COMPARISON OF DIRECT TECHNIQUES FOR ESTIMATING LFG GENERATION RATES

by

Gary R. Walter, Stewart Smith, and Jinshan Tang[1]

INTRODUCTION

Estimation of the rate of landfill gas (LFG) generation may be performed for several purposes: to satisfy regulatory requirements to estimate non-methane organic carbon emissions under 40 CFR Subtitle D (Subtitle D); to design LFG and methane control systems; or to evaluate and design LFG-to-energy projects. At least in the second two cases, the success of the project depends on the reliability of the LFG generate rate estimate. In the first case, over-estimation of the LFG generation rate can lead to installation of a costly and unnecessary LFG collection system. This paper discusses the fluid dynamic principles, reliability and practical considerations underlying four methods of estimating the LFG generation rate using empirical testing methods. These methods are gas extraction rate testing, surface flux measurements, differential pressure testing, and baro-pneumatic testing.

EXTRACTION WELL TESTING

Extraction well testing, such as that described in the Tier 3 method in Subtitle D and its variants (e.g., Emcon, 1980), involves extracting gas from a well constructed in the refuse and, based on measurements of the LFG extraction rate, pressure drop induced in the refuse at various distances from the well, and the composition of the extracted gas, computing the LFG generation rate within the "radius of influence" (ROI, r_e) of the well. The Tier 3 testing configuration is illustrated in Figure 1. The ROI is typically defined as the radial distance from the well at which the difference between the average refuse pressure during extraction (P_e) and the average static refuse pressure (P_0) are less than the precision of the pressure measurements (commonly 0.1 or 0.01 inches of water [in H_2O]). The "influence" based on this concept can be expressed as:

$$\Delta P_e = \overline{P_0} - \overline{P_e} \qquad \textbf{(1)}$$

Given an estimation of the ROI and knowing the extraction rate, the assumption is made that the extraction rate is equal to the LFG generation rate within the ROI, that is, the volume specific LFG generation rate is computed by:

[1]Hydro Geo Chem, Inc., 51 W. Wetmore, Tucson, AZ 85705 520-293-1500 http:\\www.hgcinc.com

$$\dot{Q} = \frac{Q_e}{p\, b_r\, r_e^2} \qquad \textbf{(2)}$$

where $\dot{Q}_{LFG}$ is the LFG generation rate per unit volume of refuse,
Q_e is the well extraction rate,
b_r is the average thickness of the refuse within the ROI.

Given one or more tests, the total LFG generation rate is computed from the average specific LFG generation rate times the volume of the refuse.

The fundamental assumption underlying extraction well methods is that the LFG generation rate within the ROI equals the extraction rate. This assumption can be demonstrated to be wrong based on fundamental principles of gas flow to wells (Walter, Interview). To illustrate this point, assume that the LFG generation rate is uniform throughout a lined landfill and that the effective gas permeability of the refuse is much larger than the gas permeability of the cover so that the vertical pressure gradient in the refuse is negligible. In this case, the average difference in pressure between the refuse and the atmosphere due to flow through the cover is given simply by Darcy's Law (Al-Hussainy and others, 1966):

$$q_{LFG} = \frac{k_c}{m} \frac{\Delta P}{b_c} \qquad \textbf{(3)}$$

or

$$\Delta P = \frac{q_{LFG}\, m b_c}{k_c} \qquad \textbf{(4)}$$

where q_{LFG} is the gas generation rate per square foot of landfill
k_c is the effective gas permeability of the cover
μ is the dynamic viscosity of the LFG
b_c is the cover thickness
ΔP is the pressure differential $P_0 - P_a$
P_a is the atmospheric pressure

Given the assumption of a uniform LFG generation rate and an areally extensive landfill, the static pressure in the refuse is $\overline{P_0} = \overline{P_a} + \Delta P_0$ and is uniform throughout the landfill.

For small pressure differentials, the pressure drop created by the extraction well (assuming an ideal gas and steady-flow conditions and ignoring compressibility effects) is given by:

$$\Delta P_e = \frac{Q_e m}{2p\, k_r b_r} P_D(r) \qquad \textbf{(5)}$$

where k_r is the effective horizontal air permeability of the refuse,
Q_e is the well extraction rate,
$P_D(r)$ is an appropriate dimensionless pressure solution for flow to the well,
ΔP_e is the difference between static and flowing pressure, and
b_r is the thickness of the refuse.

For the case of a highly permeable refuse in a lined landfill with a relatively low permeability cover, the appropriate P_D function is that given by Hantush (1964) for a leaky, confined formation without fluid storage in the confining bed:

$$P_D = K_0(r / B); B = \left(\frac{k_r b_r b_c}{k_c} \right)^{1/2} \qquad \textbf{(6)}$$

where K_0 is the modified Bessel function of zero order

Thus, (5) becomes

$$\Delta P_e = \frac{Q_e m}{2p\, k_r b_r} K_0(r / B) \qquad \textbf{(7)}$$

The absolute pressure within the refuse during extraction is then $\overline{P_e} = \overline{P_0} + \Delta P_e$. The generalized absolute pressure in the refuse based on (7) is illustrated in Figure 2 along with its relationship to the static pressure. In the extraction well methodology, the ROI is defined as the radial distance from the extraction well at which the difference between the absolute pressure during extraction and the static absolute pressure is zero, that is, $\overline{P_0} - \overline{P_e} = 0$ within measurement error. Using the Tier 3 criteria,

$$\Delta P_e \cong 0 = \frac{Q_e m}{2p\, k_r b_r} K_0(r_e / B) \qquad \textbf{(8)}$$

Equations (7) and (8) and Figure 2 illustrate two problems with the Tier 3 approach. First, although the pressure drop induced by the extraction well approaches zero as r increases ($K_0$60 as r64), it never actually reaches zero. Thus, the value of r_e determined from the test depends entirely on the pressure measurement precision. Second, and more importantly, the LFG generation rate plays no role in (7) or (8) so that the distance (r_e) at which ΔP is zero within measurement error is independent of the LFG generation rate. Therefore, the LFG generation rate cannot be determined using the Tier 3 methodology.

The fatal flaw in extraction well testing can also be demonstrated simply by considering the effect of the gas pressure measurement precision on the ROI and the resulting LFG generation rate calculations. To illustrate this, consider the example of a landfill with a refuse thickness of 30 feet, refuse gas permeability of 50 darcies, and cover thickness of 2 feet. Finally, assume that an extraction test is performed at an extraction rate of 100 standard cubic feet per minute (scfm) and that the actual area specific LFG generation rate is uniform and constant at 5.6×10^{-4} scfm per ft^{-2}, equivalent to 1,750 scfm over a 72 acre landfill. Figure 3 shows the static and extraction pressures versus distance for a cover permeability of 0.1darcies (approximately equivalent to saturated hydraulic conductivities of 1×10^{-4} cm/s). Also shown in Figure 3 are the ROIs determined assuming measurement errors of 0.01 in H_2O and 0.1 in H_2O. The ROIs in this case are 720 ft and 408 ft for the lower and higher measurement errors, respectively. The LFG generation rate determined by dividing the extraction rate, Q_e, by the volume within the ROI and then multiplying by the landfill area, yields two different estimates of the LFG generation rate, neither of which is correct. In this particular example, both LFG estimates are less than the actual. A more general analysis (Walter, Interview) shows that the actual LFG generation rate may be either over or under estimated.

In summary, the LFG generation rate cannot be directly calculated from extraction well tests. Such tests may be useful for estimating the LFG yield and quality from individual wells. Such tests can only be used to estimate the actual LFG generation rate, however, if the tests are analyzed to estimate the pneumatic gas flow properties of the refuse and the landfill cover in conjunction with measurement of the excess refuse pressure. A discussion of such methods is outside the scope of this paper, however.

SURFACE FLUX MEASUREMENTS

Another direct measurement technique is the Surface Isolation Flux Chamber (flux chamber) described in EPA (1986). The concept behind the flux chamber is illustrated in Figure 4. The flux chamber is designed to measure the mass emission rate of gases from the subsurface which could include emissions from a landfill. The fundamental assumption behind the flux chamber is that the interior of the chamber is maintained at the average, ambient atmospheric pressure during the period of the measurement so that the flux chamber does not disturb the pressure gradient between the refuse and the atmosphere. Thus, the emission rate of specific constituents in the LFG can be determined by analyzing the composition of the gas within the chamber. The flux chamber is not directly capable of measuring the volumetric rate of LFG emissions, only the mass rate of emission of specific constituents. In principle, if the composition of the LFG within the refuse was known, the volumetric LFG emissions through the landfill cover could be back-calculated from the constituent specific mass flux rates.

Although flux chamber measurements have been used to estimate methane emissions from landfills (such as, http://www.aquafoam.com/papers/comparison.html), we are not aware that they have been used to estimate LFG volumetric generation rates. As mentioned above, they are capable of such measurements if 1) the measurements are performed long enough to establish average flux rates, 2) the flux chamber does not disturb the pressure gradient between the refuse and the atmosphere, and 3) the composition of the LFG in the refuse is known and is not modified by passing through the landfill cover.

ZISON'S METHOD

Zison (1991) patented a method for estimating the LFG generation rate that involved measuring the average pressure gradient within the landfill cover and the gas permeability of the cover materials. His method is illustrated in Figure 5. By then applying Darcy's Law for gas flow, the LFG flux through the cover at the measurement locations can then be computed using equation (3). The pressure measurements are made in the cover and in the atmosphere so that a gradient can be computed if the thickness of the cover is known. Because of natural atmospheric barometric pressure variations, the average pressure gradient must be determined from a series of pressure measurements that is long enough to determine a reliable average. Zison recommends using measurements collected over "a week or a month". Zison's method could also be applied by measuring the pressure gradient between the upper portion of the refuse and the atmosphere, although Zison excludes this approach in his patent for some reason. As for the gas permeability of the cover, Zison's method involves laboratory gas permeability tests on soil core samples collected from the landfill cover. He suggests samples be collected at random locations over the landfill at various times during the period of the pressure measurements. The pressure gradient measurements and gas permeability estimates can then be combined to compute spatially and temporally averaged LFG emission estimates using various statistical methods.

Zison's method involves two fundamental assumptions that can strongly affect the reliability of the LFG generation rate estimate. First, his approach assumes that all of the LFG leaves the refuse through the cover. Although this assumption may be valid for lined landfills with relatively high permeability covers, it is certainly not valid for many older, unlined landfills with native soil covers or store-and-release covers. At such landfills, LFG can leave both through the cover and through the native soil underlying and surrounding the refuse. Ultimately, the percentage of LFG that is emitted through the cover depends on the gas permeability of the cover relative to that of the underlying soil, and also on the structure of the landfill.

The second important assumption in Zison's method is that laboratory gas permeability measurements provide a reliable estimate of the in-situ gas permeability of the cover. Soil cover properties are highly variable, even in well-engineered covers. Features such as dessication cracks, animal burrows, and root tubes can significantly increase the effective gas permeability of the cover, yet the effect of these features is rarely captured in soil cores. Also, disturbance of the sample during collection can significantly change the permeability of the sample. For example, native soils and store-and-release cover soils may be so incohesive that they must be repacked for laboratory testing which can significantly change their permeability. Inasmuch as the LFG flux estimate by Darcy's Law is linearly proportional to the gas permeability estimate, very large errors could result from these uncertainties.

BAROMETRIC PRESSURE TESTING

The barometric pressure testing approach for estimating the LFG generation rate is based on mathematical analysis of the pressure response in the refuse and, in some cases, the surrounding or underlying soil, to variations in the atmospheric pressure, and to the excess pressure generated by the release of LFG from the refuse. It is similar in some ways to Zison's method in that the analysis fundamentally rests on Darcy's Law which relates the average, excess refuse pressure to the LFG generation rate and the gas permeability of the cover. It also recognizes that gas flow may occur through the soil surrounding the refuse and that the pressure distribution may be affected by the structure of the landfill. It is fundamentally different from Zison's method because the cover and surrounding soil gas permeabilities are determined in situ from the analysis of the barometric pressure response in the subsurface.

The pressure distribution within a landfill depends on the rate of gas production, the effective gas permeability and air-filled porosity of underlying soil and overlying cover materials that surround the landfill, and the gas pressure at the landfill boundaries (controlled primarily by changes in barometric pressure). The higher the gas generation rate, and the lower the gas permeability of the fill and surrounding materials, the higher will be the average pressure within the landfill as a result of gas generation. Assuming simple conditions of a lined landfill with a low permeability cover and high permeability fill, the excess pressure in the landfill is a function primarily of the gas permeability of the cover, as described by equation (3). In this case, the LFG generation rate can be computed from the excess pressure if the gas permeability of the cover is known. Under conditions typical of older landfills where the landfill is not lined (so that gas can escape both through the cover and through the sides and base of the landfill) and where the gas permeability contrast between the fill and the cover may not be large, the situation becomes more complex. The excess pressure is then a function of the LFG generation rate, the gas permeability of the cover, fill, and underlying soils, and the geometry of the landfill. If the relevant gas permeabilities can be reliably estimated, then the LFG generation rate can be computed using an appropriate mathematical model.

Under many circumstances, the analysis of pressure variations in the fill and underlying soil due to barometric pressure fluctuations provides a means for estimating the gas permeability of these materials which then serves as the basis for computing the LFG generation rate based on the average excess pressure. Various investigations, such as Weeks (1978) and Lu (1999), have presented methods for estimating the vertical gas permeability of soils based on the analysis of barometric pressure responses in the soil. All of these methods are based on a recognition that 1) the barometric pressure response at a given depth in the subsurface depends on the pneumatic diffusivity (affected by gas permeability, porosity and gas compressibility) of the overlying material, and 2) the pressure response is attenuated and its amplitude is reduced with depth as a function of the pneumatic diffusivity. Thus, by appropriately analyzing the barometric response at various depth within and beneath the landfill, the gas permeability can be estimated. In more complex geometries, where the barometric pressure response has a significant horizontal component, the estimate of gas permeability requires a 2- or 3- dimensional analysis. In either case, given the average excess pressure, the LFG generation rate can also be estimated.

Because the rate of LFG generation is expected to be relatively constant over the short term (days to weeks), the only factor affecting gas pressures at fixed measuring points within the refuse will be changes in boundary pressures related to changes in barometric pressure, and changes in gas permeability. For example, a reduction in average gas permeability of cover materials during a rainfall event would be expected to result in an increase in gas pressure within the landfill. In addition, rainfall infiltration into the refuse could increase LFG generation. Otherwise, the only factor expected to create short-term changes in pressure within the landfill would be changes in boundary pressure resulting from barometric pressure fluctuations.

Based on fluid flow principles and observation, changes in barometric pressure propagating through porous materials undergo a phase shift (or lag) and an attenuation in amplitude (Weeks,1978). The lag and amplitude attenuation increase with depth. The lag and attenuation depend on the vertical permeability and porosity of the subsurface materials, with lower-permeability, higher-porosity materials resulting in greater lag and attenuation of the response.

If the variation in barometric pressure is assumed to be a simple harmonic function and the water table acts as an impermeable boundary to air flow, then the temporal variations in pressure in the subsurface is given by (Lu, 1999):

$$P^2 = A \sin(w t + e + q) + \overline{P}_a{}^2 \qquad \textbf{(9)}$$

where A is the amplitude of the pressure variation at depth z
q is the phase lag at depth z
g is the initial phase lag.

Both A and q are related to functions of the pneumatic diffusivity, $K_a \overline{P_a} / q m$, by transcendental functions that are not reported here. Nevertheless, if the porosity can be independently estimated, (8) provides a basis for estimating the vertical pneumatic diffusivity and vertical air permeability based on an analysis of barometric pressure signals at depth. Equation (8) also indicates that the excess landfill pressure can be determined by separating the barometric pressure response from the excess landfill pressure or by long-term pressure averaging of the absolute pressure and the LFG generation rate determined from the excess landfill pressure using (3).

Unfortunately, this simple approach is not feasible under most landfill conditions because:

a. the vertical air permeability is not uniform,
b. the barometric pressure signal is not a simple harmonic function, and
c. the air flow is not strictly vertical.

These limitations can be overcome, however, by analyzing the pressure response using a numerical model. The measured barometric pressure is imposed as a boundary condition, and the permeabilities and porosities of the fill and surrounding materials adjusted until the simulated pressure at the fixed measurement point has the same lag and amplitude attenuation as the measured pressure. Because the porosity of the landfill and surrounding materials will vary less than the permeability, reasonable values for porosity can usually be assumed and changes in the signal attributed only to the permeability distribution. The calculated permeability distribution and LFG generation rates will, of course, depend on the accuracy of the porosity estimate. If necessary, the uncertainty associated with the porosity estimate can be reduced by performing extraction well tests to independently estimate the refuse and cover permeabilities.

Figures 6 and 7 illustrate the application of the method to a closed MSW landfill in southern Arizona. Figure 6 shows the pressure response in a vapor probe completed in refuse at a depth of 75 feet to barometric pressure over a period of 1.6 days. The pressure response at 75 feet lags behind and is attenuated with respect to the barometric pressure. Figure 7 shows the results of numerical simulation of the pressure response. The open circles represent the measured pressures, and the heavy line represents the pressure simulated using a numerical model that includes LFG generation. The light line shows the simulated pressure if no LFG was being generated. This line parallels the measured data quite well because the model was first calibrated by adjusting the refuse and soil permeabilities to match the time lag and attenuation in the barometric pressure response. The off-set between the light line and the measured data is due to the excess pressure generated in the refuse. The line with LFG generation matches the measured data because LFG generation was added to the simulation. Based on analysis of the pressure response in this probe and others at the site, the total LFG generation rate for the landfill was estimated to be approximately 100 scfm. This estimate compares to 600 scfm estimated previously based on extraction well testing. An LFG collection system was designed and constructed on the basis of the previous estimate, but was never successfully operated due to low LFG yield.

SUMMARY

Four methods for estimating LFG generation rates based on direct measurements were reviewed: extraction well testing, surface flux chambers, Zison's pressure testing and permeability measurement method, and baro-pneumatic testing. Extraction well testing is the most common method used to directly estimate LFG generation rates. This method was shown to lack a sound, physical basis and to yield LFG generation rate estimates that are incorrect and depend only on the accuracy of the pressure measurements. Surface flux chambers have the potential to directly measure LFG emissions through landfill covers, but only if the chemical composition of the LFG is known apriori. The surface flux chamber cannot be used to measure the total LFG generation rate of unlined landfills where a substantial portion of the LFG may exit through the soil surrounding and underlying the refuse.

Zison's method is based on sound gas flow principles, but, once again, is limited in application to landfills were the majority of the LFG is emitted through the cover. The accuracy of Zison's method depends strongly on the ability to develop estimates of the cover gas permeability that are representative of in situ conditions. The ability of soil core samples to yield such representative values is questionable.

As with Zison's method, the baro-pneumatic testing method is also based on well-established principles of gas flow. Although it requires a higher level of mathematical analysis than Zison's method, it has several significant advantages. First, the baro-pneumatic method bases the LFG generation rate calculations on in situ permeability estimates developed from analysis of the lag and attenuation of barometric pressure signals in the subsurface. Second, it is also capable of estimating the LFG generation rate of unlined landfills where a significant fraction of the LFG may exit through the subsurface soils. Finally, despite the mathematical sophistication required to interpret the baro-pneumatic test results, the tests themselves are relatively simple to perform requiring only pressure measurement probes and accurate pressure measurement equipment.

REFERENCES

Al-Hussainy, R., H.J. Ramey, Jr., and P.B. Crawford. 1966. The Flow of Real Gases Through Porous Media. Journal of Petroleum Technology. Vol. 237:624-636.

Emcon. 1980. Methane Generation and Recovery from Landfills. Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan.

Hantush, M.S. 1964. Hydraulics of Wells in Advances in Hydroscience, Volume I. V.T. Chow Ed. Academic Press, New York.

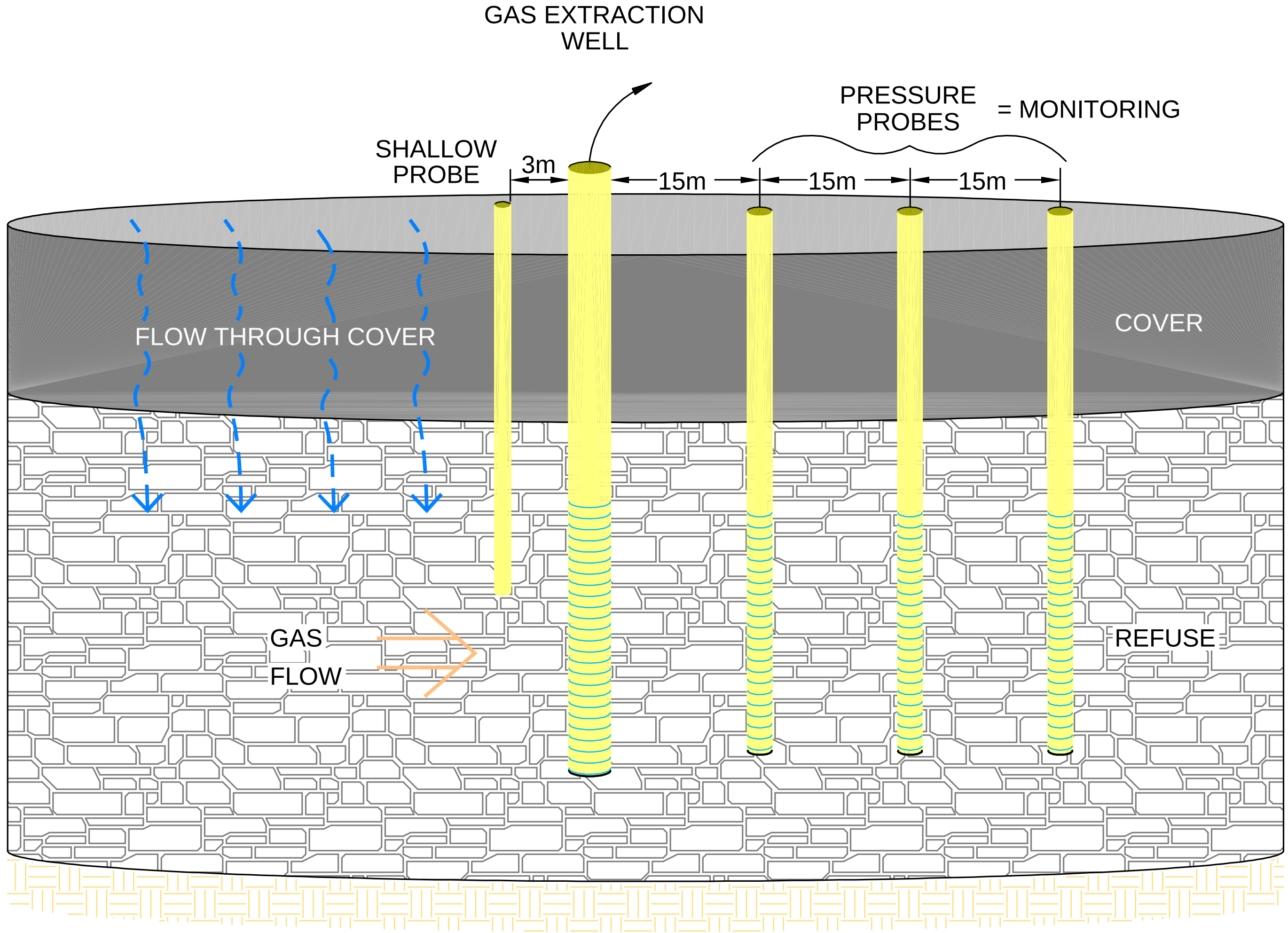
Lu, N. 1999. Time-series analysis for determining vertical air permeability in unsaturated zone. J. Geotechnical and Environmental Engineering. January. Pp. 69-67.

U.S. Environmental Protection Agency (EPA). 1986. Measurement of Gaseous Emission Rates from Land Surfaces Using an Emission Isolation Flux Chamber, Users Guide. EPA Environmental Monitoring Systems Laboratory, Las Vegas, Nevada

Walter, G.R. In review. Fatal flaws in measuring landfill gas generation rates by empirical well testing. Submitted to Journal of the Air Waste Management Association.

Weeks, E.P. 1978. Field determination of vertical permeability to air in the unsaturated zone. U.S. Geological Survey Professional Paper 1051.

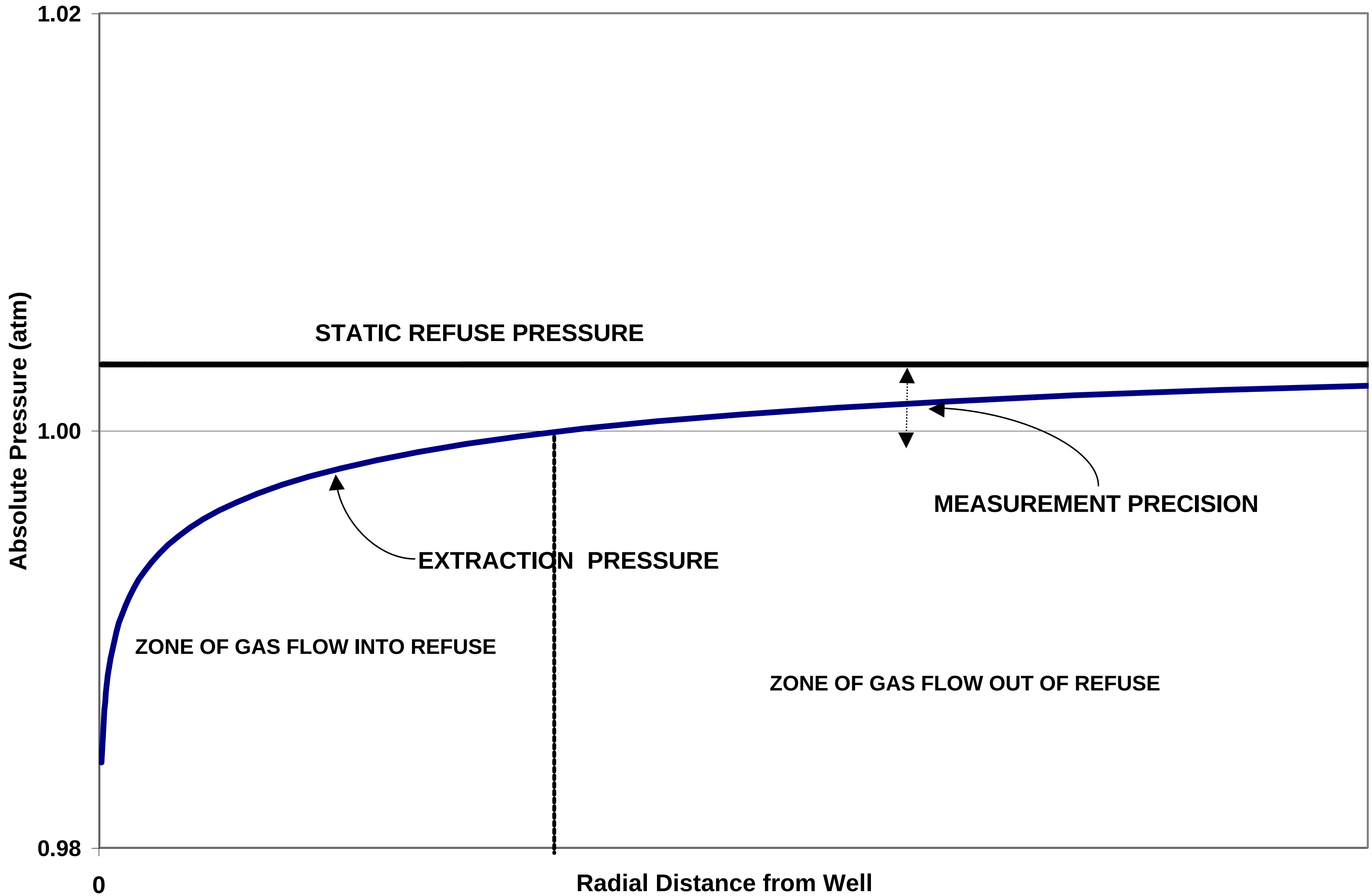
Zison, S. W. 1991. Landfill gas production testing and extraction method. U.S. Patent No. 5,063,519.



HYDRO GEO CHEM, INC.

SCHEMATIC LAYOUT OF
A TIER 3 TEST WITH A
SINGLE EXTRACTION WELL

Approved	Date	Revised	Date	Reference:	FIG.
GW	4/30/02				1

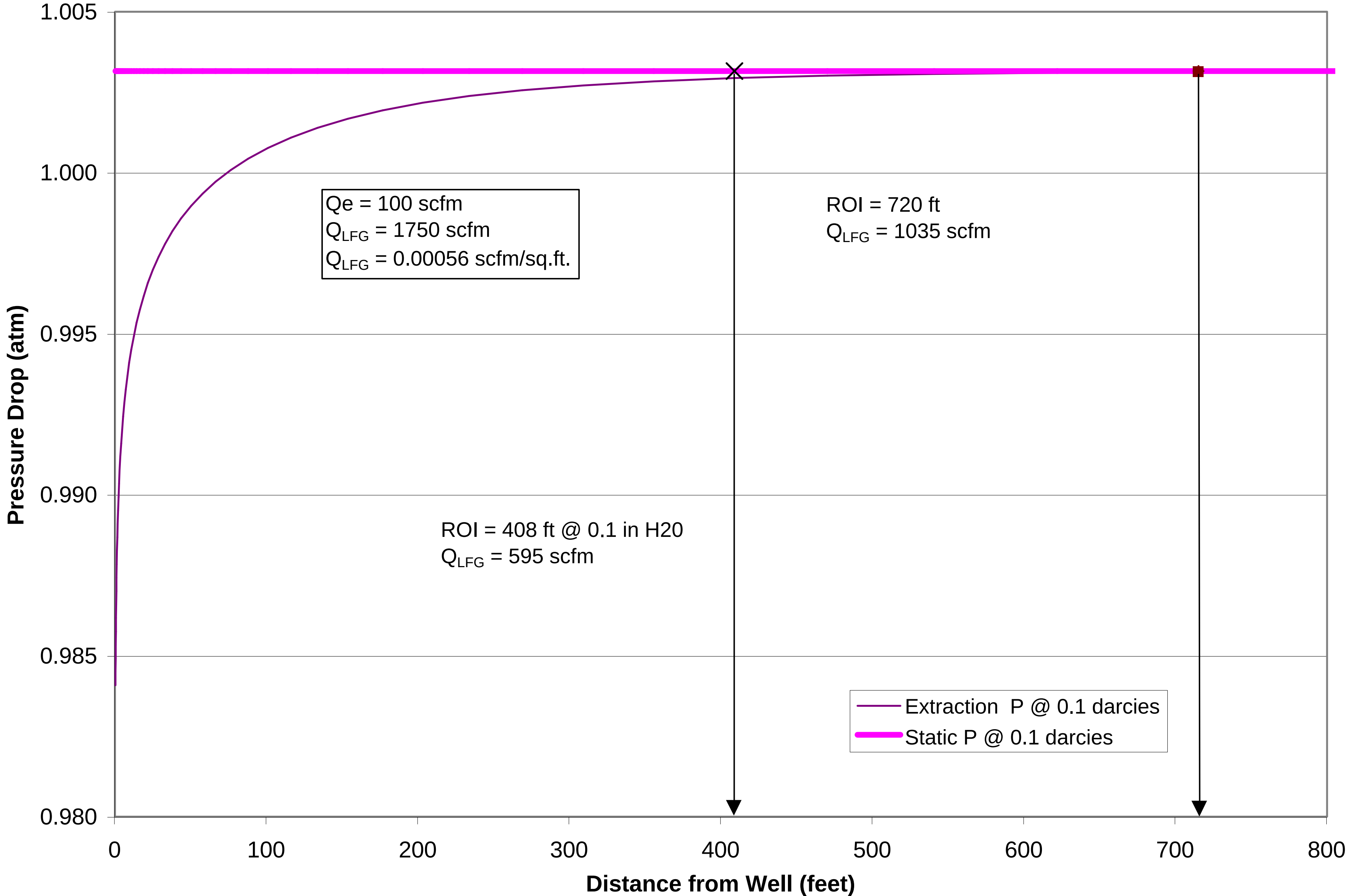


HYDRO GEO CHEM, INC.

GENERALIZED RELATIONSHIP BETWEEN STATIC PRESSURE AND EXTRACTION PRESSURE

APPROVED	DATE 4/30/2002	FIGURE 2

H:\0860\lfgpaper\tier3.xlsFigure 2

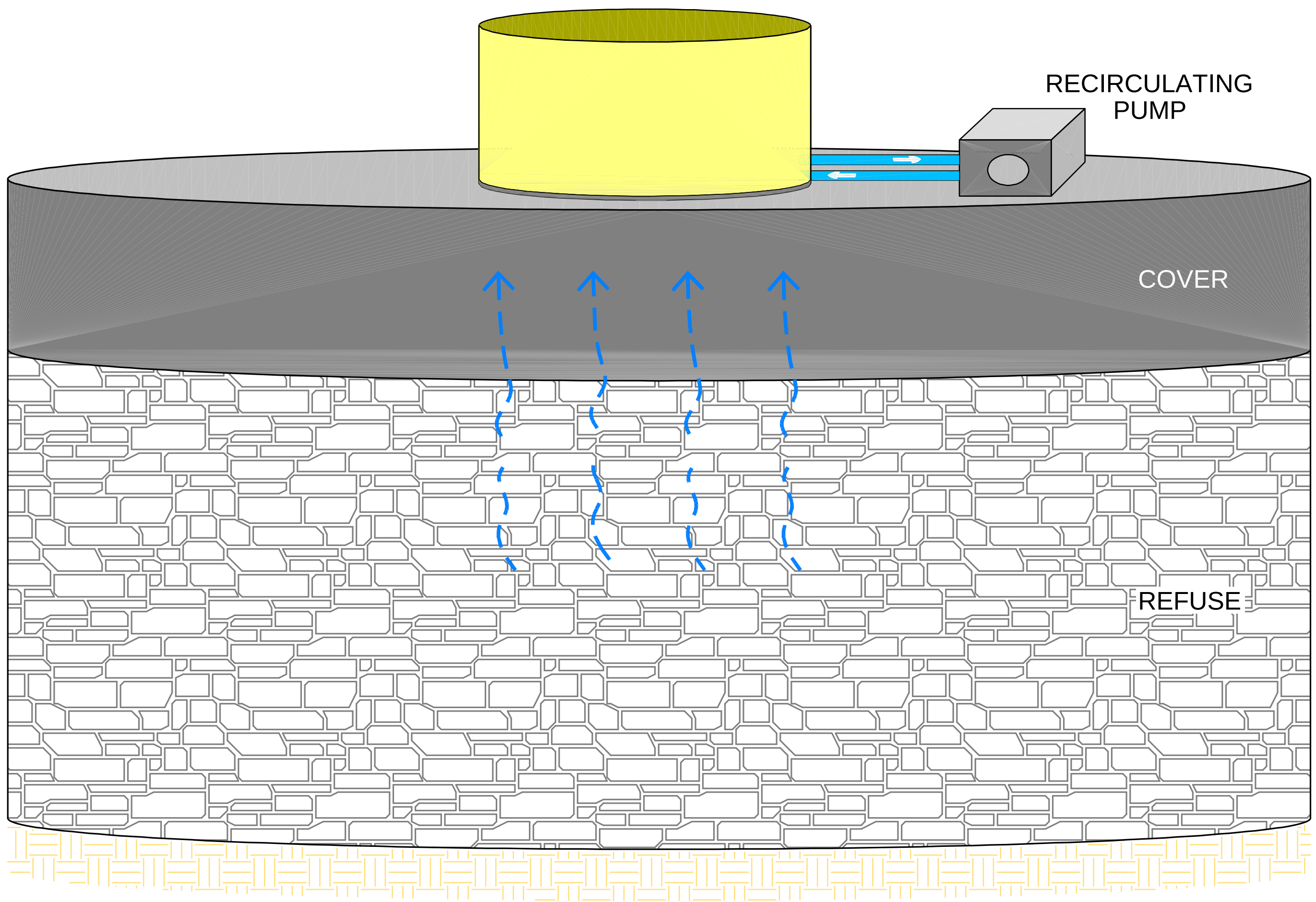


HYDRO GEO CHEM, INC.

PRESSURE AND RADII OF INFLUENCE OF COVER PERMEABILITIES OF 0.1 DARCIES, MEASUREMENT ACCURACY 0.01 AND 0.1 in H_2O

APPROVED	DATE	FIGURE
	4/30/2002	3

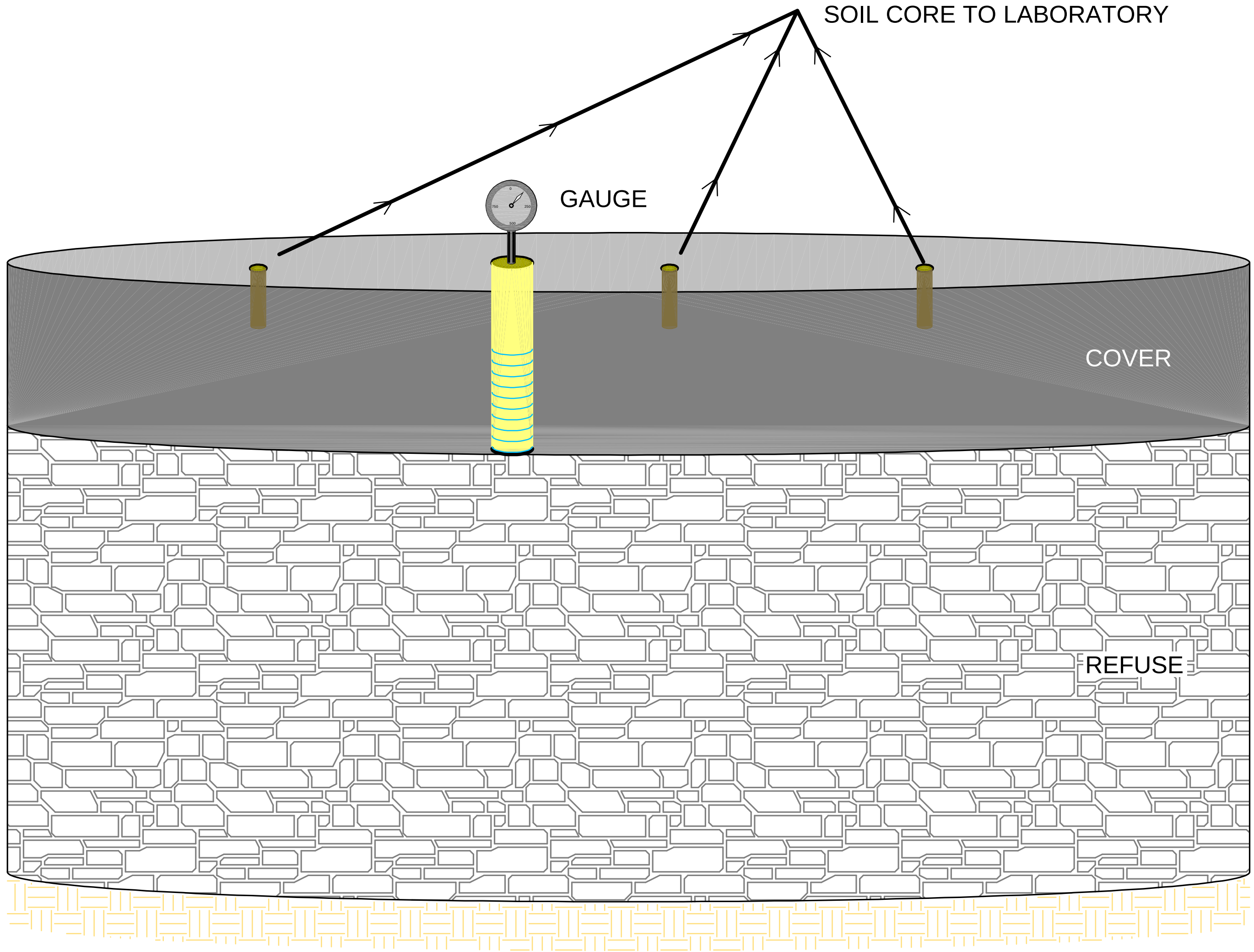
H:\0860\LFG Paper\tier3.xls: ROIvAccur Chart 1



HYDRO GEO CHEM, INC.

SCHEMATIC ILLUSTRATION OF SURFACE FLUX CHAMBER

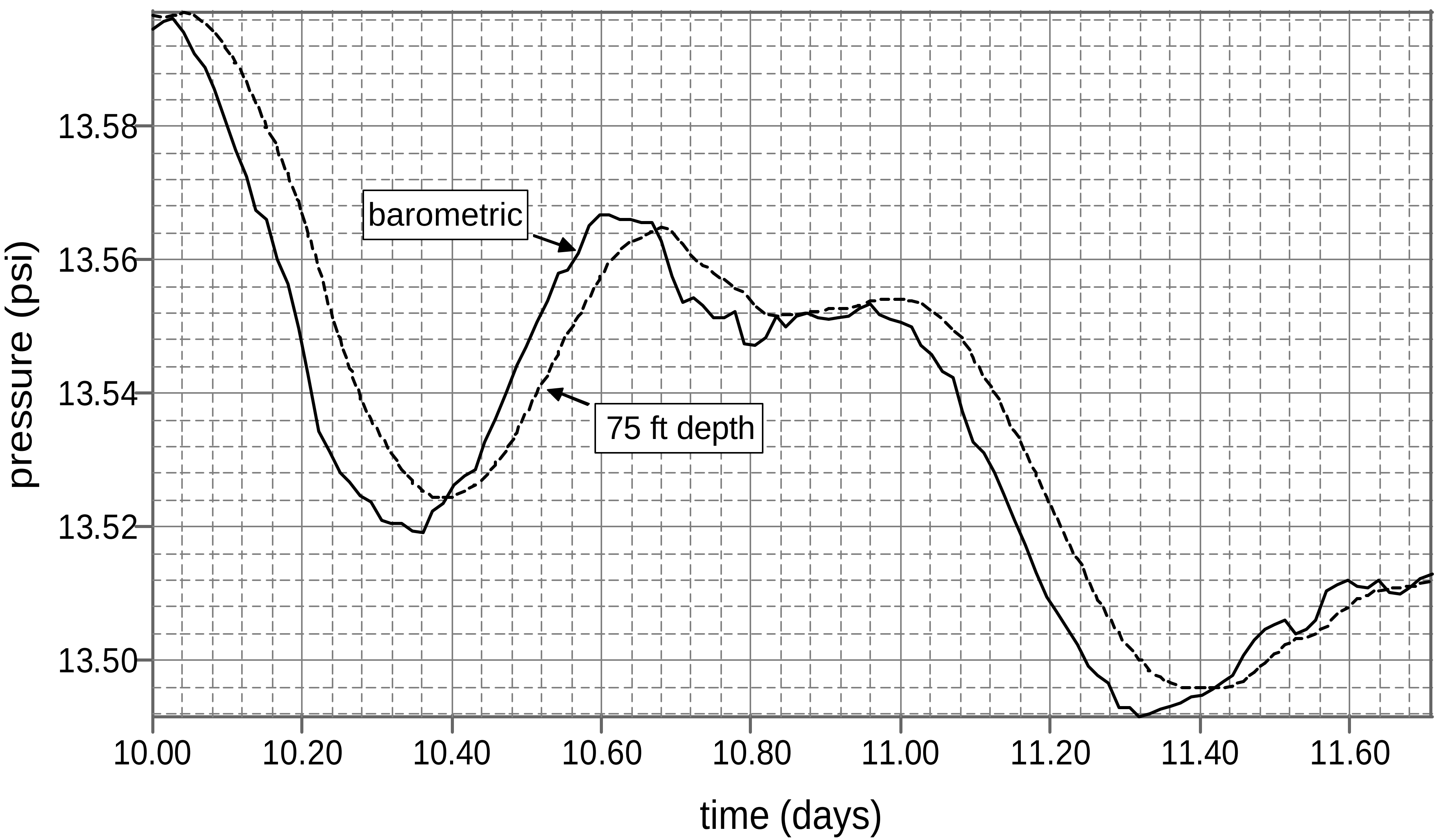
Approved	Date	Revised	Date	Reference:	FIG.
GW	4/30/02				4



HYDRO GEO CHEM, INC.

SCHEMATIC REPRESENTATION OF ZISON'S METHOD

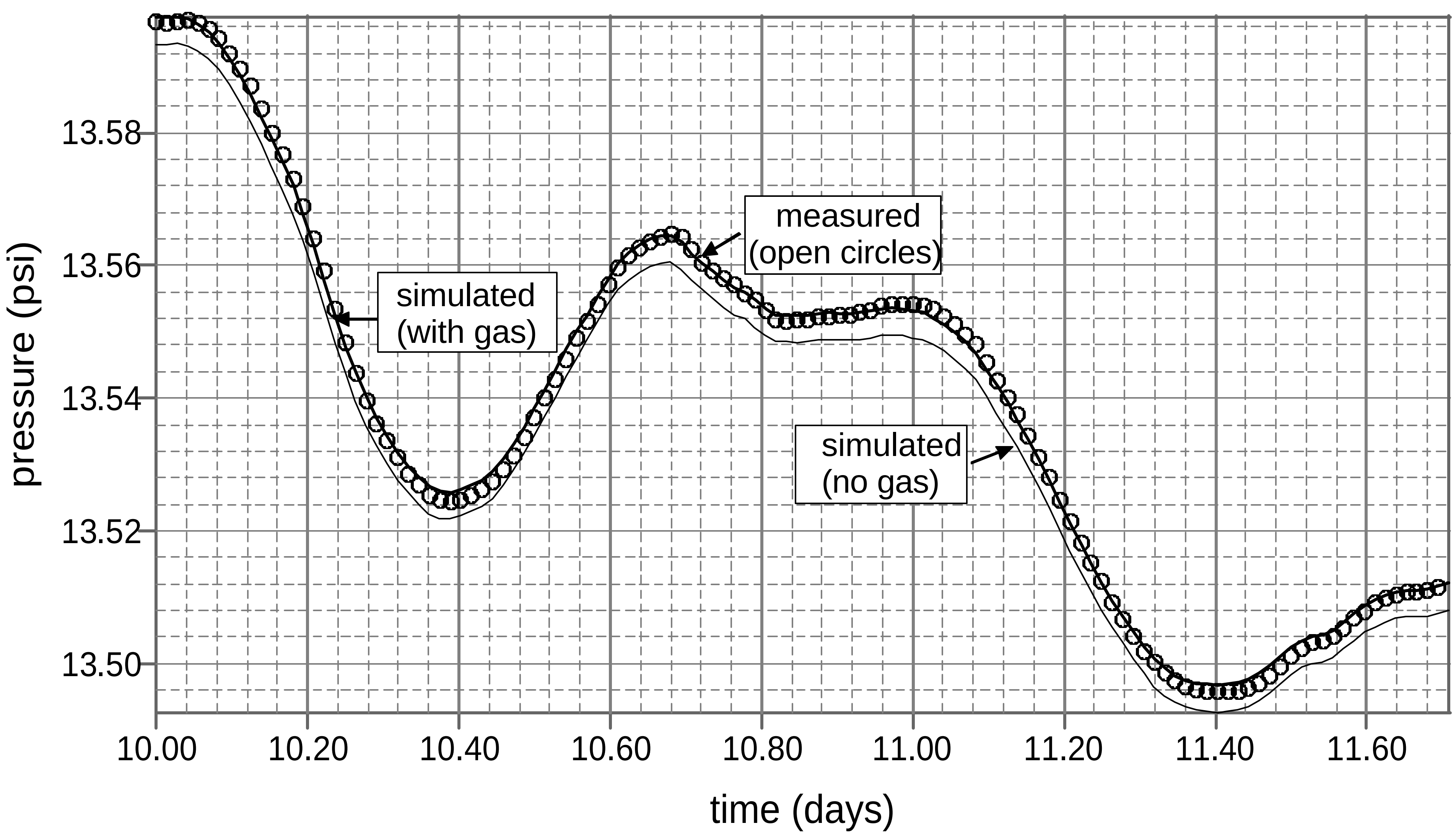
Approved	Date	Revised	Date	Reference:	FIG.
GW	4/30/02				5



HYDRO GEO CHEM, INC.

MEASURED PRESSURE DATA
BAROMETRIC AND 75 FEET DEEP IN LANDFILL
TUCSON, ARIZONA

Approved	Date	Reference	Figure
		H:/0861_landfill_market/landfill Presentations/azswanafigure6.srf	6



HYDRO
GEO
CHEM, INC.

SIMULATED RESULTS AT 75 FOOT DEPTH IN LANDFILL WITH AND WITHOUT GAS GENERATION. TUCSON, ARIZONA

Approved	Date	Reference	Figure
		H:/0861_landfill_market/landfill presentations/azswanafigure7.srf	7