\kappa$, the temperature is given by

$$T(t) = T_o + \frac{Q}{4\pi\lambda}(\ln t + \beta) \qquad (5)$$

where β is a constant which can be regarded as including the effect of the thermal resistance at the interface between the pile material and a cylindrical liner surrounding the linear heat source (Jaeger, 1956). The units of the parameters in this equation are: T and T_0 in °C, t in hours, Q in W m^{-1}, λ in W m^{-1} K^{-1} and β is dimensionless.

If the heat source is switched off at t_s (hours) and $(t-t_s) >> r^2/4\kappa$, the temperature at time t during the cooling phase ($t > t_s$) is given by

$$T(t) = T_o + \frac{Q}{4\pi\lambda} \ln\left(\frac{t}{t-t_s}\right) \qquad (6)$$

Thermal conductivity in the porous medium can be determined either from the temperature rise at the heat source using Equation (5) or from the temperature decrease at the position of the heat source during cooling, after the heat is switched off, using Equation (6).

2. Instrumentation

To measure the thermal conductivity of material in waste rock piles at mine sites, a thermal conductivity probe has been designed by **Ansto** for use in drilled probe holes. The probe currently used is a modified version of the one described by Blackford and Harries (1985).

A detailed block diagram of the thermal conductivity measurement system is shown in Figure 1. The thermal conductivity probe is connected to the heater control box by a 9 m cable. The control box is joined to a Datataker by a 25 pin communication cable and the Datataker is in turn connected to the laptop computer by an RS232 communication cable. Details of the individual components of the system are discussed below.

2.1 Probe

The probe is designed to behave as a line source of heat in the waste rock pile so has a small diameter and a large length-to-diameter ratio to minimise end effects. The probe is 1.15 m long with an external diameter of 36 mm, consisting of eight

longitudinal nichrome heating wires supported on Teflon disks mounted at 15 cm intervals along a steel rod. Figure 2 shows the details of a section of the probe. A foam strip around the edge of each disk brushes against the liner and prevents the convection of heat up the probe. The nichrome wires are joined in pairs at the bottom of the probe and the four pairs are connected in parallel across the supply voltage. The total resistance of the nichrome heating wires is 5.0 Ohms.

Each of the three thermistors mounted on the probe (spaced 30 cm apart) were calibrated to obtain the temperature versus resistance relationship using a temperature calibrator, model D55SE, made by Jofra Instruments AS, Farum, Denmark. The precision thermistors, model YSI 44030, were made by Yellow Springs Instrument Co, Yellow Springs, Ohio, USA. The estimated standard deviation on temperatures measured with these calibrated thermistors is approximately ±0.04 ^{o}C over the range from 0 to 65 ^{o}C.

2.2 Control Box

A constant voltage is applied to the nichrome wires for heat generation through a 7 V voltage regulator in the control box. The relay in the control box is used to switch the heater on and off upon receiving digital signals from the laptop computer.

2.3 Data Acquisition

The resistances of the thermistors are monitored by a Datataker model DT100, made by Data Electronics (Aust) Pty Ltd, Boronia, Vic, Australia. The Datataker directly measures resistance in the range from 0 to 25000 Ohms. The resistances of the thermistors are scanned every four minutes and recorded by the computer, as are the supply voltage to the probe and the time at which the scan was made. Scanned data is written to disk only every half an hour, to save power.

Figure 3 shows a detailed flow chart of the computer program which was written in TurboBasic to control the instrument and data acquisition system.

2.4 Power Supply

The power required by the control box, the Datataker and the computer can all be supplied by a 12 V car battery. The constant voltage supplied on the probe is designed to be kept at 7 V. At the regulated voltage of 7 V which is supplied to the nichrome wires when the heater is turned on, the power supplied is 6.35 W per metre of probe. This power is Q, the constant heat supply rate, which appears in Equations (5) and (6).

3. Field Measurement

The thermal conductivity measurement involves lowering the probe down the probe hole liners installed in the pile. The probe is left at the desired depth long enough for the probe to reach thermal equilibrium with its surroundings, typically about 20 minutes. Once equilibrium is reached the heater is switched on for a typical time of 10 hours.

The detailed procedure for field measurements is presented below, including some instructions which are specific to the **Ansto**-built instrument but which are given for completeness.

(i) Connect one end of the 9 m cable to the thermal conductivity probe (TCP) and the other end to the control box, which is then joined to the Datataker (socket 4) by a 25 pin communication cable. The RS232 Datataker communication cable connects the data taker (IN socket) to the computer (Comms port). Refer to Figure 1.

(ii) After checking that there is no water in the probe hole, lower the TCP to the desired depth and fix the probe in place using a stopper or some other mechanism. If the probe does become wet inadvertently, it must be dried thoroughly before it can be used again.

(iii) Use a 12 V car battery to supply power to the control box, Datataker (socket 3) and laptop computer. Earth the Datataker to the negative terminal of the car battery.

(iv) Boot the computer using a system disk and insert data disk in a floppy drive for data storage. The data can also be stored on the computer hard disk if required.

(v) Load the computer program and enter the initialisation information.

(vi) The data acquisition system records the resistances of the three thermistors on the probe, which should all be about the same; investigate any major discrepancy. These resistances are scanned and recorded once every 4 minutes.

(vii) After the probe and the thermistors reach thermal equilibrium with their surroundings, usually about 20 minutes, heating is switched on automatically. The resistances measured prior to the heater being switched on will be used to determine the initial temperatures in the probe hole, which appear as T_0 in Equations (5) and (6).

(viii) The probe is heated for 10 hours and is then automatically switched off.

(ix) Check the voltage of the car battery after, say, 10 hours and replace it if necessary. This will not usually be necessary for a well-maintained battery.

(x) After the heater is switched off, temperatures during the cooling phase are recorded for at least another 10 hours before the experiment is stopped automatically.

(xi) The experiment can be stopped manually; the data accumulated to that time will be saved automatically before the program quits.

(xii) Check that the data has been recorded on the disk and make a backup copy before relocating the TCP for the next measurement.

4. Data Analysis

As has been described above, the temperature at the probe is monitored to give a temperature curve for the heating phase. After the heater is switched off, the temperature at the probe continues to be monitored to give the temperature curve for the cooling phase. Both the heating and cooling curves are used to give independent estimates of the thermal conductivity of the pile material.

Although three thermistors are used to monitor the temperature at the probe, in most cases it is sufficient to use the temperature measured by the middle thermistor in the analysis. The data collected during a measurement can be presented as a temperature curve by plotting temperature measured at the probe versus the time after heating was switched on. In the typical temperature curve shown in Figure 4 the two distinct sections correspond to the heating and cooling phases of the measurement, both of which can be analysed separately to obtain estimates of the thermal conductivity.

The profile in Figure 4 shows a rapid rise after the heating element is switched on, due to the thermal resistance of the plastic liner which is interposed between the probe and the dump material. (The heating and cooling times, T_s, for this particular experiment can be seen to have been 13.5 hours, rather than the generally recommended time of 10 hours.) The lower rate of temperature rise from one to two hours after the start of heating is influenced predominantly by the thermal properties of the dump material itself. This section of the temperature curve is well-described by Equation (5) and is used for the thermal conductivity determination during the heating phase. Figure 5 shows the result of the non-linear least squares fitting of Equation (5) to the data, where T_0 and Q were supplied and values for the thermal conductivity, λ, and the constant, β, were returned.

When the heater is switched off the temperature drops sharply initially, but the rate of cooling becomes much lower one to two hours afterwards. This flatter section of the temperature profile is described by Equation (6) and is used for the determination of thermal conductivity during cooling. Figure 6 shows the result of the fitting procedure, with Q, T_0 and T_s being supplied, as described in Sections 2.4 and 3 (vii) of this report, and λ being returned.

Estimates of the error on the thermal conductivity values are provided by the curve-fitting package, where the individual temperature data points are assigned a random error over the range of interest of ± 0.04 ^{o}C, as judged from the reproducibility of measurements made with the calibrated thermistors.

The thermal conductivity values obtained from the heating phase and those from the cooling phase should not be significantly different from each other and so an average value can be obtained. In the example presented here, the values were (1.02 ± 0.01) and (1.05 ± 0.03) W m^{-1} K^{-1} respectively. It is possible however that changes in the physical conditions within the pile during the course of a measurement, such as in moisture content, can result in different values being obtained.

Thermal conductivity values can be converted to thermal diffusivity using Equation (2). The parameters required include the bulk density and specific heat of the solids and water that constitute the waste rock pile. Typical values of specific heat are 870 J kg^{-1}K^{-1} for waste rock solids (Harries and Ritchie, 1981) and 4200 J kg^{-1}K^{-1}

for pore water; the bulk densities of dump solids and water will clearly vary from site to site.

Measurements made by the authors at several mine sites, from tropical to Arctic regions, have indicated that the values of thermal conductivity in waste rock piles can be expected to range from 0.6 to 3.0 $W\,m^{-1}\,K^{-1}$, with errors on individual determinations of less than ±5%.

13. References

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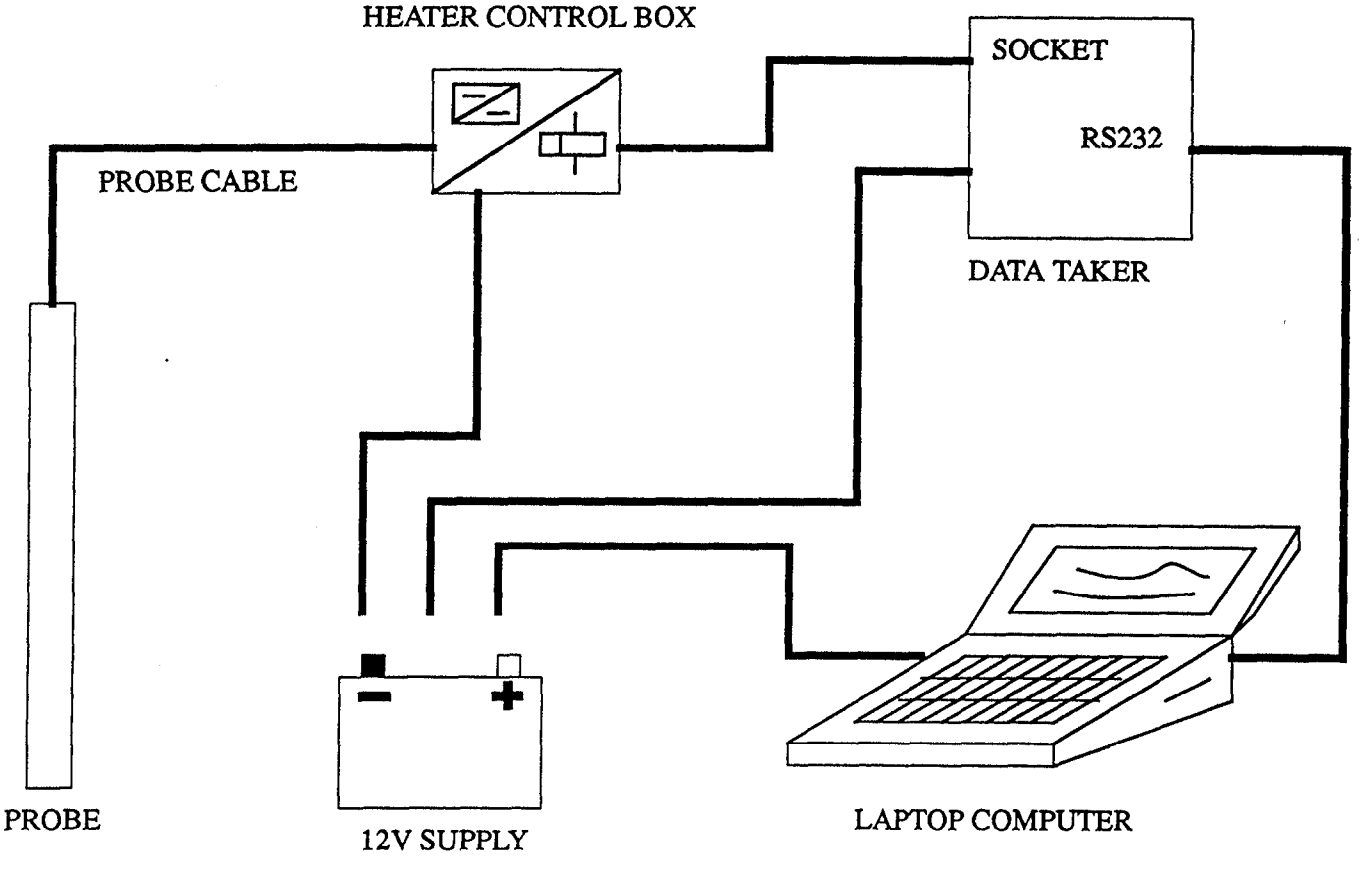

Figure 1. Block diagram of the thermal conductivity measurement system.

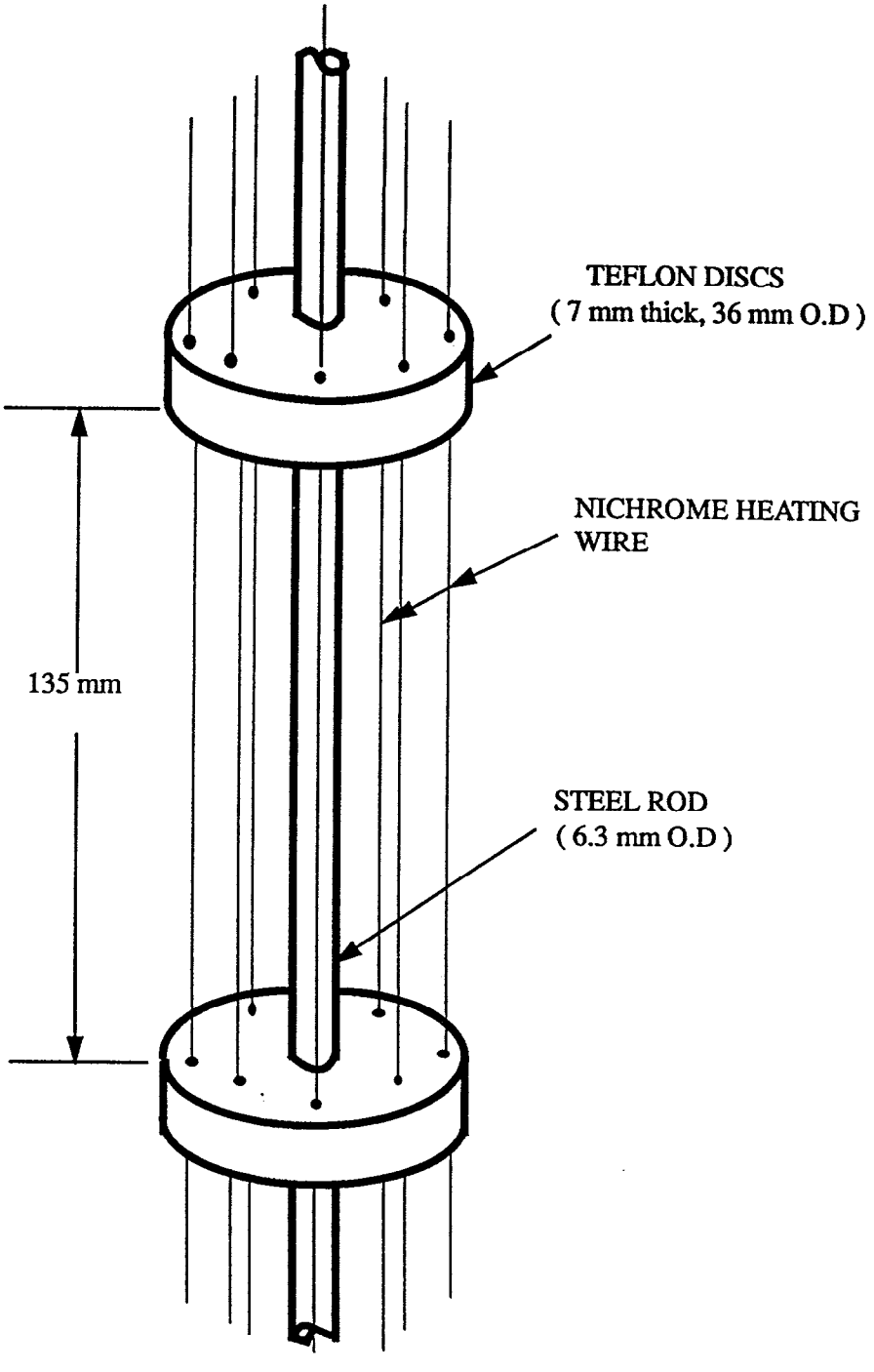

Figure 2. Section of the thermal conductivity probe.

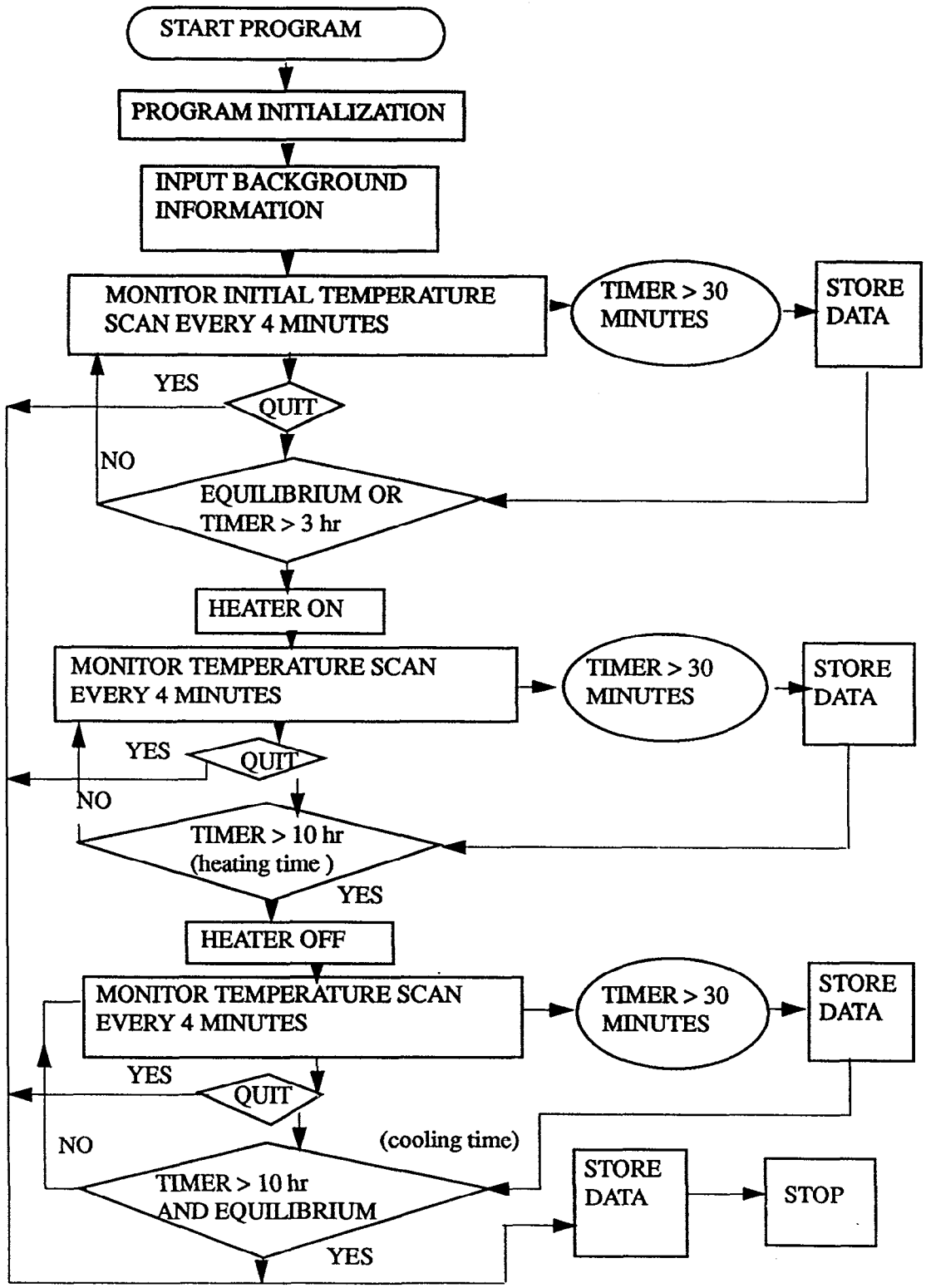

Figure 3. Flow chart of the computer program for the field thermal conductivity determinations.

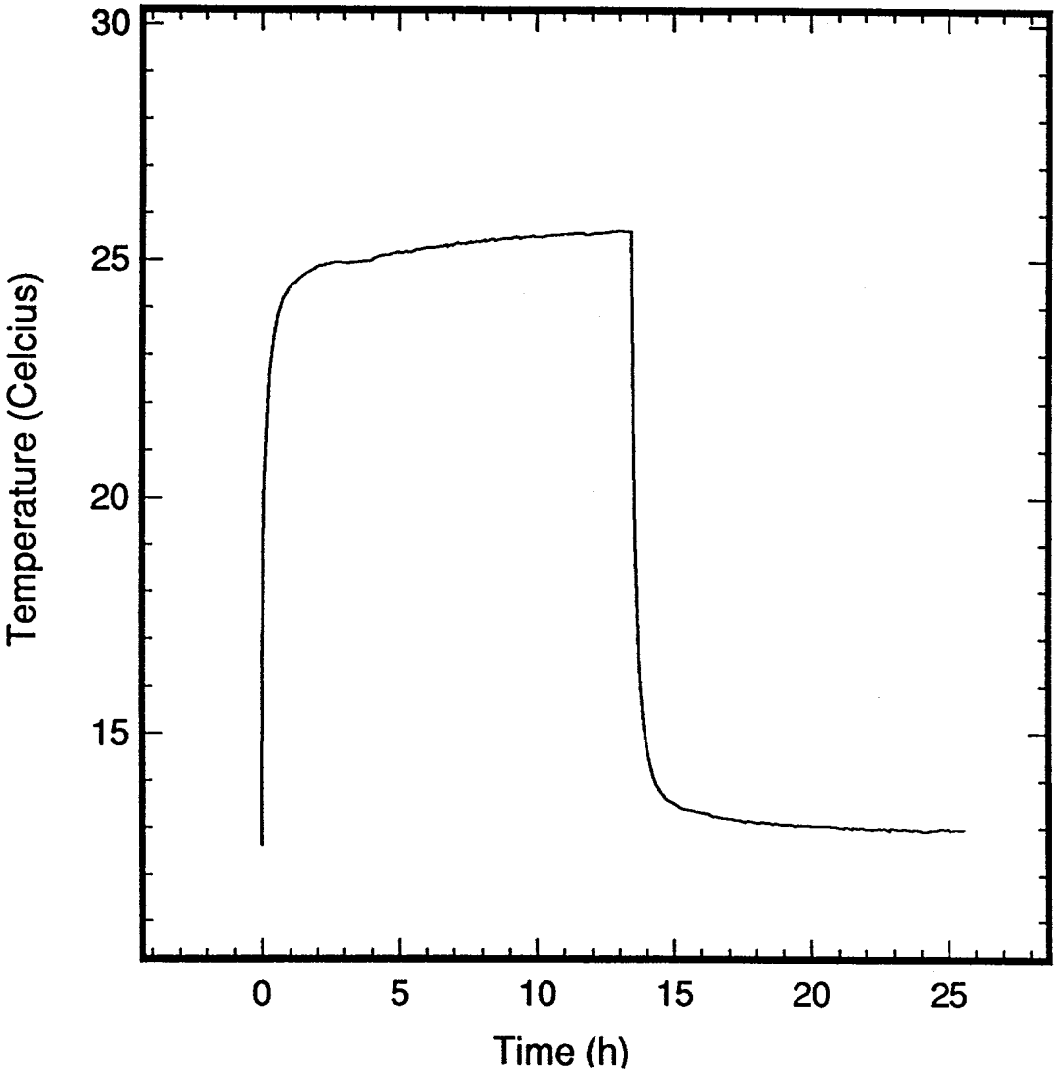

Figure 4. A typical temperature curve of the heating and cooling phases.