FATAL FLAWS IN MEASURING LANDFILL GAS GENERATION RATES BY EMPIRICAL WELL TESTING

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ABSTRACT

Well testing procedures, such as the Tier 3 methodology specified in the United States Code of Federal Regulations Subtitle D, are commonly used for directly estimating landfill gas (LFG) emissions at municipal solid waste landfills. Such procedures are also used to estimate LFG generation rates for the design of LFG-to-energy projects. These methodologies assume that the LFG generation rate equals the extraction rate of a test gas well within the radius of influence (ROI) of the test well. The ROI is defined as the distance from the extraction well at which the induced pressure drop is immeasurable by some standard of precision.

Based on fluid dynamic principles, Tier 3 and similar methodologies are demonstrated to be incapable of providing reliable estimates of the LFG generation rate. These tests may either over- or under-estimate the LFG generation rate depending on the precision with which the ROI is determined, but will only coincidentally produce an estimate that accurately represents the actual LFG generation rate. Fluid dynamic principles dictate that the actual LFG generation rate can only be estimated if the pneumatic properties of the refuse and cover materials as well as the excess pressure in the refuse due to LFG generation are known or can be estimated.

INTRODUCTION

Estimation of landfill gas (LFG) generation rates is required for the calculation of non-methane organic compound emissions by the United States Code of Federal Regulations (40CFR Subtitle D) and for design of LFG-to-energy projects. Most commonly, LFG generation rates are estimated either by using general correlations based on landfill mass and age, or by empirical well testing methods such as those specified in the Tier 3 method described in Subtitle D. The Tier 3 methodology involves field testing at the landfill of interest and is very similar to that described by Emcon (1). Variations on the Tier 3 method are also common in practice.

Ham (2) discussed some of the practical difficulties, such as accounting for variations in barometric pressure and the effect of pressure measurement accuracy in determining the radius of influence (ROI), associated with estimating LFG generation rates using extraction well testing methods similar to those in Tier 3. Ham did not consider the fundamental validity of extraction well testing methods, however. This paper discusses the assumptions underlying empirical well testing methods and their fluid dynamic basis. In the following discussion, empirical well testing methods for estimating LFG generation rates will be referred to as “Tier 3 methods” even though variations in the Tier 3 procedure are common. The Tier 3 methodology and any variations on it that rely on similar assumptions will be demonstrated to be incapable of providing a reliable estimate of landfill gas generation rates.

BACKGROUND

The Tier 3 method involves extracting gas from one or more gas extraction wells completed in the refuse and measuring the resulting pressure response in an array of monitoring probes completed at various depths and distances from the extraction well. The simplest layout for a Tier 3 test is illustrated in Figure 1. The calculation of the LFG generation rate hinges on two factors: the ROI of the extraction well and the penetration of atmospheric gases into the refuse during the test.

The ROI is defined as the distance at which the difference between the temporally averaged absolute pressure during extraction and the temporally averaged static pressure (that is the pressure in the landfill in the absence of gas extraction) is zero within measurement error. The "influence" can thus be defined as:

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

where $\overline{P_0}$ is the average static absolute pressure and $\overline{P_e}$ is the average extraction absolute pressure. The radial distance (r_e) at which I becomes zero is determined by direct measurement in probes at various distances or, as is most commonly done, by extrapolating the ROI from a semi-logarithmic plot of the I versus the log of radial distance. Assuming that the average static and extraction pressures can be reliably determined in the presence of natural variations in atmospheric pressure and that the extraction rate is constant, the LFG generation rate within the ROI is assumed to equal the gas extraction rate.

As a constraint on the method, the LFG composition is also monitored for indications of intrusion of atmospheric gases due to surface leakage into the refuse within the ROI. A nitrogen concentration exceeding 20% by volume at 3 meters (m) from the extraction well is taken as an indication of excess surface leakage within the ROI and the test must be repeated at a lower extraction rate. The Tier 3 approach thus consists of two components: 1) determining the ROI based pressure measurements and 2) evaluation of the extent of surface leakage based on the gas composition. The following analysis will illustrate that neither of these components, either separately or in combination, results in a reliable estimate of the LFG generation rate.

PNEUMATIC ANALYSIS

The Tier 3 method and its variants rest entirely on the assumption that the LFG generation rate equals the gas extraction rate within the ROI (2). This assumption is inconsistent with fundamental principles of gas flow to wells in porous media. To illustrate this, consider the simple case of a lined landfill with a cover of low gas permeability with respect to the refuse. Further, assume that the LFG generation per unit volume of refuse is uniform, that the refuse is of uniform thickness, and the landfill is of large areal extent. Given that the gas permeability of the refuse is large with respect to the cover, the average excess static pressure within the refuse can be computed from Darcy's Law (3) as:

$$\Delta P_0 = \frac{q_{LFG}\,\mu\, b_c}{k_c} \qquad \textbf{(2)}$$

where q_{LFG} is the gas generation rate per unit area 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_0 is the pressure differential $P_0 - P_a$
P_a is the atmospheric pressure

The average static pressure in the refuse is then:

$$\overline{P_0} = \overline{P_a} + \Delta \overline{P}_0 \qquad \textbf{(3)}$$

When a gas extraction well is operated in the landfill, the pressure change created by the extraction well can be computed using an appropriate mathematical solution for gas flow to the well. For the sake of simplicity, assume that the LFG behaves as an ideal gas and that the extraction pressures are sufficiently close to atmospheric pressure so that variations in the gas density can be ignored. In this case, the pressure change created by the extraction well can be described by (3):

$$\Delta P_e = \frac{Q_e \mu}{2\pi k_r b_r} P_D(r) \qquad \textbf{(4)}$$

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
b_r is the thickness of the refuse

For example, Lofy (4) used a simple hemispheric flow, dimensionless pressure function to analyze pressure drawdown due to an extraction well partially penetrating a thick refuse. Considering the vertical anisotropy likely to exist in the refuse gas permeability and the finite gas permeability of landfill covers, dimensionless pressure functions derived for a radial flow regime are more appropriate for the analysis of gas flow to extraction wells provided that the wells penetrate a substantial portion of the refuse, as they do in the Tier 3 methodology. Assuming steady-state conditions within a highly permeable refuse with a low permeability cover, an appropriate P_D function is that given by Hantush (5) for flow to a well producing at a constant rate from a formation bounded by a low permeability confining bed without fluid storage in the confining bed:

$$P_D = K_0(r / B); B = \left(\frac{k_r b_r b_c}{k_c} \right)^{1/2} \qquad \textbf{(5)}$$

where K_0 is the modified Bessel function of zero order.
Equation (4) then becomes:

$$\Delta P_e = \frac{Q_e \mu}{2\pi k_r b_r} K_0(r / B) \qquad \textbf{(6)}$$

The average absolute pressure at a given radial distance from the extraction well is then given by:

$$\overline{P_e} = \overline{P_a} + \Delta P_0 - \Delta P_e \qquad \textbf{(7)}$$

The generalized relationship between $\overline{P_e}$ and $\overline{P_a}$ is shown in Figure 2. According to the Tier 3 method, the influence, I, is the difference between the extraction and the static pressures which is simply ΔP_e. The ROI is then taken as the radial distance at which ΔP_e is zero within measurement error (specified in the Tier 3 methodology as ± 0.02 mm Hg).

The development above reveals the two fundamental flaws in the Tier 3 approach. First and most important is the fact that ΔP_e is independent of the LFG generation rate according to eq6. Thus, the ROI based on ΔP_e does not provide any information about the LFG generation rate. Second, ΔP_e as determined from eq6 never actually goes to zero because the Bessel function in eq6 does not go to zero at any radial distance. The same would be true of any other dimensionless pressure function that satisfies the principles of fluid flow in porous media. Thus, the ROI is not an actual fluid dynamic feature, but depends only on the precision of the pressure measurement. The influence of the precision of the pressure measurement on the ROI and calculation of the LFG generation rate has been noted by Ham (2). The lower the precision of the pressure measurement, the smaller the ROI.

To illustrate these points and their implications for the reliability of the Tier 3 approach, consider the example of a landfill with a refuse thickness of 30 feet (9 meters [m]), refuse gas permeability of 50 darcies, and cover thickness of 2 feet (0.6 m). Assume that a Tier 3 test is performed at an extraction rate of 100 standard cubic feet per minute (scfm) (2.8 m^3/minute) and that the area specific LFG generation rate is uniform and constant at 5.6 x 10^{-4} scfm per ft^{-2} (1.7 x 10^{-4} m/minute), equivalent to 1,750 scfm over 72 acre landfill (approximately 30 hectares). Figure 3 shows the static and extraction pressures versus distance for cover permeabilities of 0.1 and 0.5 darcies (approximately equivalent to saturated hydraulic conductivities of 1 x 10^{-4} cm/s and 1 x 10^{-3} cm/s, respectively). Also shown in Figure 3 are the ROIs determined for these two cases assuming a measurement error of 0.02 mm Hg (2.63 x 10^{-5} atm or 2.7 Pa), as specified in the Tier 3 methodology. The ROIs in this case are 720 ft (220 m) and 360 ft (95 m) for cover permeabilities of 0.1 and 0.5 darcies, respectively. According to Tier 3, the area specific LFG generation rate would be determined by dividing the extraction rate, Q_e, by the area within the ROI. The Tier 3 approach then results in two different estimates of the LFG generation rate depending on the cover permeability, 6.3 x 10^{-5} sfcm/ft^{-2} (1.9 x 10^{-5} m/minute) and 3.3 x 10^{-4} sfcm/ft^{-2} (1.0 x 10^{-4} m/minute) for the cover permeabilities of 0.1 darcies and 0.5 darcies, respectively. Neither of these calculated rates equals the specified LFG generation rate; the first, underestimating the actual rate by a factor of 8.9 and the second, by a factor of 1.7.

For the case described above and the pressure measurement precision specified, the Tier 3 approach underestimates the LFG generation rate. The pressure measurement precision described in Tier 3 is difficult to achieve in practice and a lower accuracy, on the order of 0.2 mm Hg (0.1 inches of water or 22.7 Pa), is more commonly used to determine the ROI. Figure 4 shows the ROIs determined for the landfill conditions described above for a measurement accuracy of 0.2 mm Hg. In this case, the calculated LFG generation rates are 1.9 x 10^{-4} sfcm/ft^{-2} (5.8 x 10^{-5} m/minute) and 1.0 x 10^{-3} scfm/ft^{-2} (3.0 x 10^{-4} m/minute) for the cover permeabilities of 0.1 darcies and 0.5 darcy, respectively, one of which is lower than the actual rate by a factor of 5.0 and the other higher by a factor of 1.8.

AIR INTRUSION TESTING

The second component of the Tier 3 methodology is to monitor for the intrusion of air into the landfill during the extraction testing. If excess air intrusion is detected at the monitoring probes located 3 m from the extraction well, then the extraction rate is reduced and a new ROI is determined for an extraction rate meeting the air intrusion threshold criteria. The air intrusion component of the Tier 3 test introduces a linkage between the extraction pressure drop and the LFG generation rate because air intrusion should only occur within radial distances where $P_e < P_a + \Delta P_0$. As illustrated in Figure 3, the absolute pressure within the refuse will generally be less than atmospheric at some locations within the Tier 3 ROI unless the extraction pressure outside the wellbore is less than the excess landfill pressure.

As specified in the Tier 3 methodology, the extraction testing is started at a flow rate at least 2 times the static flow rate (Q_0). The static flow rate is defined as the free flow from the well at the static refuse pressure, that is, without forced venting. Under free flowing conditions, the wellbore pressure is then atmospheric (except for very small pressure losses within the well casing) whereas the pressure in the refuse outside the wellbore is greater than atmospheric pressure, but less than the static refuse pressure. At any higher extraction rate, the pressure at some locations in the refuse outside the wellbore must be less than atmospheric, leading to air intrusion.

At a location outside the radius (r_0) where the average extraction pressure (P_e) exceeds the average atmospheric pressure, all of the gas flowing toward the extraction well is LFG. Inside this radius, some portion of the gas flowing toward the well is derived from the atmosphere unless the cover is truly impervious. Assuming radial flow within the refuse to the extraction well, the flow ($Q_T(r_0)$) through the cylindrical surface defined by r_0 is given by:

$$Q_T(r_0) = 2\pi\, r_0 b_r \frac{k_r}{\mu} \frac{\partial P(r_0)}{\partial r} \qquad \textbf{(8)}$$

Within this radius, r_0, a portion of the total flow toward the well is derived from the atmosphere by flow through the cover because P_e is less than atmospheric, as illustrated in Figure 3. At any such distance, the flow toward the well is

$$Q_T(r) = 2\pi\, r b_r \frac{k_r}{\mu} \frac{\partial P(r)}{\partial r} \qquad \textbf{(9)}$$

Assuming that the extraction pressure is given by eq 6, the pressure gradients in eq 7 and eq 9 are given by:

$$\frac{\partial P}{\partial r} = \frac{\partial \Delta P_e}{\partial r} = \frac{Q_e \mu}{2\pi\, k_r b_r} \frac{1}{B} K_1(r / B) \qquad \textbf{(10)}$$

where we note that (6)

$$\frac{\partial K_0(r / B)}{\partial r} = -\frac{1}{B} K_1(r / B) \qquad \textbf{(11)}$$

and K_1 is the modified Bessel function of first order.

From these considerations, the fraction of atmospheric gases (R_f) flowing through the refuse at any radial distance from the extraction well at which P_e is less than atmospheric is:

$$R_f = 1 - \frac{Q_T(r_0)}{Q_T(r)} \qquad \textbf{(12)}$$

Substituting eq8, eq9, and eq11 into eq12 and rearranging gives:

$$R_f = 1 - \frac{r_0 K_1(r_0 / B)}{r K_1(r / B)} \qquad \textbf{(13)}$$

According to eq13, R_f depends on r, the cover thickness, and the ratio of cover gas permeability to refuse permeability through B. Less obviously, R_f also depends on the extraction rate and the LFG generation rate through r_0. This dependency can be seen by noting that r_0 is the radius at which the pressure drop induced by the extraction well equals the excess landfill pressure. Using eq2 and eq6, this radius is determined by solving

$$\frac{q_{LFG} b_c}{k_c} = \frac{Q_e}{2\pi\, k_r b_r} K_0(r_0 / B) \qquad \textbf{(14)}$$

for r_0. Using eq13 and eq14, we can now determine if the Tier 3 air intrusion monitoring procedure provides a constraint that allows the LFG generation rate to be determined from the ROI concept.

To answer this question, consider the specific landfill described previously. According to the Tier 3 methodology, the extraction rate is gradually increased from two times the static flow rate until air intrusion (defined as 20 % nitrogen or 25% of the atmospheric nitrogen concentration) is detected at the 3-meter monitoring probes. Figure 5 shows the resulting extraction rates and calculated LFG generation rates for cover gas permeabilities of 0.05, 0.1, 0.2, 0.5 and 1 darcies determined by iteratively solving eq13 and eq14. In each case, two ROIs were computed, one at the distance at which the pressure in the refuse was within 0.02 mm Hg or less of atmospheric pressure, and the other where the pressure was 0.2 mm Hg or less of atmospheric. The area specific LFG generation rates were computed assuming that the LFG generation rate within the ROI equaled the extraction rate, that is:

$$q_{LFG} = \frac{Q_e}{\pi r_e^2} \tag{15}$$

Clearly, the computed LFG generation rates are significantly less than the actual rate when the pressure measurement accuracy is 0.02 mm Hg. For the case where the pressure measurement accuracy is 0.2 mm Hg, the calculated rates under-estimate the actual LFG generation rate for low cover permeabilities but over-estimate the rate at high cover permeabilities. Thus, the imposition of the air intrusion constraint does not lead to a reliable estimate of the LFG generation rate based on the ROI concept.

AN ATTRACTIVE ALTERNATIVE

Despite the problems with the Tier 3 methodology, the concept of using extraction well testing to directly estimate the LFG generation rate is very attractive. Given that the conventional Tier 3 methodology is fundamentally incapable of yielding a reliable estimate of the LFG generation rate, is there an alternative approach based on extraction well testing that is reliable? A possible modification to the conventional approach would be to define the ROI as the distance at which the pressure induced by the extraction well equals the excess landfill gas pressure, that is, the radius at which $\overline{P_a} - \overline{P_e} = 0$, and to assume that Q_e represents the LFG generation rate within the ROI. The attractiveness of this definition is that it establishes a relationship between the influence of the extraction well and the LFG generation rate. Using eq2 and eq6, this approach implies:

$$\Delta P = \frac{q_{LFG} \mu b_c}{k_c} = \frac{Q_e \mu}{2\pi k_r b_r} K_0(r_e / B) \tag{16}$$

Multiplying through by πr_e^2 allows eq16 to be expressed in terms of the total LFG generation rate within the ROI as:

$$\frac{Q_{LFG} b_c}{k_c} = \frac{Q_e r_e^2}{2 k_r b_r} K_0(r_e / B) \tag{17}$$

where Q_{LFG} is the total LFG generation rate within r_e. If the hypothesis that Q_e equals Q_{LFG} within the ROI (r_e) is correct, then

$$\frac{Q_{LFG}}{Q_e} = 1 = \frac{k_c r_e^2}{2 k_r b_r b_c} K_0(r_e / B) \tag{18}$$

This hypothesis can be tested by determining if eq18 is generally correct. To do this, consider the specific landfill properties discussed previously. Given the assumed refuse and cover thicknesses, the right hand side of eq18 depends only on the ratio of k_c to k_r and r_e. The ratio of Q_{LFG} to Q_e for ratios of k_c/k_r of 10^{-3} to 1 as a function of r_e is shown in Figure 6. In no case does Q_{LFG} equal Q_e ($Q_{LFG}/Q_e = 1$) and, in fact, the maximum ratio is approximately 0.25 indicating that the hypothesis that the LFG generation rate within the radius at which the pressure drawdown equals the landfill excess pressure is not correct. In fact, for the range of parameters considered, the LFG generation rate would be underestimated by at least a factor of 4 if the hypothesis were accepted.

CONCLUSIONS

The results of the analysis above indicate that not only is the Tier 3 methodology for estimating LFG generation rates fundamentally flawed, but so is the concept that the LFG generation rate can be empirically determined by extraction well testing. The Tier 3 methodology and its variants may either over- or under-estimate the LFG generation rate at a specific landfill. Overestimates of the LFG generation rate are most likely when the pressure drop in the refuse is measured with low accuracy or when the gas permeability of the cover is relatively high. The LFG generation rate is more likely to be underestimated when the ROI is determined with high precision or when the permeability of the cover is relatively low. The inaccuracy of the Tier 3 methodology may be particularly serious when the resulting LFG generation rates are used to design LFG collection systems or LFG-to-energy projects that involve significant capital investment.

Fluid dynamic principles dictate that the LFG generation rate cannot be determined from extraction well testing and pressure monitoring unless the pneumatic properties of the cover and refuse are known or can be estimated. As suggested by Bentley and others (7) and Zison (8), eq2 provides a basis for estimating the LFG generation rate if the effective gas permeability of the cover is known. The pneumatic properties of the cover and refuse can also be estimated by analysis of pressure data collected during extraction well testing using various solutions to (5).

REFERENCES

(1) EMCON. *Methane Generation and Recovery from Landfills*. EMCON Associates, San Jose, CA. Ann Arbor Science Publishers, Ann Arbor, MI. 1980.

(2) Ham, R.K. Field testing for evaluation of landfill gas yields in *Landfilling of Wastes: Biogases*, ed. T.H. Christensen, R. Cossu, and R. Stegmann. E + FM Spon, London. 1996.

(3) Al-Hussainy, R., H. J. Ramey, Jr., and P. B. Crawford. The Flow Of Real Gases Through Porous Media. *Journal of Petroleum Technology*, Volume 237, pp. 624-636. 1966.

(4) Lofy, R.J. Predicted effectiveness of active gas extraction in *Landfilling of Wastes: Biogases*, ed. T.H. Christensen, R. Cossu, and R. Stegmann. E + FM Spon, London. 1996.

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

(6) Abramowitz, M. and I.A. Stegun, eds. *Handbook of Mathematical Functions*. Dover Publications. New York. 1972.

(7) Bentley, H. W., G.R. Walter, S.J. Smith, J. Tang, and C.T. Williamson. U.S. Patent Application. Doc. No. 6005.102US. 2001.

(8) Zison, S.W. U.S. Patent 5,063,519. 1991.

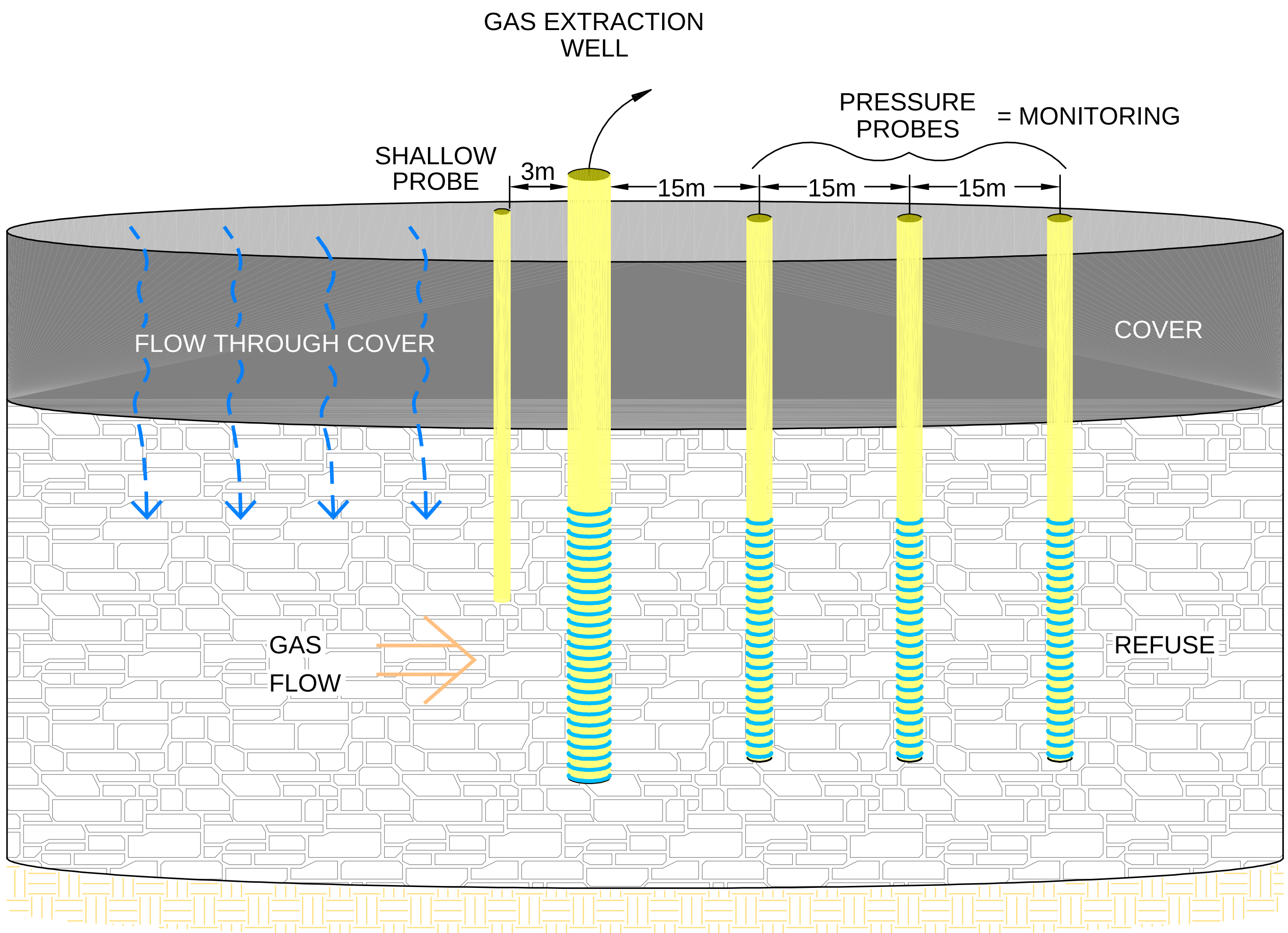

FIGURE 1: SCHEMATIC LAYOUT OF A TIER 3 TEST WITH A SINGLE EXTRACTION WELL

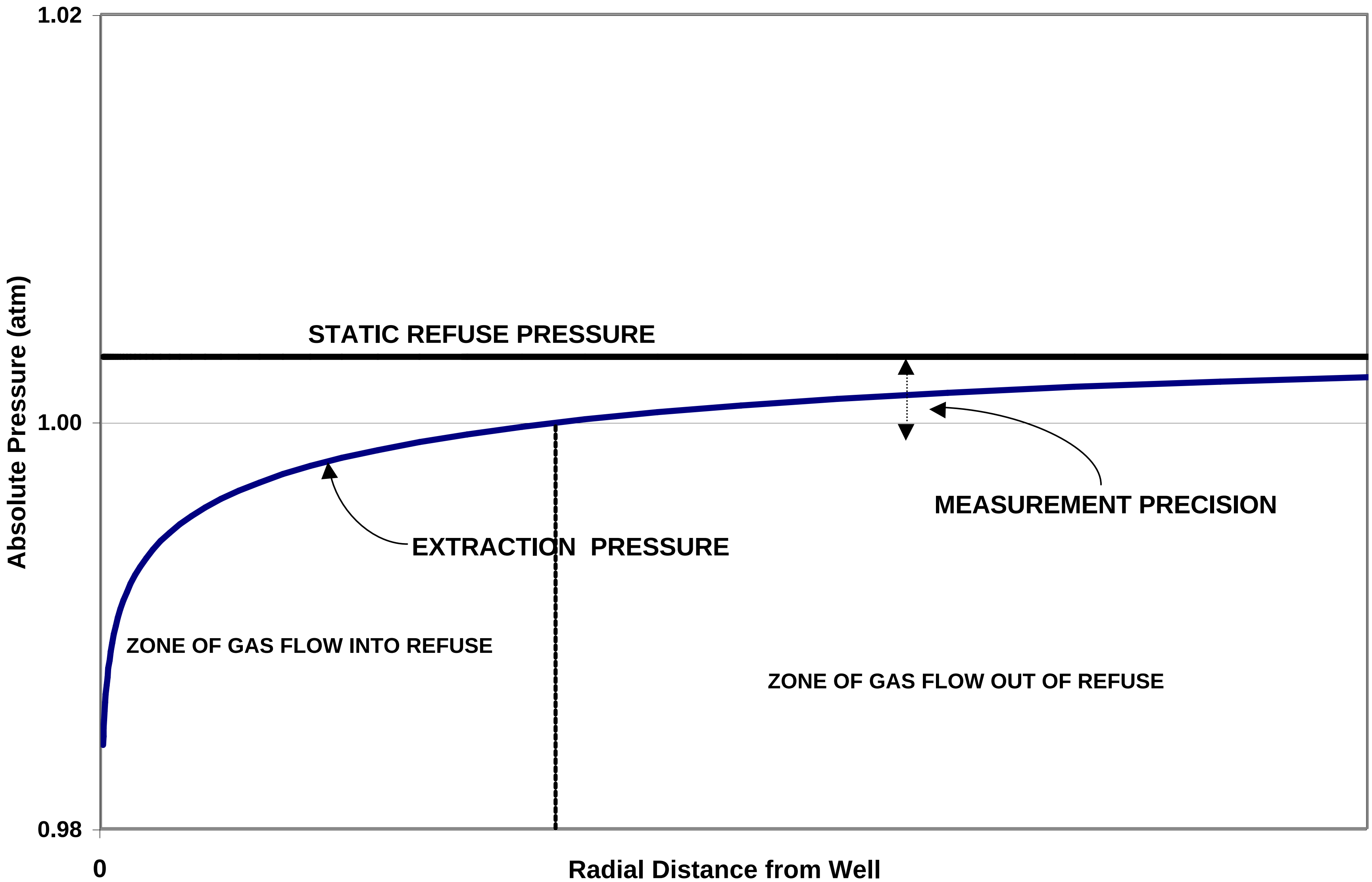

Figure 2: Generalized Relationship Between Static Pressure and Extraction Pressure

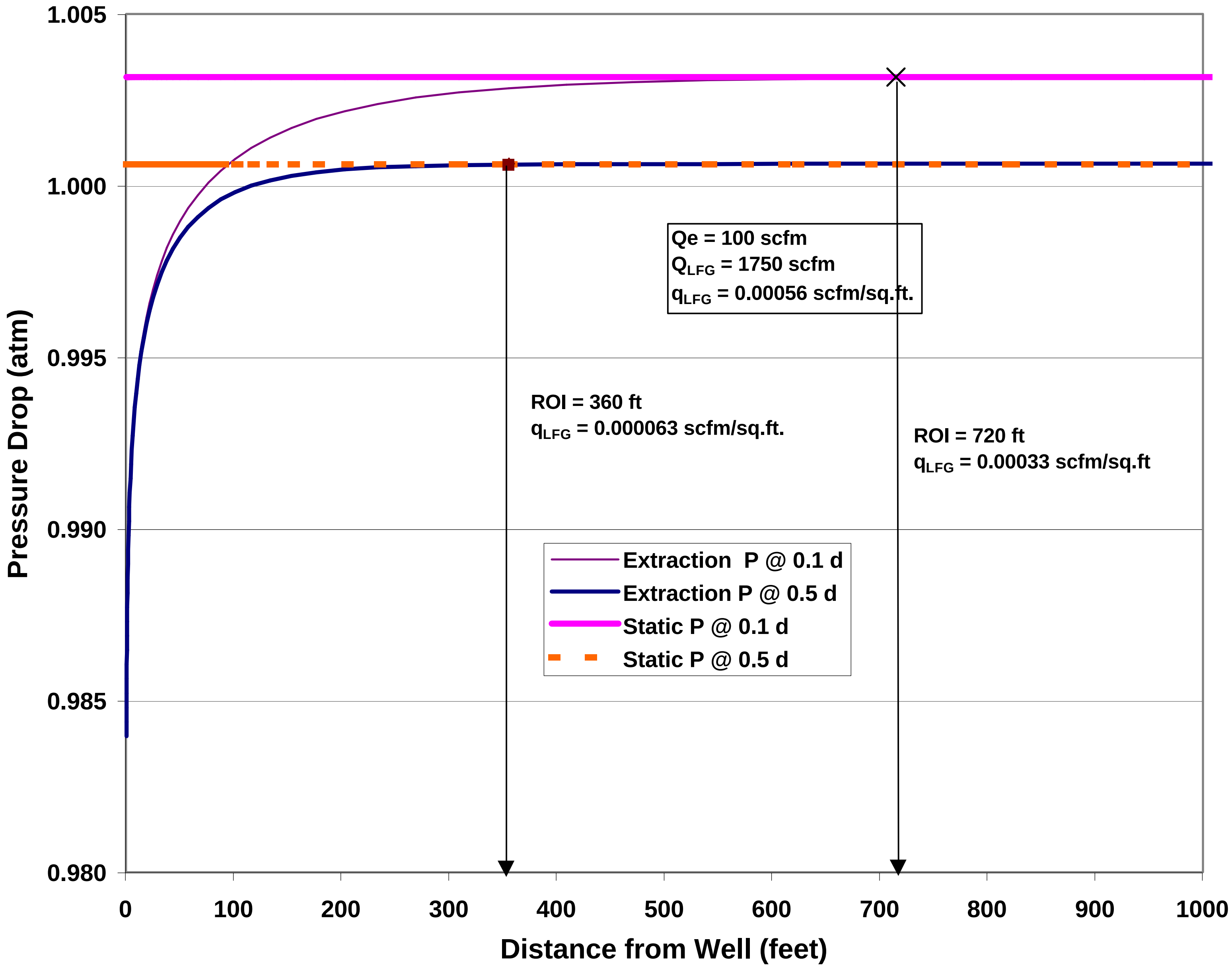

Figure 3: Pressure and Radii of Influence of Cover Permeabilities of of 0.1 and 0.5 darcies, Measurement Accuracy 0.02 mm Hg

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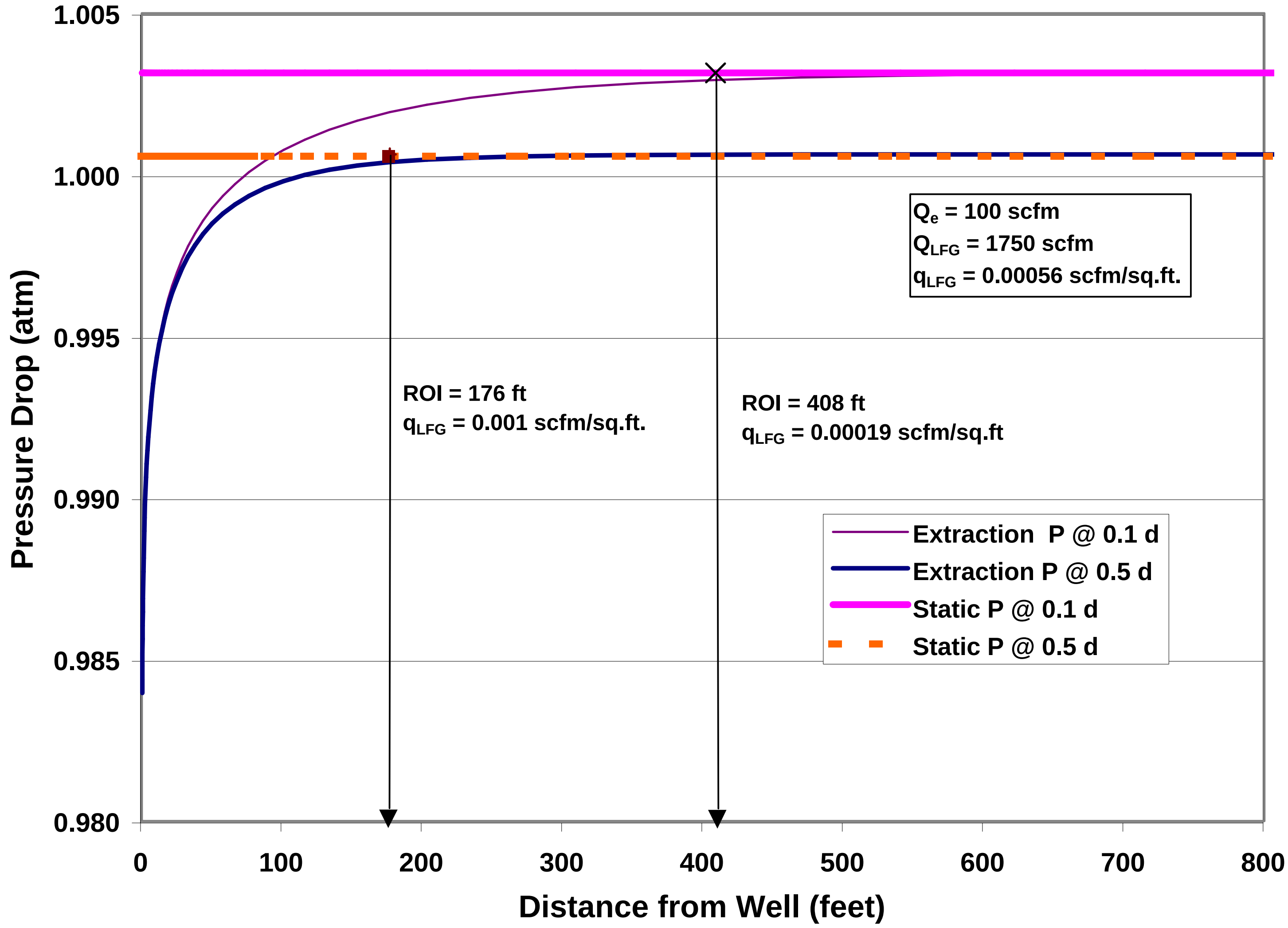

Figure 4: Pressure and Radii of Influence of Cover Permeabilities of of 0.1 and 0.5 darcies, Measurement Accuracy 0.2 mmHg

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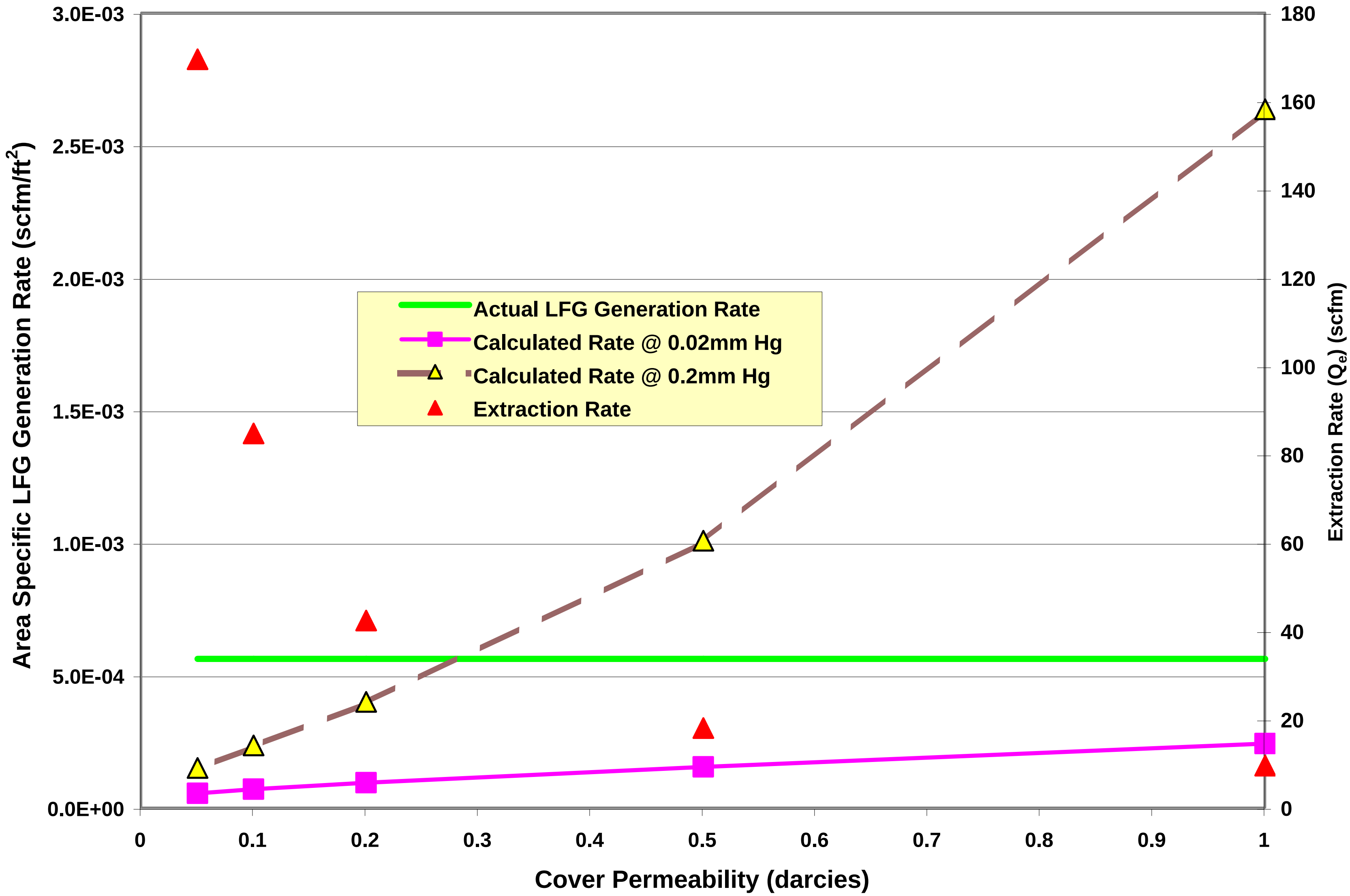

Figure 5: Specific LFG Generation Rates versus Cover Permeability

H:\0860\lfgsurfflow2.xls\lfgsurfflow2.xlsFigure 5

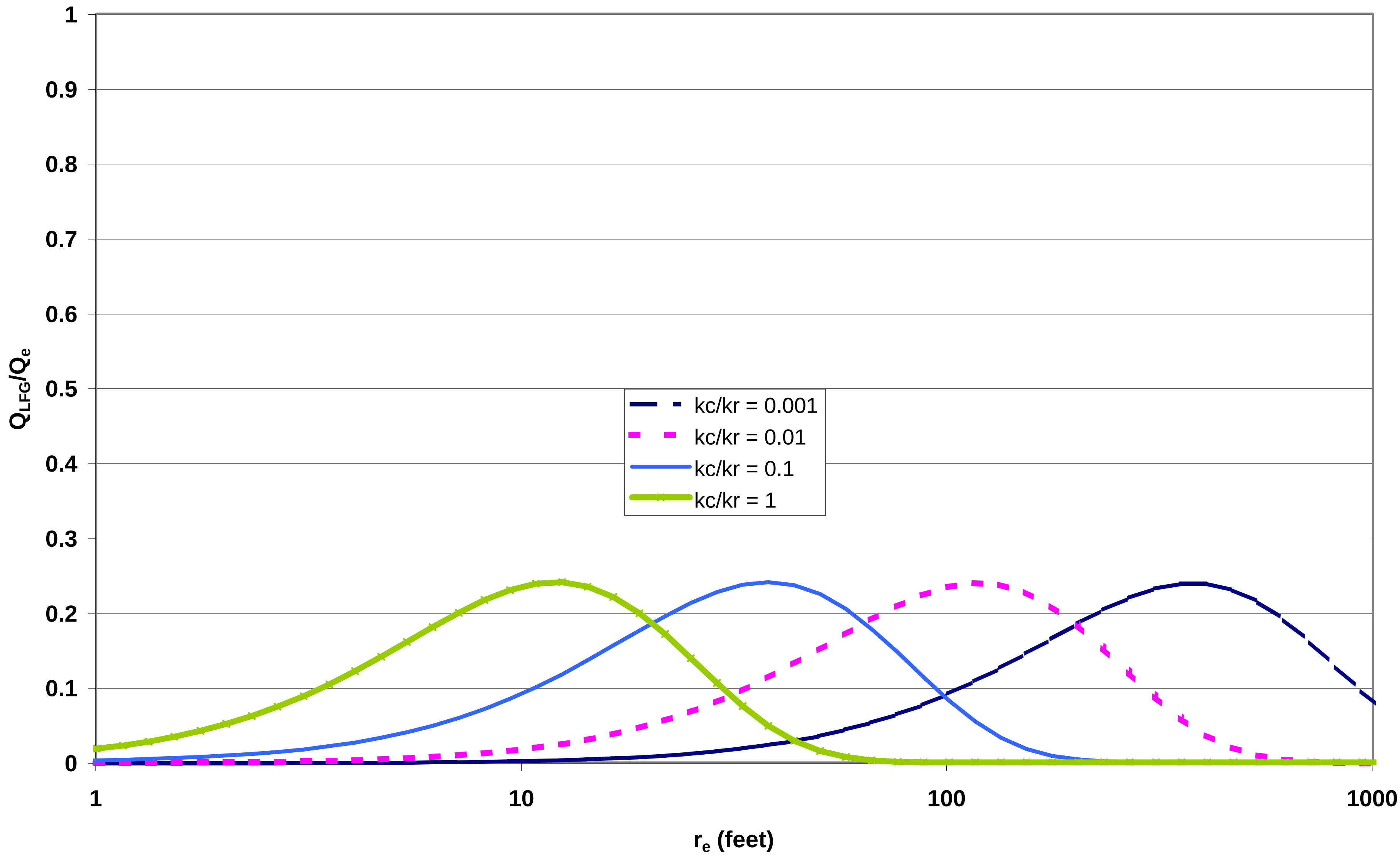

Figure 6: Ratio of LFG Generation Rate to Extraction Rate Versus Cover to Refuse Permeability Ratio Using Alternative ROI Definition