IMPROVED METHOD FOR ESTIMATING LANDFILL GAS PRODUCTION

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1. INTRODUCTION

Estimation of the rate of landfill gas (LFG) generation is required for calculation of non-methane organic compound (NMOC) emissions under 40 CFR Subtitle D (Subtitle D), and for successful design of LFG-to-energy projects. Subtitle D requires a landfill owner to calculate emissions using a tiered approach based on estimates and/or measurements of LFG generation and NMOC concentrations within the landfill. Tiers 1 and 2 utilize a formula for LFG generation that is based in part on the size and age of the landfill and that does not involve direct measurement. Because this formula is designed to be conservative, estimates of LFG generation by this method are likely to be higher than the actual rate, especially for landfills in arid environments where low refuse moisture content may limit LFG generation. Tier 3 (40 CFR Ch. 1, Pt60, App. H) involves measurement of LFG generation and is very similar to the approach detailed in EMCON (1980). Similar methods are typically employed to estimate LFG generation rates when designing LFG-to-energy projects.

The Tier 3 methodology is generally not employed for calculation of NMOC emissions unless calculations by Tiers 1 and 2 exceed 50 megagrams per year (MG/yr) in which case, Subtitle D requires the landfill owner to install an LFG control system. Operation of the control system is then required until NMOC emissions drop below 50 MG/yr, which will occur eventually for a closed landfill as it ages. Periodic recalculation of NMOC emissions is required, however, to demonstrate that emissions are below this threshold, resulting in additional expense. Although the Tier 3 methodology is time consuming and expensive, its use may be justified if it results in a lower estimate of LFG production and NMOC emissions of less than 50 MG/yr.

Overestimation of LFG generation by any of these methods is costly to the landfill operator if it results in estimated NMOC emissions greater than 50 MG/yr and requires the installation of an LFG control system. Additional costs are incurred if an LFG control system is overdesigned based on an inflated estimate of LFG production, especially if the recovered LFG is to be flared. The same applies to the design of an LFG-to-energy system for which economics are often critically dependent on accurate estimation of LFG production. Overestimation of LFG generation will be especially costly if the actual rate is inadequate to economically justify the energy system.

Independent of cost, the Tier 3 methodology is technically flawed and does not provide an accurate estimate of either LFG production or NMOC emissions. The same inadequacies of the method were identified and discussed in EMCON (1980) and are summarized in Section 2.2. Hydro Geo Chem, Inc (HGC). has developed an alternative to the Tier 3 methodology that is more accurate, technically defensible, and less expensive to perform. The alternative method addresses many of the inadequacies of Tier 3 which were recognized by EMCON (1980). Discussion of the HGC alternative methodology is the subject of the remainder of this paper.

2. BACKGROUND

The Tier 3 method involves pumping a gas extraction well or cluster of wells completed in landfilled materials and measuring pressure drawdown in monitoring probes completed at various depths and distances from the extraction well(s) to determine the extraction wells' "radius of influence" (ROI). Pressure drawdown is defined as the difference between "average static pressure" in the landfill measured prior to gas extraction and the average pressure measured during extraction. Average pressures are used in an attempt to remove the influence of barometric pressure fluctuations on the measurements. The assumption is made that the "average static pressure" is determinable as a reference pressure to calculate pressure drawdown after extraction begins. The fractional pressure drop, or "influence" at a given distance from the extraction well is defined as:

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

where $\overline{P_0}$ is the average static absolute pressure

$\overline{P_e}$ is the average extraction absolute pressure

The ROI is typically taken to be the distance at which no measurable pressure drop occurs. The ROI may be determined directly either as the furthest distance from the extraction well at which I # 0 (within measurement error) or by extrapolating the measured I values using a semi-logarithmic regression to determine the radius (r_e). The accuracy of the pressure measurements is specified to be ± 0.02 mm of mercury or $4\text{x}10^{-4}$ pounds per square inch (psi).

Gas samples are also collected from the extraction well and monitoring probes during extraction and analyzed for nitrogen to determine whether leakage of atmospheric air into the landfill from the surface is contributing significantly to the flow to the extraction well(s). Nitrogen concentrations in excess of 20% are taken to indicate excess surface leakage. Typically, samples are also analyzed for methane, carbon dioxide, and oxygen to determine the effects of extraction on LFG quality. If excess surface leakage is not indicated by gas analysis or by negative gauge pressures in shallow monitoring probes, then the rate of gas extraction by the well(s) is assumed to be equal to the rate of LFG generation within the volume of landfilled materials encompassed by the ROI. Landfill materials outside the ROI are not considered to contribute to gas flow to the extraction well.

2.1 Limitations of the Tier 3 Method

The Tier 3 methodology is very similar to an approach for estimating LFG generation described in EMCON (1980). A number of theoretical and practical limitations of this methodology were identified by EMCON (1980), including:

1) “The validity of estimating the ROI from a semi-logarithmic extrapolation to withdrawal of gas from landfills remains to be verified.”

2) “A completely satisfactory method of estimating a landfill’s gas production rate from extraction testing that draws only from a confined radius of influence has not been demonstrated.”

3) “The influence of gas withdrawal [actually] extends to the limits of the landfill boundary (and beyond).”

4) “The distance taken as the ‘radius of influence’ depends on the precision of the instruments used to measure landfill gas pressures and on the effects of diurnal (barometric) pressure fluctuations.”

With regard to the effect of barometric pressure fluctuations on calculation of pressure drawdown, the Tier 3 technique specified under Subtitle D attempts to account for the effects of changing barometric pressure by specifying that barometric pressure be monitored and included in the drawdown calculations. This is accomplished by adding landfill gauge pressure readings to the barometric pressure readings during the “static” measurement period (prior to gas extraction) and during gas extraction (yielding absolute pressure), and comparing the average pre-extraction and extraction period pressures to determine the radial distance at which the absolute pressure in the landfill is not affected by pumping. However, if the average barometric pressure before extraction differs from the average pressure during extraction, the ROI will be either under- or over-estimated. This point will be discussed in more detail later.

EMCON (1980) further suggests that:

> “An accurate theoretical mass balance on the landfill gas remains to be developed and would prove invaluable in making such estimates [of landfill gas production]. The mass-balance could account for refuse characteristics (e.g. permeability) and continuous gas production, the gas composition and extraction rate and the observed internal landfill pressure (or influence) distribution could be related to available equations for convective and diffusive gas flow, accounting for recovery, efficiency, and loss of gas to the atmosphere as a function of distance from extraction well, landfill geometry, cover conditions, etc.”

These factors notwithstanding, the Tier 3 methodology rests entirely on the assumption that the gas extraction rate equals the LFG generation rate within the volume of the refuse between the extraction well and the ROI . This assumption is inconsistent with fundamental principles of gas flow to wells. To illustrate this point, assume that the LFG generation rate is uniform throughout the 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 refuse and the atmosphere due to flow through the cover is given simply by Darcy’s Law (Al-Hussainy and others, 1966):

$$q_{LFG} = \frac{k_c}{m}\frac{\Delta P}{b_c} \qquad \textbf{(2)}$$

or

where	q_{LFG}	is the gas generation rate per square foot of landfill

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

k_c	is the effective gas permeability of the cover
μ	is the dynamic viscosity of the LFG
b_c	is the cover thickness
$?P$	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:

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

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,
	$?P_e$	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 within 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:

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

where	K_0	is the modified Bessel function of zero order

Thus, (4) becomes

$$\Delta P_e = \frac{Q_e m}{2p k_r b_r} K_0(r / B) \tag{6}$$

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 (6) is illustrated in Figure 1 along with its relationship to the static pressure. In the Tier 3 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,

$$\Delta P_e \cong 0 = \frac{Q_e m}{2p k_r b_r} K_0(r_e / B) \tag{7}$$

where r_e is the radius of influence.

Equation (6) and (7) and Figure 1 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 (6) or (7) so that the distance (r_e) at which ? P 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.

To further illustrate this point, consider the pressure drop curves shown in Figure 2 that were computed using (6) with the following parameters: Q_e= 100 scfm; b_r= 30 feet; b_c= 2 feet; and k_r= 50 darcies. Two curves are shown in Figure 2, one for a cover permeability of 0.5 darcies (roughly equivalent to a saturated hydraulic conductivity of $5x10^{-4}$ cm/s) and the other for a cover permeability of 2.5 darcies (• 2.5 x 10^{-3} cm/s). Clearly, the Tier 3 methodology would predict two different values of r_e for these two cases and yields two different estimates of the LFG generation rate could be the same, the only variable being the cover permeability. It is interesting to note that if the landfill actually had a cover meeting the substitute D specifications of 1 x 10^{-7} cm/s hydraulic conditions, the ROI as determined by Tier would be greater than 5,000 feet at the specified extraction rate.

A possible modification to Tier 3 might be to base the LFG generation rate on the well extraction rate and radius at which the pressure drop equals the excess static landfill pressure (? P_0), that is, the radius at which P_a-P_e=0. Using (3) and (6), this approach would imply:

$$\Delta P = \frac{q_{LFG} m b_c}{k_c} = \frac{Q_e m}{2p k_r b_r} K_0(r_e / B) \tag{8}$$

Multiplying through by pr_e^2 to get the total LFG generation rate within r_e gives:

$$\frac{Q_{LFG} m b_c}{k_c} = \frac{Q_e m r_e{}^2}{2 k_r b_r} K_0 (r_e / B) \tag{9}$$

If the hypothesis that Q_e equals Q_{LFG} for an ROI of r_e is correct, then

$$\frac{Q_{LFG}}{Q_e} = 1 = \frac{k_c r_e{}^2}{2 k_r b_r b_c} K_0 (r_e / B) \tag{10}$$

This hypothesis can be tested by evaluating whether eqn(10) is generally correct. To answer this question, consider the specific case of a landfill with a refuse thickness (b_r) of 30 feet and a cover thickness (b_c) of 2 feet. Given these parameters, the right hand side of (10) depends only on the ratio of k_c to k_r and r_e. Figure 3 shows 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. In no case does Q_{LFG}/Q_e equal 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 differential 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. The results of this analysis indicate that the concept of empirically estimating the LFG generation rate based on extraction rates and pressure drops is fundamentally flawed. A more detailed discussion of the deficiencies of extraction well testing to estimate LFG generation rates is provided in Walter (in review). The LFG generation rate can only be estimated by pressure measurements if the gas permeability of the cover and, in some cases, that of the refuse and subsoil have been independently determined or estimated.

2.2 Alternative Methodology

The proposed methodology recognizes the need to base the LFG generation rate on sound gas flow principles and independent estimates of the gas permeability of the cover, refuse, and surrounding soil. We have found that in many cases, the LFG generation rate can be reliably estimated by a methodology that includes accurate measurement of the average difference between pressure in the landfill and barometric pressure and the analysis of the pressure response in the landfill to natural variations in barometric pressure.

This methodology relies on very accurate and sensitive pressure measurement devices, and a numerical model that automatically satisfies mass balance and can be designed to account for landfill geometry, cover conditions, and other realistic conditions. In most cases, because the parameters needed for the numerical model can be derived by “static” pressure monitoring alone, the performance of a gas extraction test is not required. Under certain landfill conditions, when an extraction test is required to measure properties such as landfill and cover permeability, only short-term, relativity low cost extraction testing is generally required.

3. THEORETICAL BASIS FOR THE ALTERNATIVE APPROACH

LFG generated within a landfill will flow through the landfill materials until it escapes through the cover, sides and bottom of the landfill. For lined, Subtitle D landfills, gas escape is primarily through the cover materials.

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 eqn(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 more realistic conditions 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 robust 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 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 fill in the short term 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. 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. Under unusual conditions, however, rainfall infiltration into the refuse could increase LFG generation.

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 attenuation of the response.

Under simple conditions where the airflow can be assumed to be only vertical, and the effective air permeability of the cover, refuse, and underlying soil are uniform, the pressure distribution is governed by the following differential equation:

$$\frac{\P P^2}{\P t} = \frac{k_a \overline{P}_a}{f m} \frac{\P^2 P^2}{\P z^2} \qquad \textbf{(11)}$$

where $\overline{P_a}$ is the average pressure.

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):

$$P^2 = A \sin(w t + e + q) + \overline{P}_a{}^2 \qquad \textbf{(12)}$$

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

Both A and ? 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, (12) provides a basis for estimating the vertical pneumatic diffusivity and vertical air permeability based on an analysis of barometric pressure signals at depth. Equation (12) 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:

1. the vertical air permeability is not uniform,
2. the barometric pressure signal is not a simple harmonic function, and
3. the air flow is not strictly vertical.

The first limitation is obvious because the subsurface materials at a landfill typically consist of relatively low permeability cover, highly-permeable refuse, and lower-permeability subsoil. The second limitation is illustrated by Figure 4 which shows the non-harmonic barometric pressure and subsurface pressure response of a landfill in Tucson, Arizona. The final limitation related to vertical air flow will be discussed later.

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.

The procedure is simplified for Subtitle D landfills which have low permeability liners, because movement of gas through the underlying soil does not need to be considered. Once the permeabilities of the fill and surrounding materials have been estimated, the measured increase in pressure resulting from LFG production can be used to estimate the rate of LFG production using the gas flow model. This is possible because the increase in pressure resulting from constant gas generation (which can be considered a steady-state effect) adds a constant to the pressure response measured in the landfill, but does not result in a lag or attenuation in amplitude of the signal. This behavior is illustrated empirically and numerically in Figure 5, which displays the results of a simulation performed at a landfill site in Tucson. In this case, LFG generation results in a constant pressure excess of 4×10^{-3} psi within the landfill over a period of 2 days. The excess pressure is dependent on the LFG generation rate through Darcy's Law as described previously. Although the landfill at this site was unlined and had a relatively high permeability cover, sufficient lag and attenuation in the signal were present to estimate both permeability of landfill and cover and the LFG generation rate. As will be discussed in Section 4, this represents the most difficult case in which to apply the method.

4. DEMONSTRATION OF THE METHOD

The LFG production measurement technique presented here is demonstrated for six hypothetical cases using TRACRN, a three-dimensional finite difference computer code developed at Los Alamos National Laboratories, that is capable of simulating gas and liquid flow, and solute transport, under conditions of variable water saturation (Travis and Birdsell, 1988). The six hypothetical cases that were simulated are described in Table 1. Three of the cases represent unlined landfills and three represent lined landfills. In all cases, the gas permeability of the fill is assumed to be high (50 darcies horizontal, 10 darcies vertical), the permeability of the surrounding soil to be relatively high (20 darcies horizontal, 2 darcies vertical), and the permeability of the cover variable, ranging from 10^{-2} darcies to 10 darcies[1]. The porosity is assumed to be constant for the various cases. In our experience, fill materials generally have high permeability but cover permeabilities vary substantially between landfills. The lower cover permeabilities are more representative of Subtitle D landfills than older landfills that are also typically unlined. Furthermore, variations in porosity are much less than variations in permeability, which can vary over several orders of magnitude, and were therefore not considered in the simulations.

A cross-section showing the simulated landfill geometry is provided in Figure 6. One half of the 60-foot thick landfill is located above grade, and one half is below grade. The sides of the above-grade portion of the simulated landfill have a slope of approximately 7E. The footprint of the landfill is 2,000 feet in diameter and is symmetrical.

4.1 Description of the Numerical Model

Two numerical models were constructed to represent the various cases, a two-dimensional, radially-symmetric model in which the footprint of the landfill is a circle with diameter of 2,000 feet, and a three-dimensional model in which the footprint of the model is a square 2,000 feet on a side. The two-dimensional model was radially symmetric, and consisted of an array of 40 non-equally spaced cells in the radial direction, and 18 non-equally spaced layers. Layers in which landfill material was represented were uniformly 5 feet thick. The model boundary was located 2,000 feet from the sides of the landfill to minimize boundary effects. The three-dimensional model consisted of a rectangular array of 48 non-equally spaced cells in the x direction, 48 non-equally spaced cells in the y direction, and 18 non-equally spaced layers. The x and y spacing within the area representing the landfill was uniformly 50 feet, and the layer thickness uniformly 5 feet. Model boundaries were located 1,500 feet from the sides of the landfill to minimize boundary effects.

One hundred and seventy feet of vadose zone soils were represented beneath the landfill in both the two-dimensional and three-dimensional model representations. The lower boundary was specified no-flow to represent the water table. Side boundaries (located far from the landfill margins) were also no-flow, and the upper boundary specified at atmospheric pressure. In both

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[1] Note that 1 darcy is approximately equal to a water saturated hydraulic conductivity of 10^{-3} cm/s.

models, the materials outside the landfill boundary that were below grade represented native soils, and the materials above grade represented “air,” specified as a very high permeability, high porosity material. Properties of the materials represented in the model are provided in Table 2.

In both the two-dimensional and three-dimensional representations, landfill gas generation was simulated by specifying a constant gas source in each cell representing landfill material. The source strength for all landfill cells in the three-dimensional model, which were of equal volume, was the same. The source strength specified for landfill cells in the two-dimensional model was varied according to cell volume to maintain a constant ratio of source strength to cell volume. The total gas generation rate for the two-dimensional model was approximately 1,750 scfm, and for the three-dimensional model, 2,300 scfm (because of larger volume).

A barometric pressure signal (shown in Figure 7) was applied at the upper boundary of each model. The signal consisted of actual pressures measured at hourly intervals at a site in Tucson. When gas generation was simulated, the pressure at the upper boundary was fixed at the average signal pressure until steady-state conditions developed, then the varying barometric pressure signal was applied. The varying barometric pressure signal was transmitted through the sides of the landfill above grade, and the soils represented in the model, via the material representing “air”. Transmission of the barometric pressure signal through materials representing “air” is nearly instantaneous due to the high permeability of the material.

The two-dimensional radial model was designed with a cell spacing that was narrow at the center of the model, and widened radially outward toward the landfill boundaries. The material properties of the center nodes were specified such that the nodes could function as a gas extraction well or pressure monitoring probe in a manner representative of the way such a probe or well would function in the field.

Because of the symmetrical geometry of both the two-dimensional and three-dimensional representations, the two-dimensional model worked equally well for illustrating the technique described in the previous section, and with much less computational effort than the three-dimensional model. The two-dimensional model was also well-suited to simulating a Tier 3 type gas extraction test when the extraction well was located at the center of the landfill. The three-dimensional model, because it contained “corners” that would occur in actual landfills, was mainly useful for investigation of edge effects or for simulating more complex landfill geometries that are not considered here.

4.2 Simulation of the Technique

The six cases listed in Table 1 were simulated using the two-dimensional model, and, for comparison, cases 1 and 3 were also simulated using the three-dimensional model. For the comparison case, the barometric signal was applied and absolute pressures measured at a depth of 30 feet at the center of the landfill in both the two-dimensional and three-dimensional models.

Figures 8 and 9 show the results of these simulations. As indicated in Figure 9, slightly higher pressures result from the two-dimensional model, although the source strength/volume ratio is the same for both. This difference is due to the higher surface area/volume ratio for the three-dimensional, rectangular model relative to the two-dimensional, cylindrical model, and illustrates the importance of taking landfill geometry into account.

The six cases were simulated using the two-dimensional model, with and without gas generation, and with application of the barometric signal. Simulated pressures were monitored in pressure monitoring probes completed a depths of 30 feet and 60 feet in the center of the landfill. Results of the simulations are depicted in Figures 10 through 15.

As indicated, the pressure lag and amplitude attenuation increase with decreasing cap permeability, and are accentuated by the presence of a liner. In the cases with the high permeability cover (cases 1 and 4), almost no measurable lag or attenuation occurs in the signal. Furthermore, there is almost no lag or attenuation between the simulated signals at 30 foot and 60 foot depths in the landfill because of the high permeability of the landfill materials.

The increase in pressure within the landfill relative to atmospheric pressure (shown by the upward translation of pressure curves in simulations with gas generation) is due to the gas source within the landfill. As shown in Figures 10 through 15, the effect of the gas generation is to translate the pressure curves upward without producing any change in shape (lag or amplitude attenuation) of the curves. This is an important observation that illustrates the separability of the steady-state and transient effects.

The results of the simulations show that under conditions where landfill permeability is high (>10 darcies) and cover permeability is relatively low (10^{-2} to 1 darcy), and porosity variations can be ignored, the lag and attenuation in amplitude of the barometric signal transmitted to the landfill are sufficient to determine the permeability of the cover material. In the cases of the lined landfills, where nearly all gas escapes through the cover, only the cover permeability needs to be determined to estimate the gas generation rate based on the measured pressure increase in the landfill relative to atmospheric pressure. The lag and attenuation of the signal that results from transmission through the high permeability landfill materials is insignificant in these cases and can be ignored.

In the case where the cover permeability is nearly the same as the landfill permeability, the permeability of both must be determined to estimate the gas generation rate. As shown in Figures 10 and 13, there may not be sufficient information in the signal to estimate permeability, except to establish a lower limit. In such cases, an independent method for estimating permeability may be required for accurate estimation of gas generation. This is accomplished by performing a gas extraction test on a gas extraction well completed in the landfill. By measuring pressure drawdown at monitoring points completed at various depths in the fill during gas extraction, and analyzing the pressure response with an appropriate well pneumatics model, the horizontal and vertical permeability of the fill (and cap permeability) can be estimated. Generally, these tests require only one to two hours of gas extraction and pressure monitoring to collect sufficient information for permeability estimation. Although in many cases where the landfill is unlined and has a relatively high permeability cover, a gas extraction test will be required, this is not always the case as was seen at the landfill site in Tucson discussed in Section 3 (Figures 4 and 5).

In the case of an unlined landfill, gas movement through the sides of the landfill below grade and through the base of the landfill must also be considered in estimating gas generation rates. This can be accomplished by a combination of barometric tests on probes completed in native soils at the site, and extraction tests on wells completed in the soils. The level of testing necessary will depend on specific site conditions and the results of initial barometric tests on the landfill itself. Clearly, most Subtitle D landfills that have liners and low permeability covers will require only barometric tests; as will unlined landfills completed in low permeability native soils.

4.3 Demonstration of Problems Associated with Tier 3

As discussed previously, the Tier 3 methodology is not based on sound principles of fluid flow and is fundamentally flawed. To further quantify the errors in the Tier 3 methodology, Tier 3 measurements of LFG production for selected cases listed in Table 2 were performed using the two-dimensional model. The simulations were performed to demonstrate the dependence of ROI estimation on the sensitivity of the pressure measuring equipment, on changes in barometric pressure, and on test duration, and to demonstrate that as stated by EMCON (1980) the effects of gas extraction actually extend to the landfill boundaries. As will be shown in section 4.3.1, this last effect essentially invalidates the usefulness of the concept of ROI for measurement of gas generation overshadowing other shortcomings in the technique. Furthermore, because the ROI will expand with increasing pressure measurement sensitivity, the estimate of gas generation will be less and less accurate as the sensitivity of the pressure measurements increases.

4.3.1 Dependence of ROI Estimation on Sensitivity of Pressure Measurement

A simulation was performed for case 3 (Table 1) in which barometric pressure was assumed to be constant and gas was extracted at a rate of 100 scfm from a well screened between 15 ft and 55 ft bls at the center of the landfill. Simulated changes in absolute pressure within the landfill during extraction at depths of 30 ft and 60 ft bls are plotted in Figure 16. As shown, if pressure measurements at 30 ft bls were sensitive to $\pm 1.6 \times 10^{-2}$ psi, then an ROI of 305 feet would be calculated. Alternatively, if pressure measurements were sensitive to $\pm 4 \times 10^{-3}$ psi, the ROI would increase to 925 feet, nearly the radius of the landfill. Similar results are evident for the 60-foot-depth measurements.

Should the ROI be determined to be as large as the landfill radius, then under Tier 3 criteria the entire landfill would be assumed to be contributing gas to the extraction well, and the total gas generation rate would be assumed to be equal to the gas extraction rate of 100 scfm. Because this is only 6% of the actual total gas generation rate of 1,750 scfm, the rate would be underestimated by a factor of nearly 18.

4.3.2 Dependence of Tier 3 ROI Estimation on Changes in Barometric Pressure

The dependence of Tier 3 ROI estimation on changes in barometric pressure results from the assumption that "average static pressure" in the landfill can be determined prior to gas extraction and that this is a relevant baseline against which to calculate pressure drawdown during gas extraction. The average static pressure is determined by measuring barometric pressure (P_{bar}) and the gauge pressure (P_g) in each monitoring probe every eight hours for several days prior to extraction, adding the gauge readings to the barometric readings to get absolute pressures, and averaging the readings at each probe to yield the average absolute static pressure P_{ia} for each probe. An identical process is employed after extraction begins to yield the average absolute pressure P_{fa} during extraction. The formula for calculating average static pressure at a measuring location is:

$$P_{ia} = \frac{\sum_{1}^{n} (P_{bar} + P_g)}{n} \tag{13}$$

Where n = the number of readings,

and the formula for calculating average pressure at a measuring location during extraction is:

$$P_{fa} = \frac{\sum_{1}^{n} (P_{bar} + P_g)}{n} \tag{14}$$

The average pressure calculation during extraction uses only those readings that were collected at an extraction rate that does not induce excess surface leakage. The ROI is then determined as the maximum distance at which the average pressure during extraction (P_{fa}) is less than or equal to the average pressure prior to extraction (P_{ia}). Clearly, however, the readings during extraction depend on the magnitude of average barometric pressure which may vary during the time of measurement.

Assuming landfill pressures respond to changes in barometric pressure, when the average barometric pressure is lower by a measurable amount during extraction, all average pressures calculated for all measurement points will be lower than the calculated average static pressures and the apparent ROI will extend to the landfill boundaries. Under these conditions, pressures would be lower even if no gas were extracted. In the case where average barometric pressure is higher during extraction, the calculated ROI would be smaller than if calculated at a time when average barometric pressure was the same before and during extraction. The effect of barometric pressure changes can only be taken into account in the calculations if the response of landfill pressure to changes in barometric pressure is incorporated, for example, using a numerical model.

4.3.3 Dependence of Surface Leakage Detection on Length of Testing

The two-dimensional numerical model was used to examine the dependence of surface leakage detection by gas analysis on length of testing for Case 1 listed in Table 1. In the model, atmospheric concentrations of nitrogen were initially specified in all cells representing “air” in the model, and the nitrogen concentration was fixed at atmospheric composition at the upper model boundary. Concentrations in all other cells were specified zero initially. Barometric pressure was assumed to be constant during the tests, and gas was extracted at a rate of 100 scfm from a well screened between 15 and 55 ft bls at the center of the landfill. The results of the simulations are presented in Figure 17, which is a plot of nitrogen concentrations detected at the extraction well, and at probes located 20 feet and 50 feet from the extraction well at depths of 20 feet bls. As indicated, nitrogen concentrations in excess of 5% were detected at the 20-foot lateral probe within 12 hours, and in excess of 20% within 2½ days after the start of the test. At the 50-foot lateral probe, nitrogen concentrations in excess of 5% were not detected until approximately 2½ days after the start, and began to stabilize at a concentration less than 15% 11 days into the test. At the extraction well, the nitrogen concentrations did not exceed 5% until approximately 2½ days into the test, and began to stabilize at a concentration less than 10% 11 days into the test. If the standard of 20% nitrogen was applied as indicative of surface leakage, the standard would be met in only the 20-foot lateral probe and only if the test duration exceeded 2½ days.

5. CONCLUSIONS

The limitations of the Tier 3 methodology for estimating gas generation rates in landfills have been demonstrated in this paper, and HGC's alternative methodology that avoids these limitations has been presented. Most of the Tier 3 limitations discussed here were presented originally in EMCON (1980).

Specifically, the limitations of the Tier 3 methodology include:
1) the theoretical basis is unsound,
2) methodology is expensive and time consuming,
3) estimates are inaccurate, and
4) estimates decrease in accuracy as the sensitivity of the pressure measurement data increases.

The alternative methodology is superior to Tier 3 for the following reasons. HGC's methodology:

1) is theoretically sound,
2) it is more accurate (and accuracy increases with pressure measurement sensitivity), and
3) the determined methodology can be performed at much lower cost in most situations.

6. REFERENCES

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TABLES

TABLE 1

SIMULATED CASES

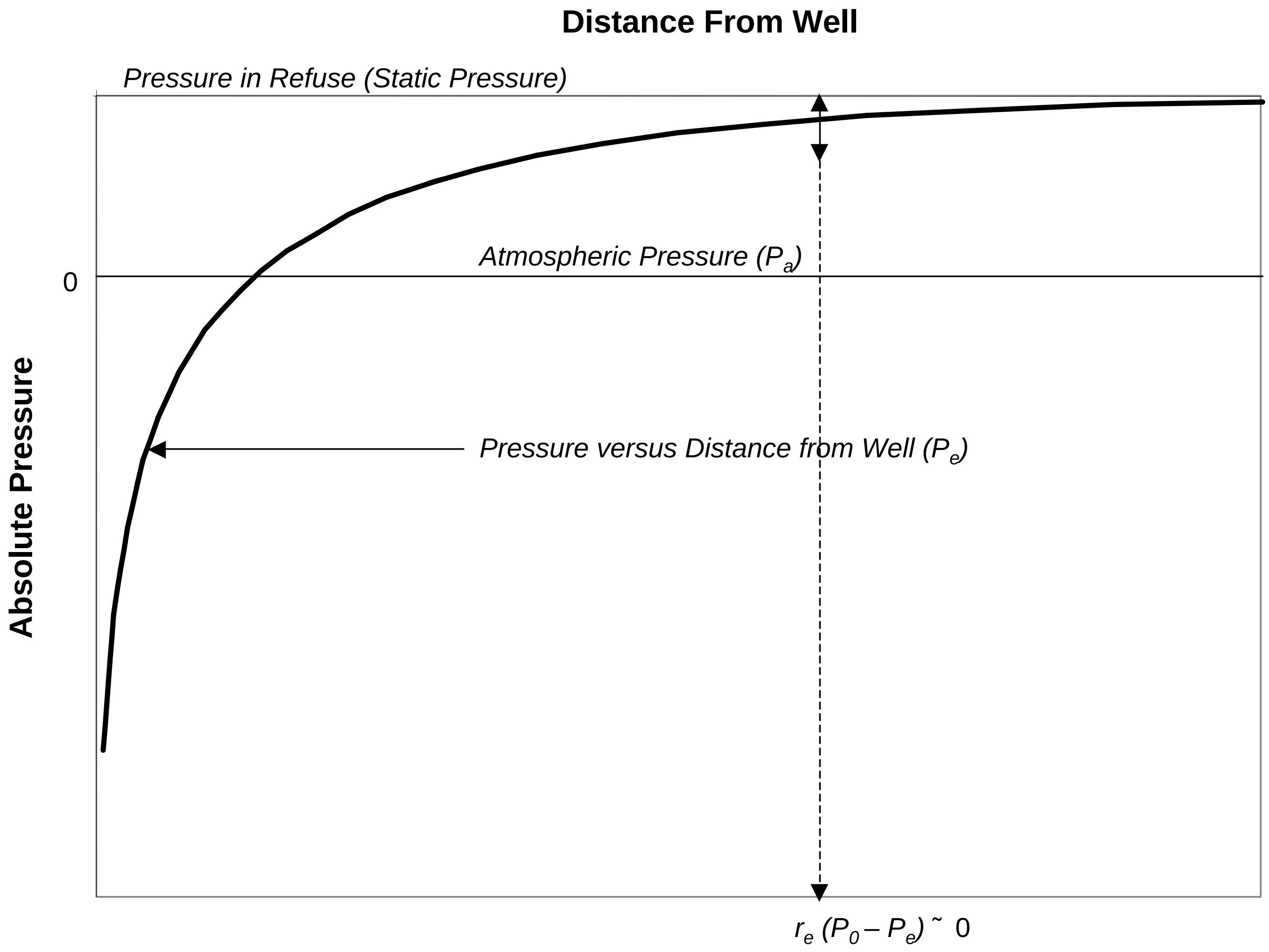
	Lined	Unlined
Cover Permeability = 10 darcies	Case 1	Case 4
Cover Permeability = 1 darcy	Case 2	Case 5
Cover Permeability = 0.1 darcy	Case 3	Case 6

TABLE 2

MATERIAL PROPERTIES USED IN THE SIMULATIONS

Property	Value
Landfill permeability (lateral, vertical)	50, 10
Soil permeability (lateral, vertical)	20, 2
“Air” permeability (lateral, vertical)	1×10^4, 1×10^4
Cover permeability (lateral)	0.1 - 10
Cover permeability (vertical)	0.1 - 10
Landfill porosity	40%
“Air” porosity	99%
All other porosity	30%

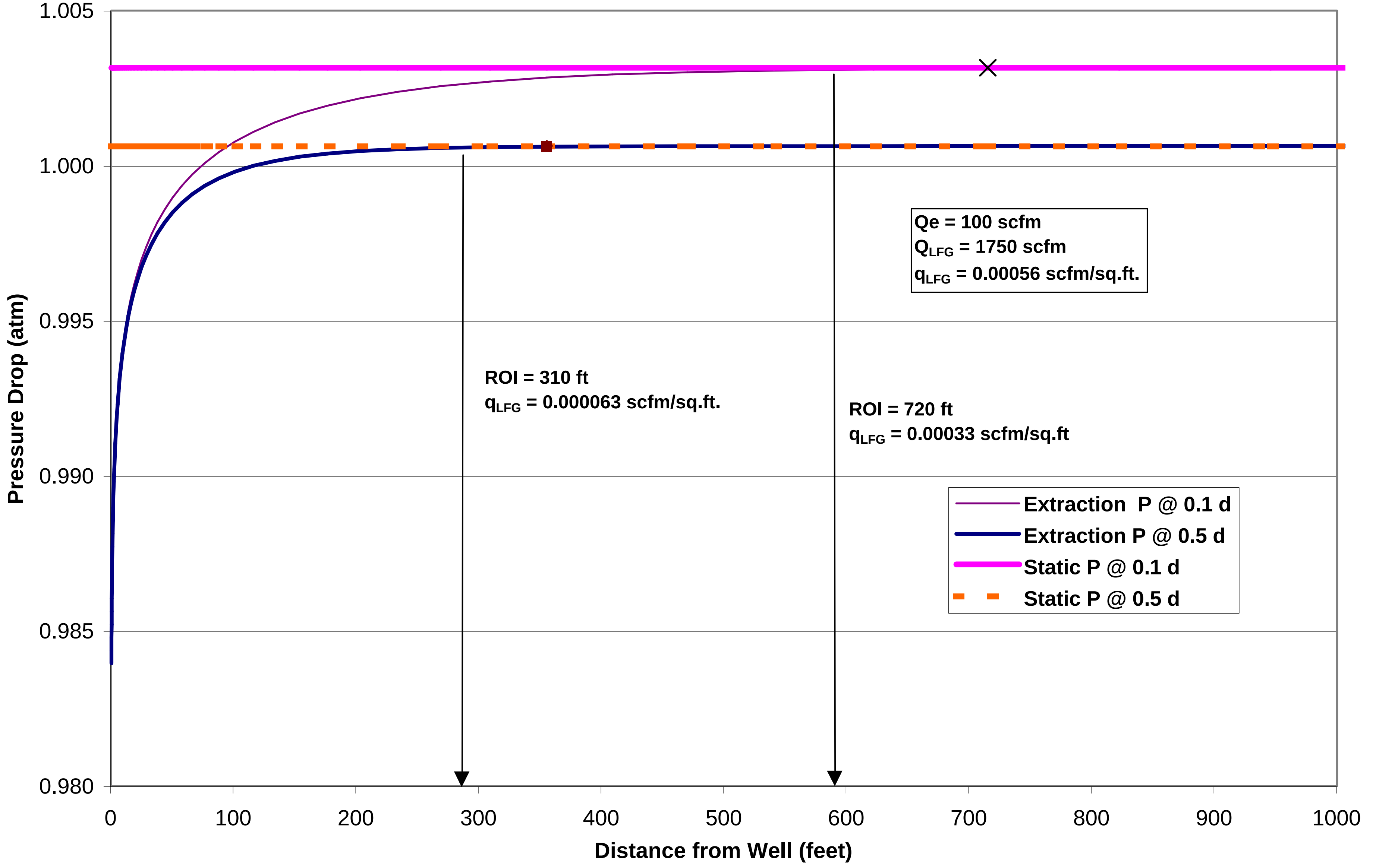
FIGURES



HYDRO GEO CHEM, INC.

GENERALIZED PLOT OF PRESSURE VERSUS DISTANCE FROM A SINGLE EXTRACTION WELL

APPROVED	DATE	REFERENCE	FIGURE
	03/19/02	H:\0860\lfg paper\FIG 1 REV.PPT	1



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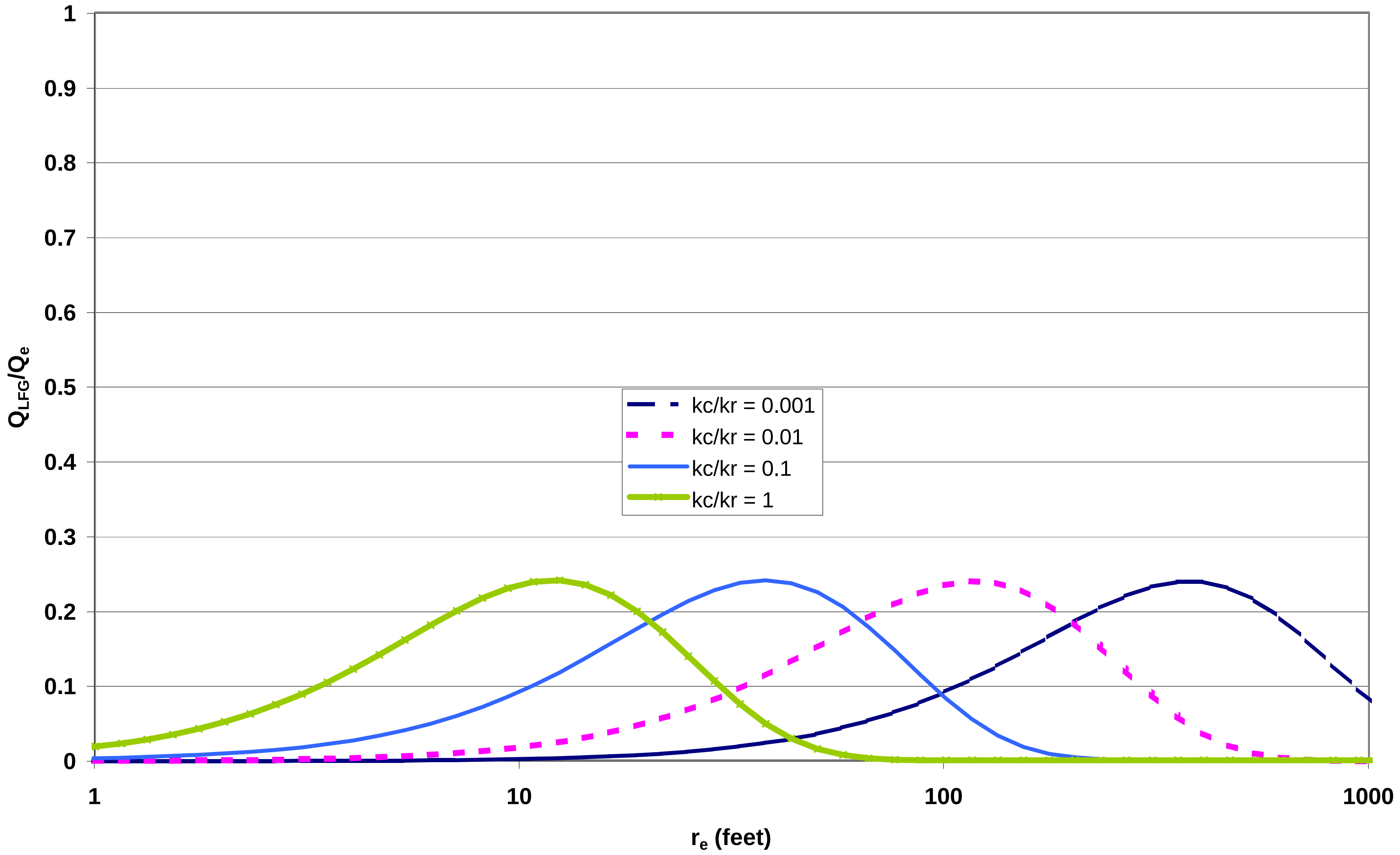
PRESSURE AND RADII OF INFLUENCE OF COVER PERMEABILITIES OF 0.1 AND 0.5 DARCIES, MEASUREMENT ACCURACY 0.02 mm Hg

APPROVED	DATE	FIGURE 2



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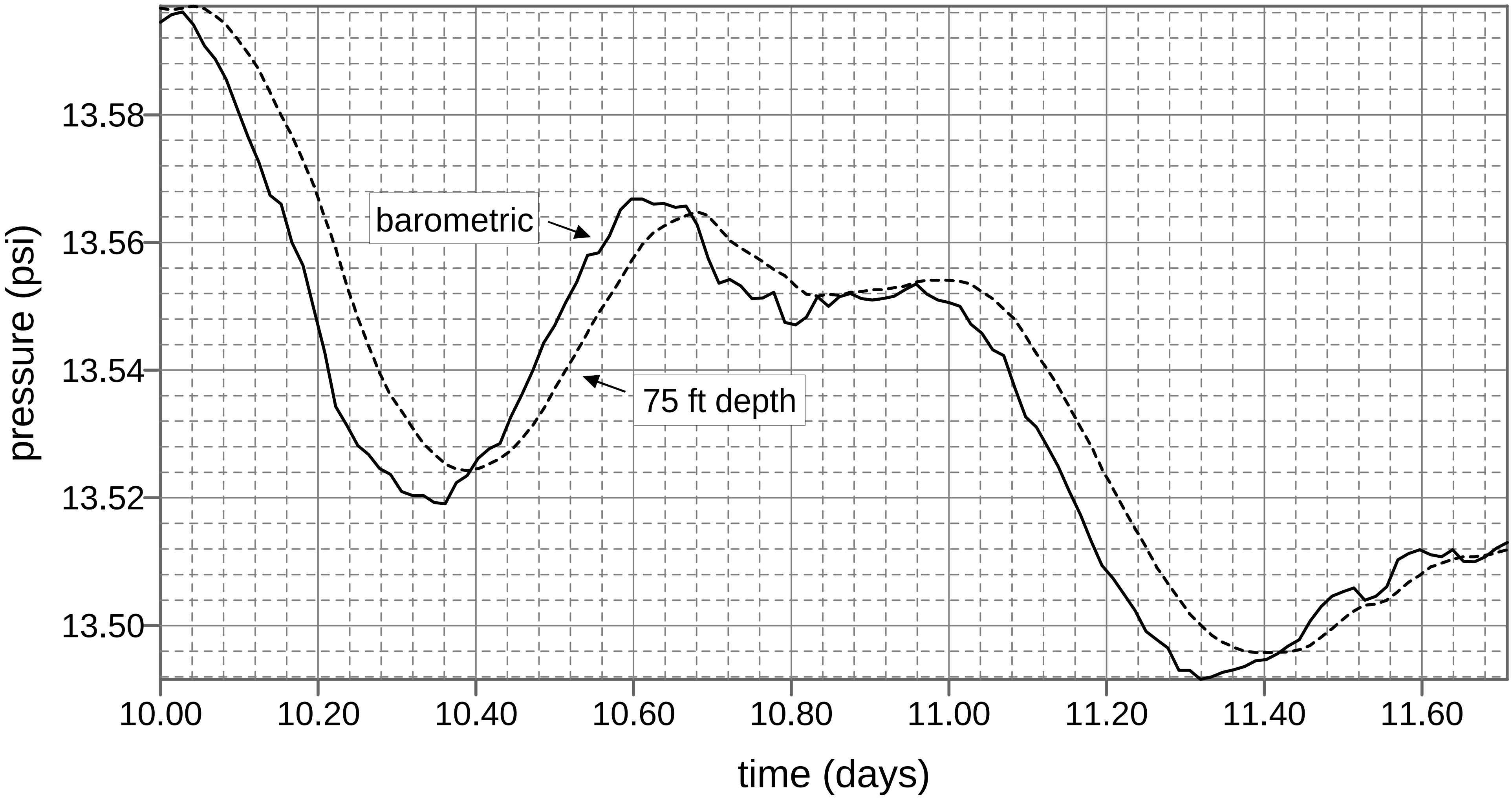
RATIO OF LFG GENERATION RATE TO EXTRACTION RATE VERSUS COVER TO REFUSE PERMEABILITY RATIO USING ALTERNATIVE ROI DEFINITION

APPROVED	DATE	REFERENCE	FIGURE
	3/19/02		3



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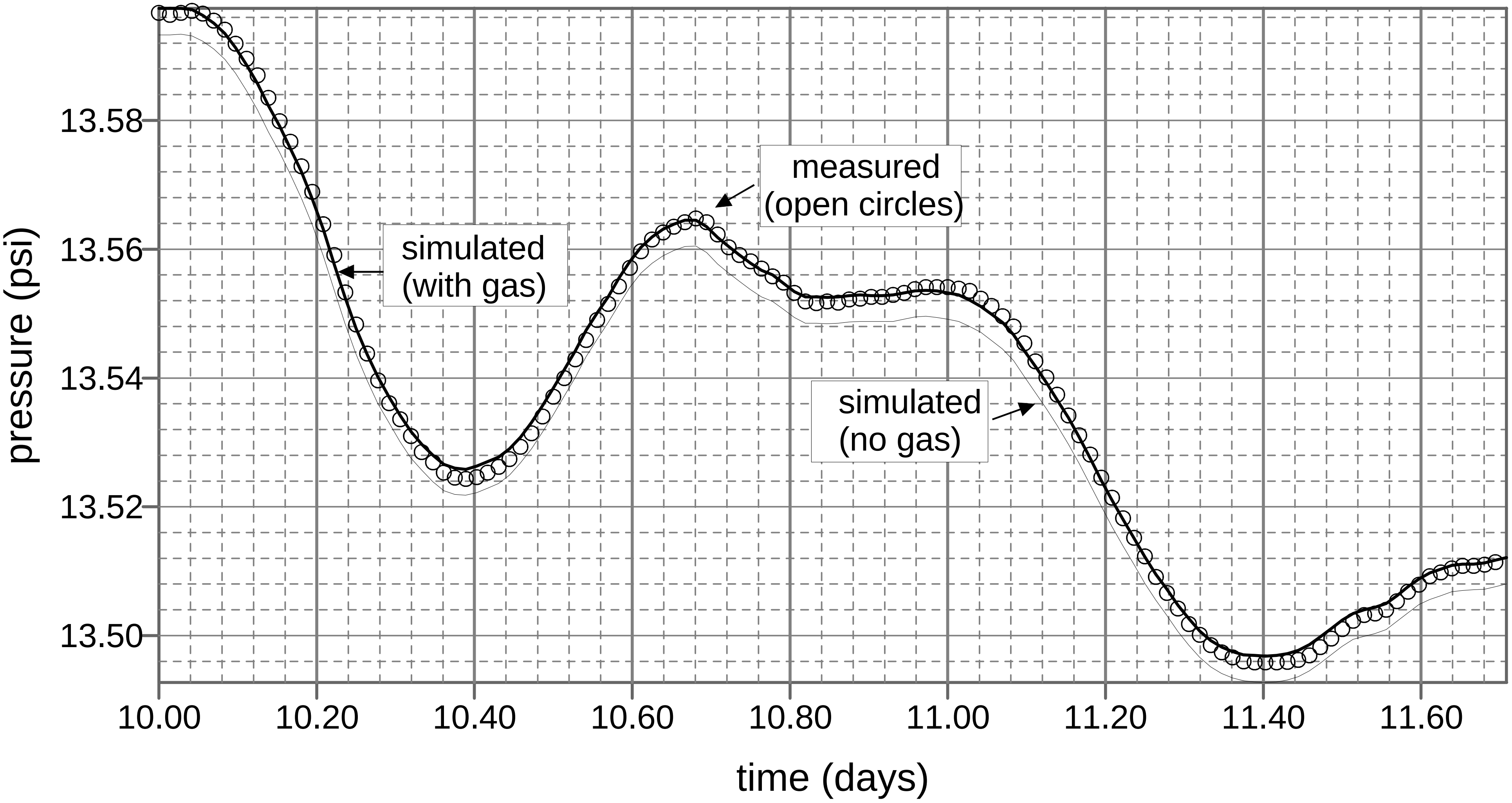
MEASURED PRESSURE DATA
BAROMETRIC AND 75 FEET DEEP IN LANDFILL
TUCSON, ARIZONA

Approved	Date	Reference	Figure
			4



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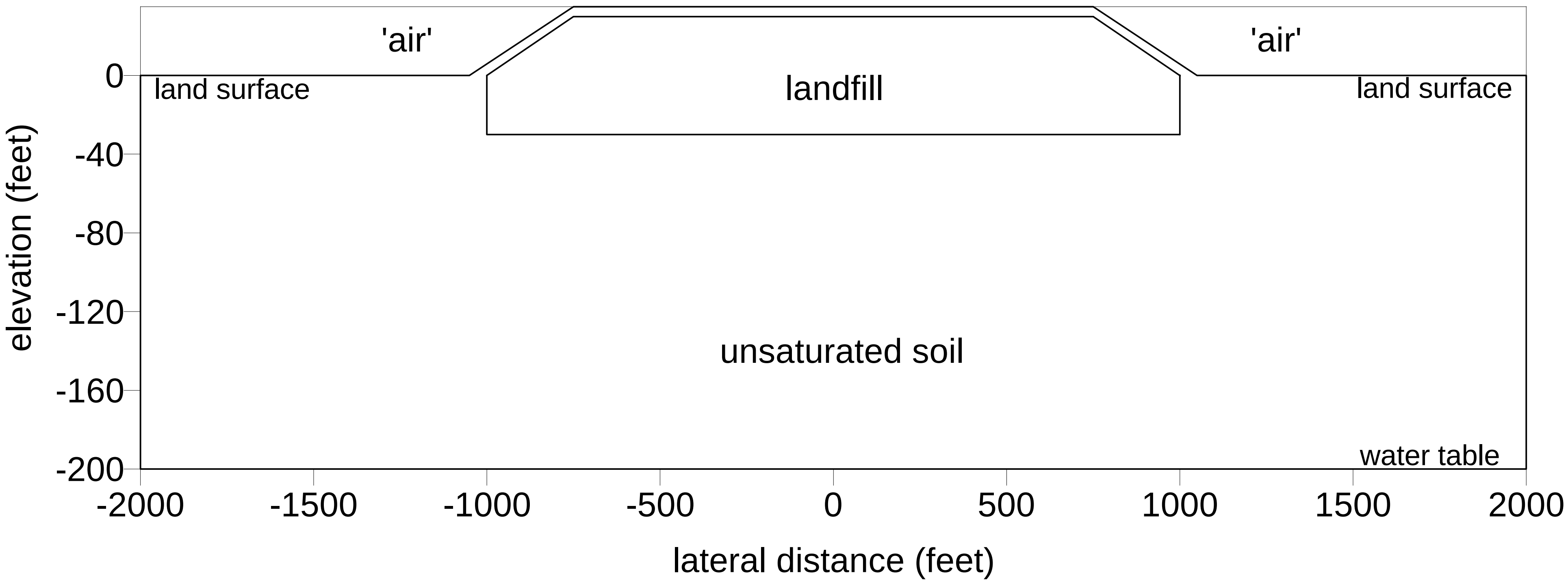
SIMULATED RESULTS AT 75 FOOT DEPTH IN LANDFILL WITH AND WITHOUT GAS GENERATION TUCSON, ARIZONA

Approved	Date	Reference	Figure
			5



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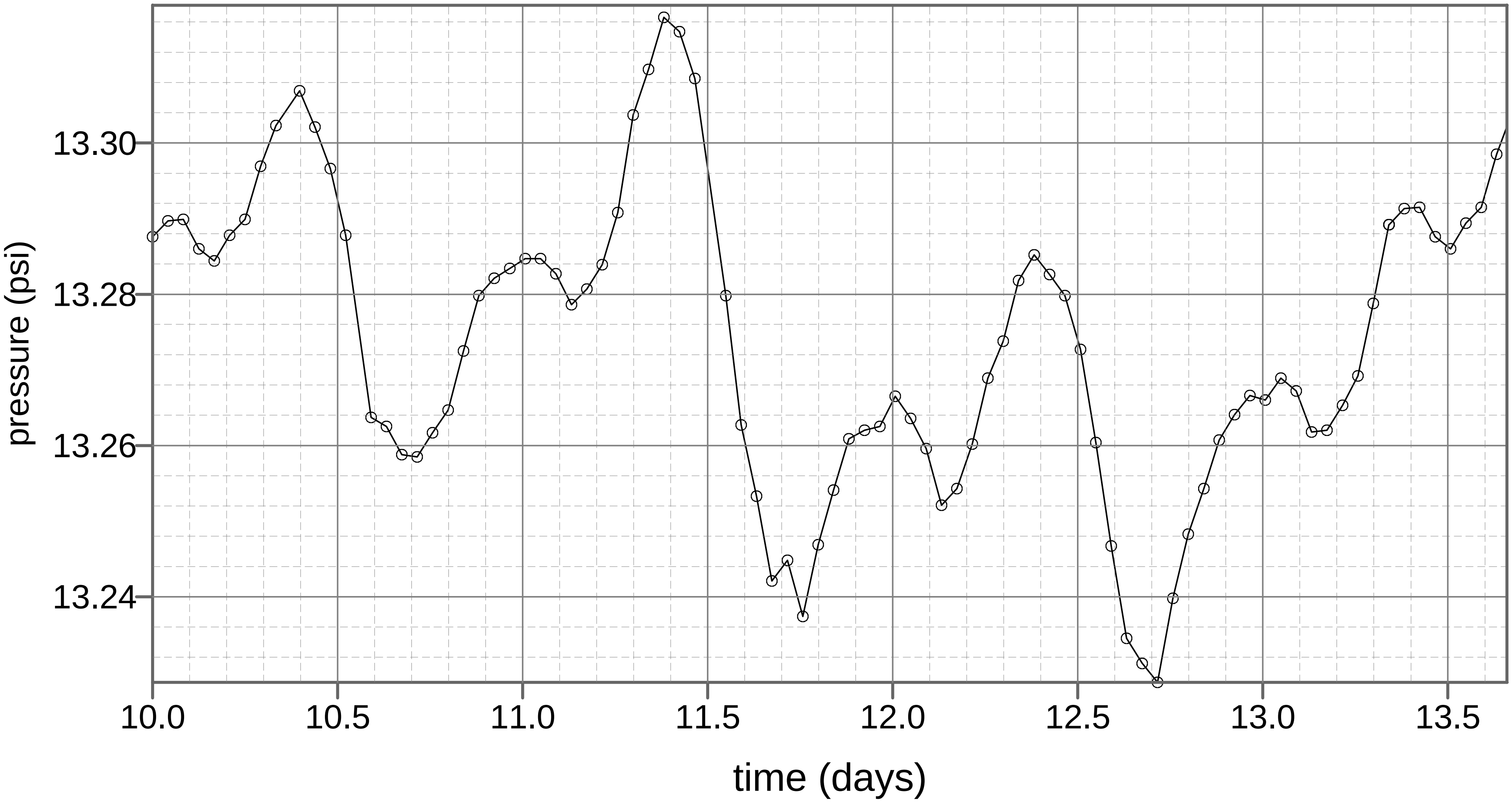
SCHEMATIC CROSS-SECTION OF LANDFILL

Approved	Date	Reference	Figure
			6



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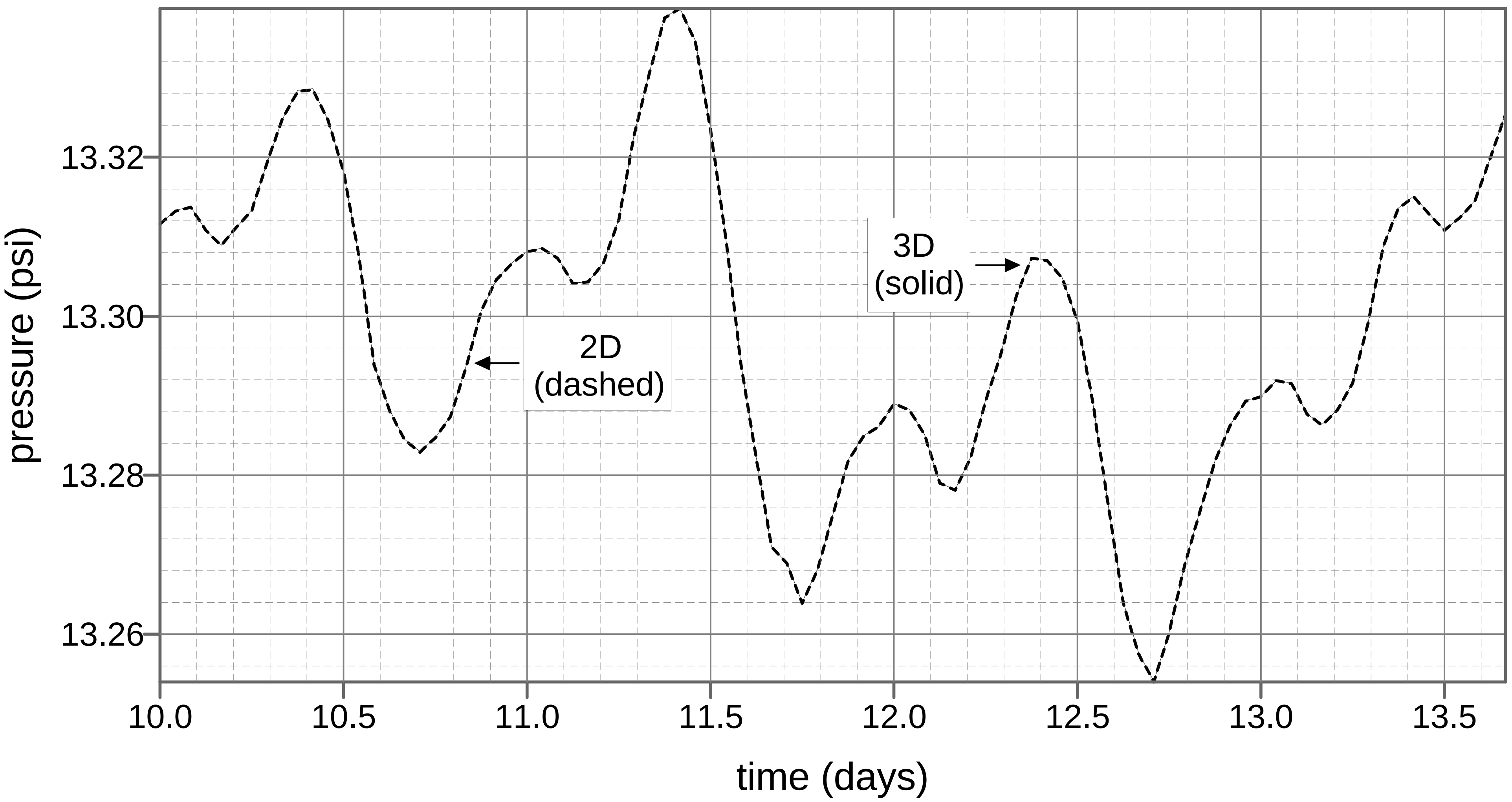
BARGMETRIC PRESSURE SIGNAL USED IN SIMULATIONS

Approved	Date	Reference	Figure
			7



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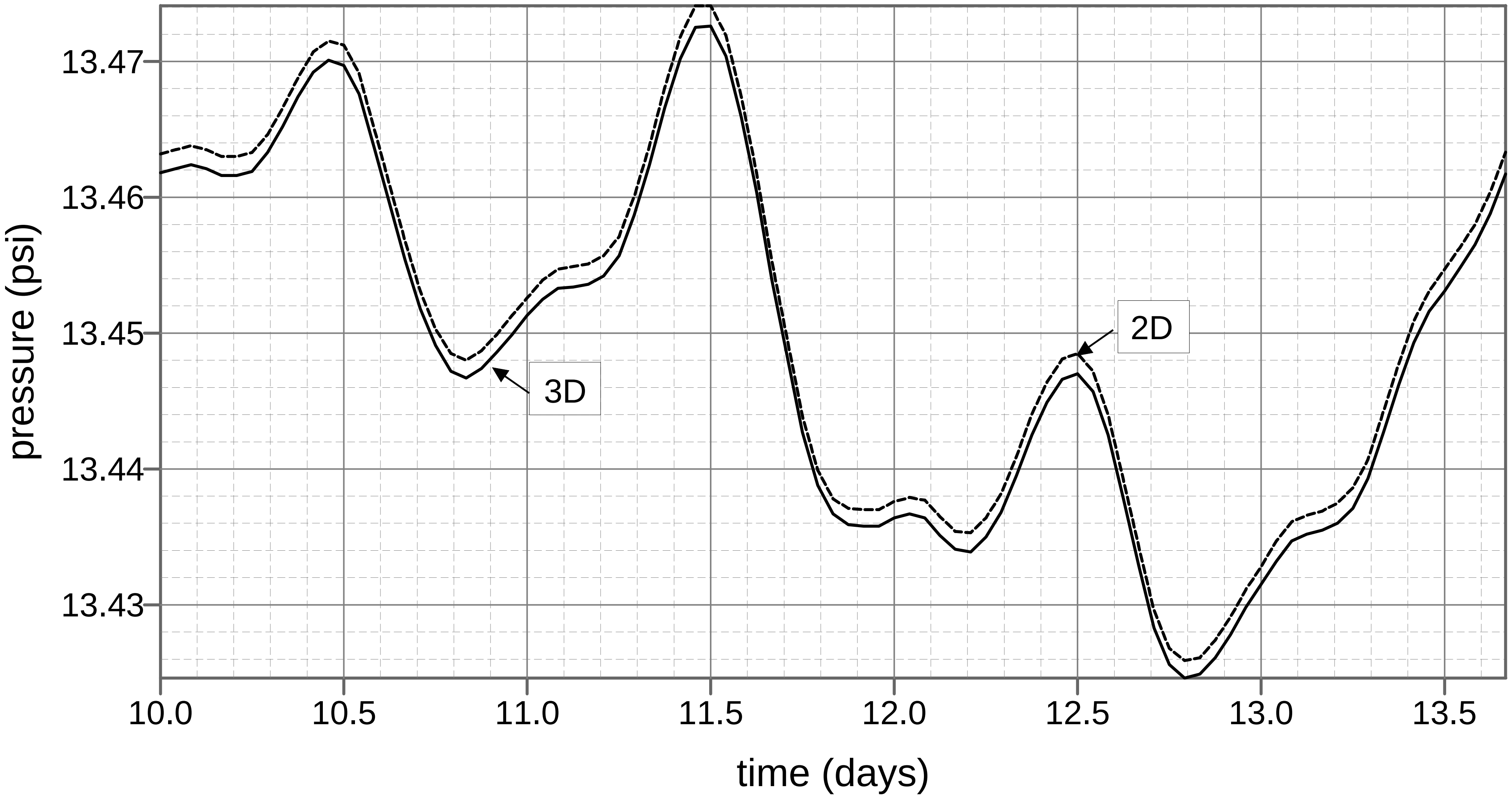
CASE 1
COMPARISON OF SIMULATED PRESSURES FOR 2-D AND 3-D MODELS

Approved	Date	Reference	Figure
			8



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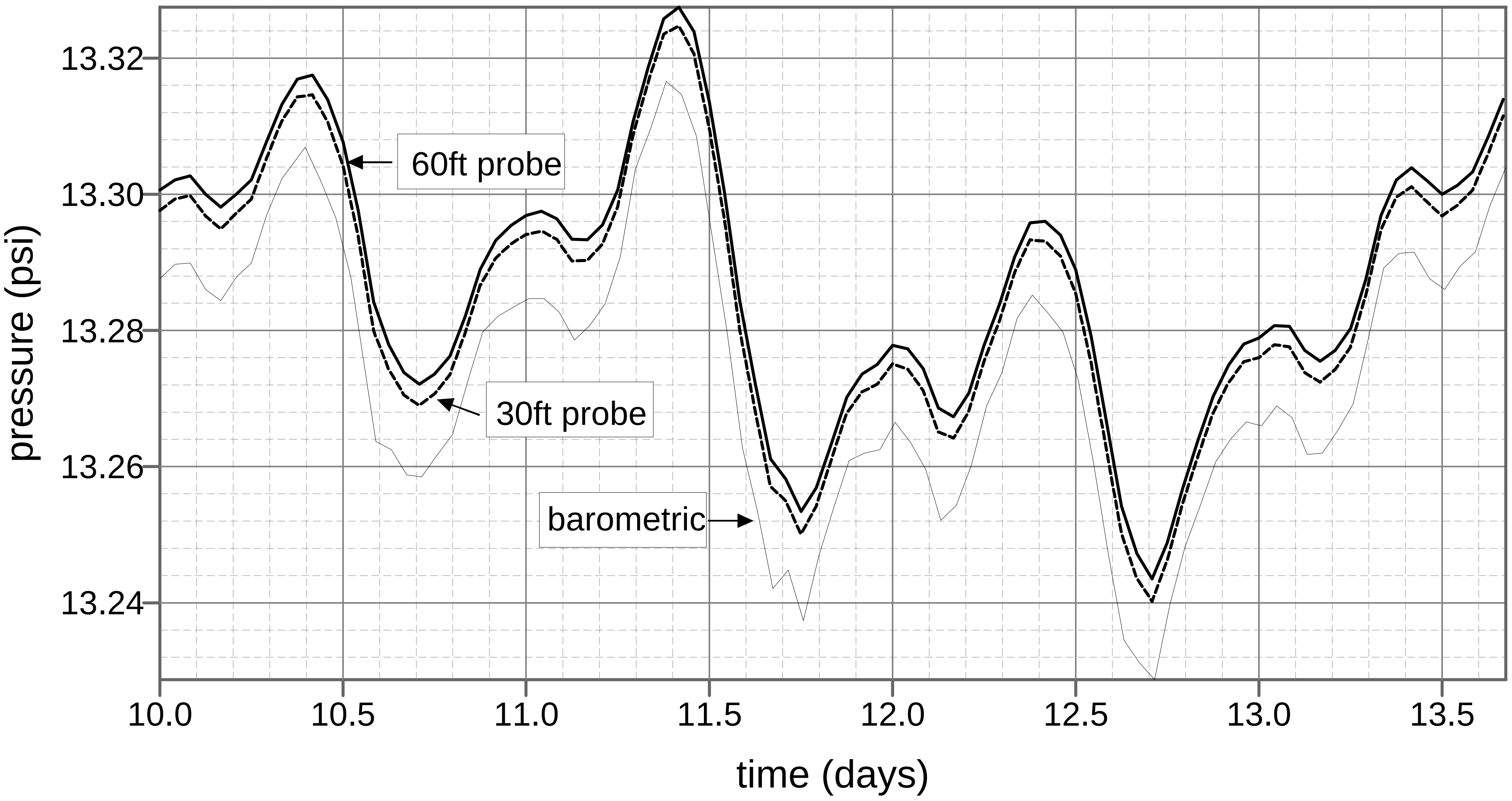
CASE 3
COMPARISON OF SIMULATED PRESSURES FOR 2-D AND 3-D MODELS

Approved	Date	Reference	Figure
			9



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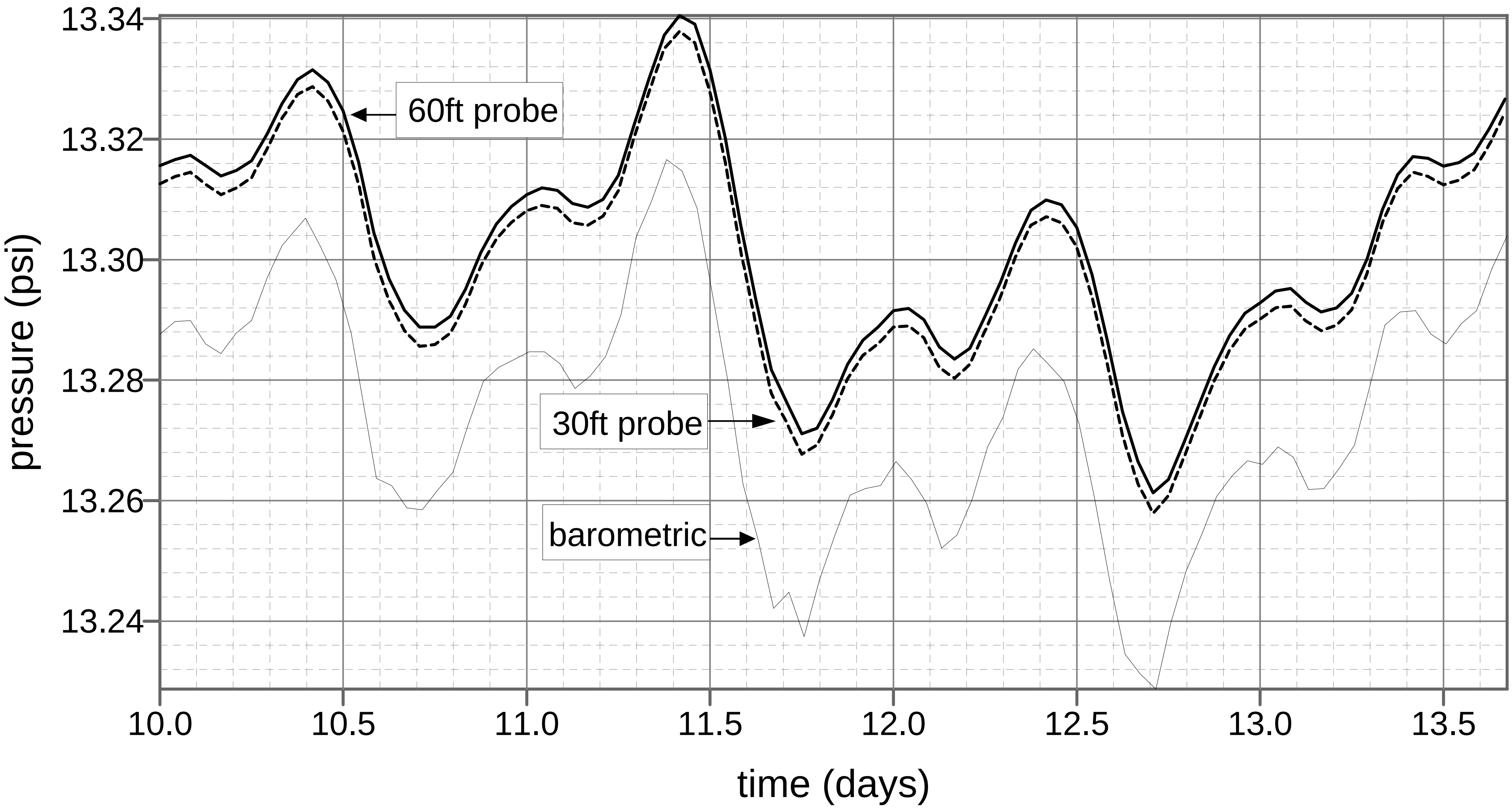
CASE 1
SIMULATED PRESSURES
AT 30 FT DEPTH AND 60 FT DEPTH PROBES

Approved	Date	Reference	Figure
			10



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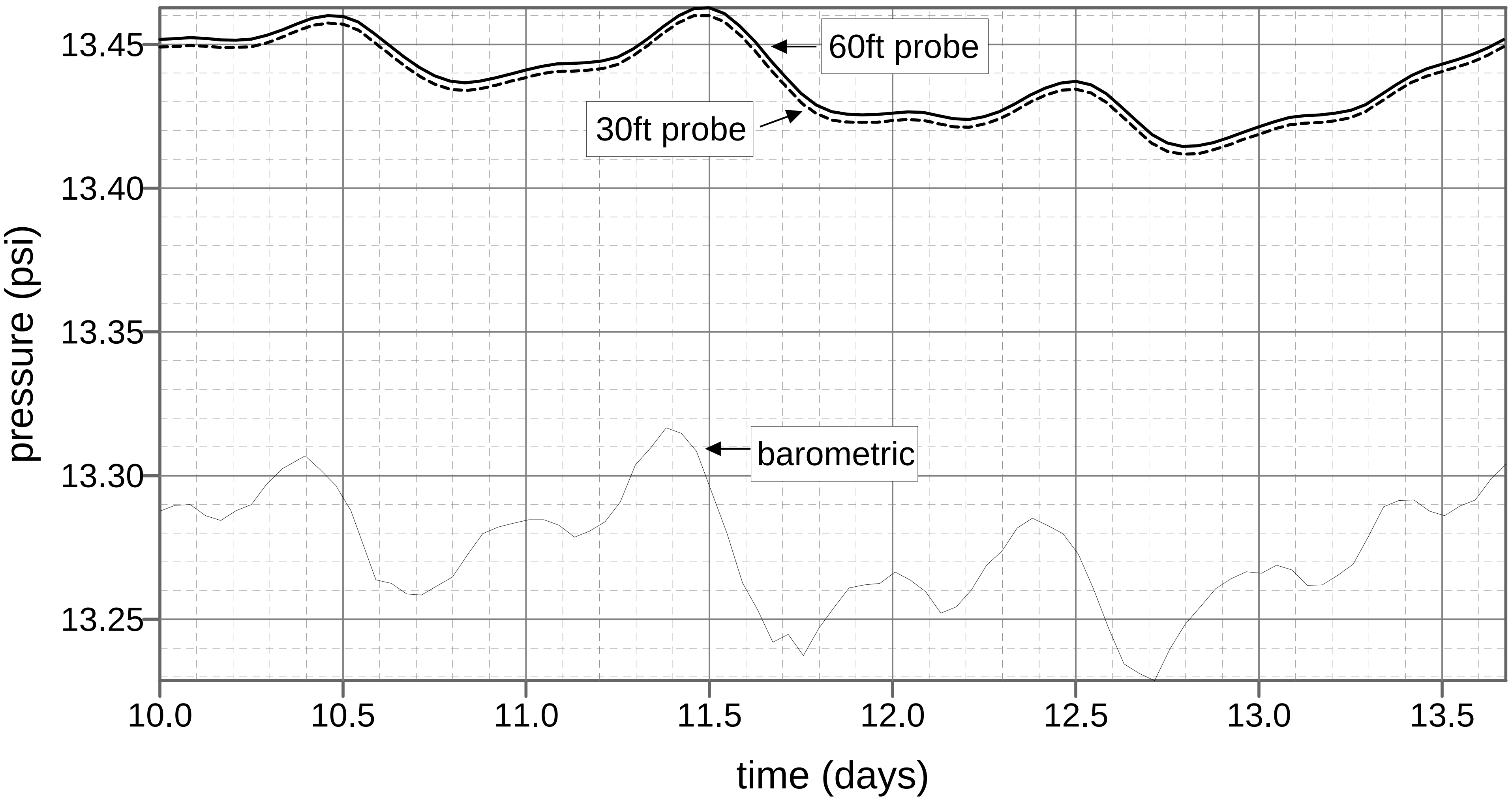
CASE 2
SIMULATED PRESSURES AT 30 FT DEPTH AND 60 FT DEPTH PROBES

Approved	Date	Reference	Figure
			11



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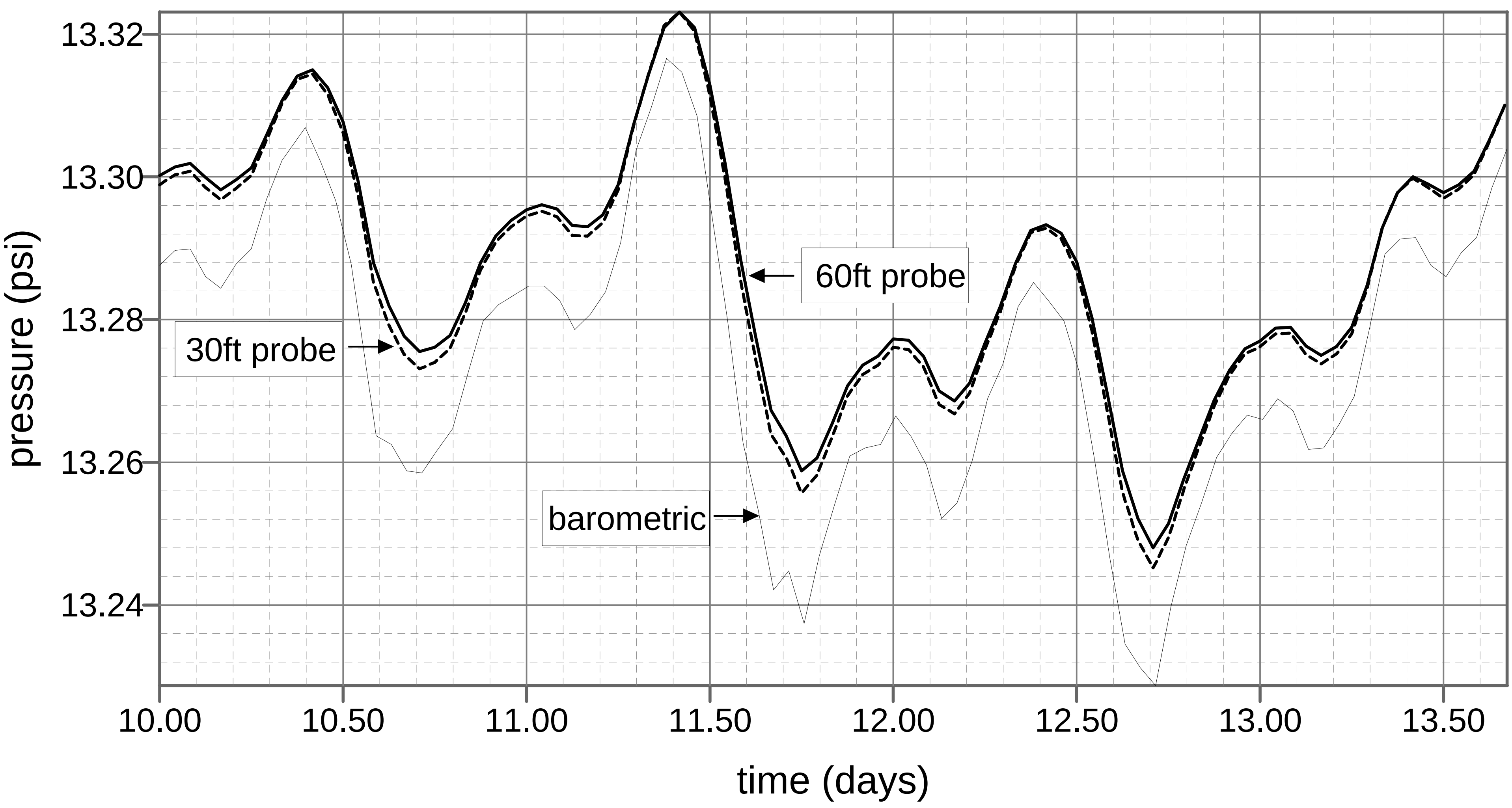
CASE 3
SIMULATED PRESSURES
AT 30 FT DEPTH AND 60 FT DEPTH PROBES

Approved	Date	Reference	Figure
			12



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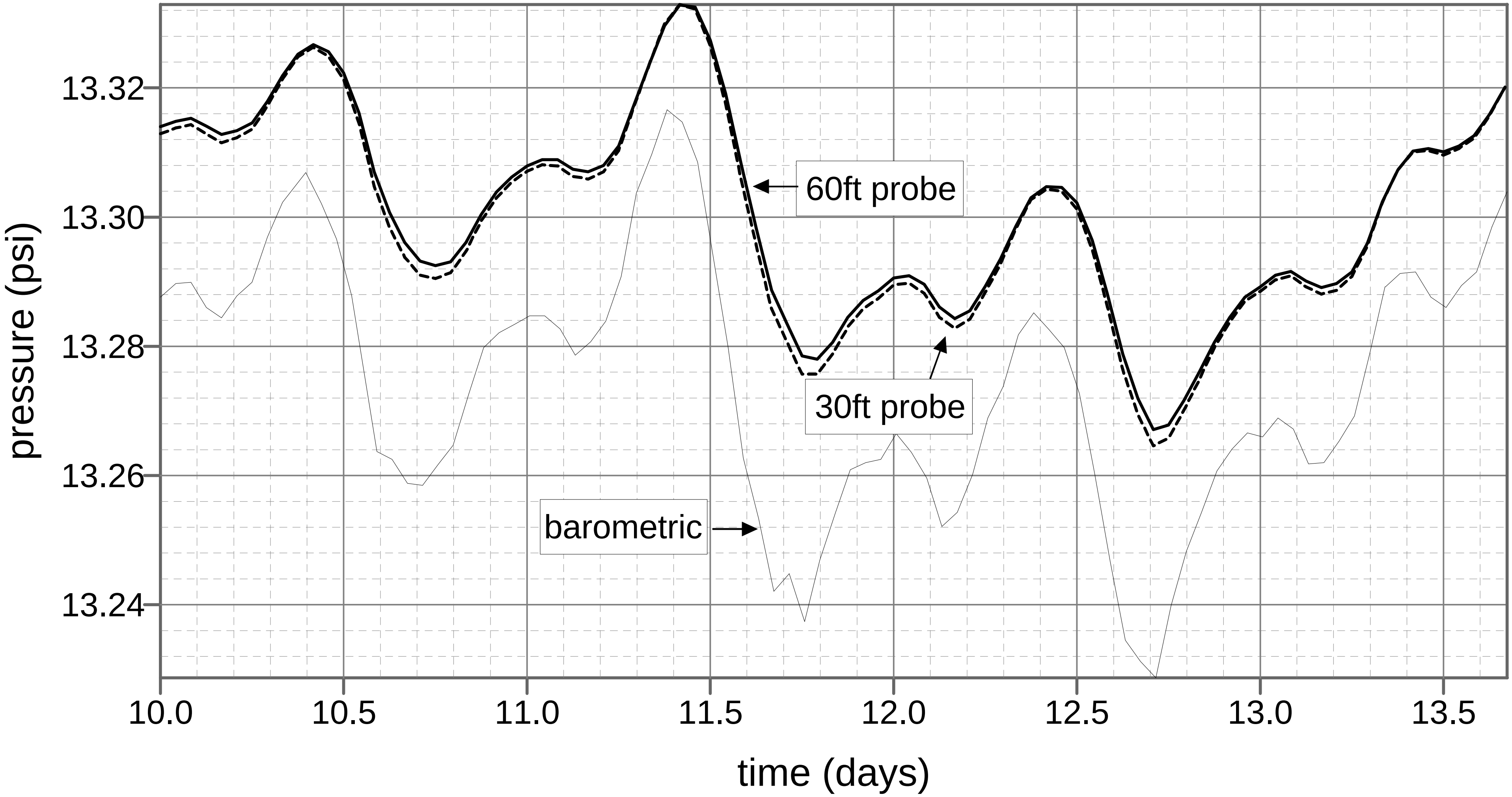
CASE 4
SIMULATED PRESSURES
AT 30 FT DEPTH AND 60 FT DEPTH PROBES

Approved	Date	Reference	Figure
			13



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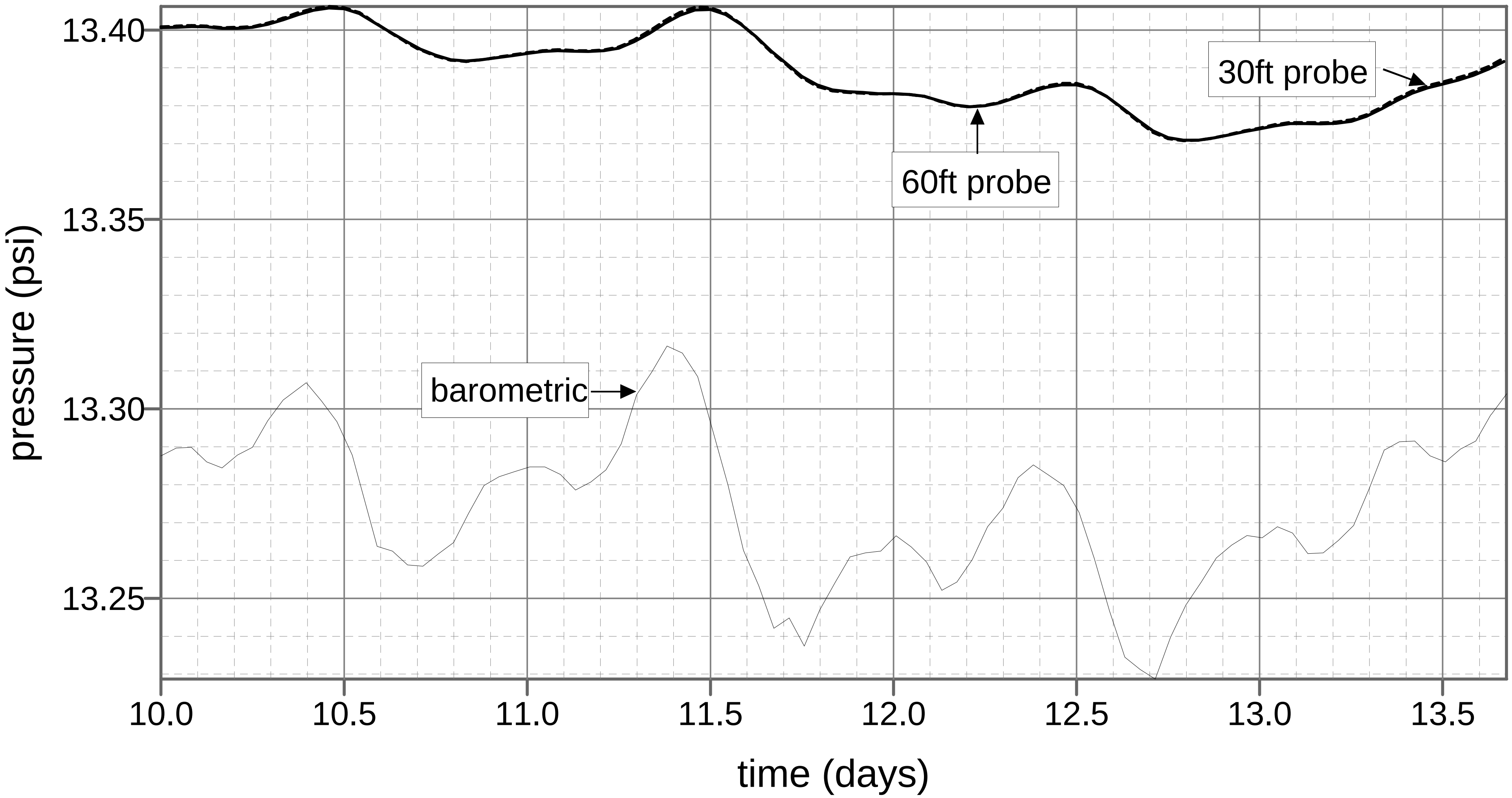
CASE 5
SIMULATED PRESSURES
AT 30 FT DEPTH AND 60 FT DEPTH PROBES

Approved	Date	Reference	Figure
			14



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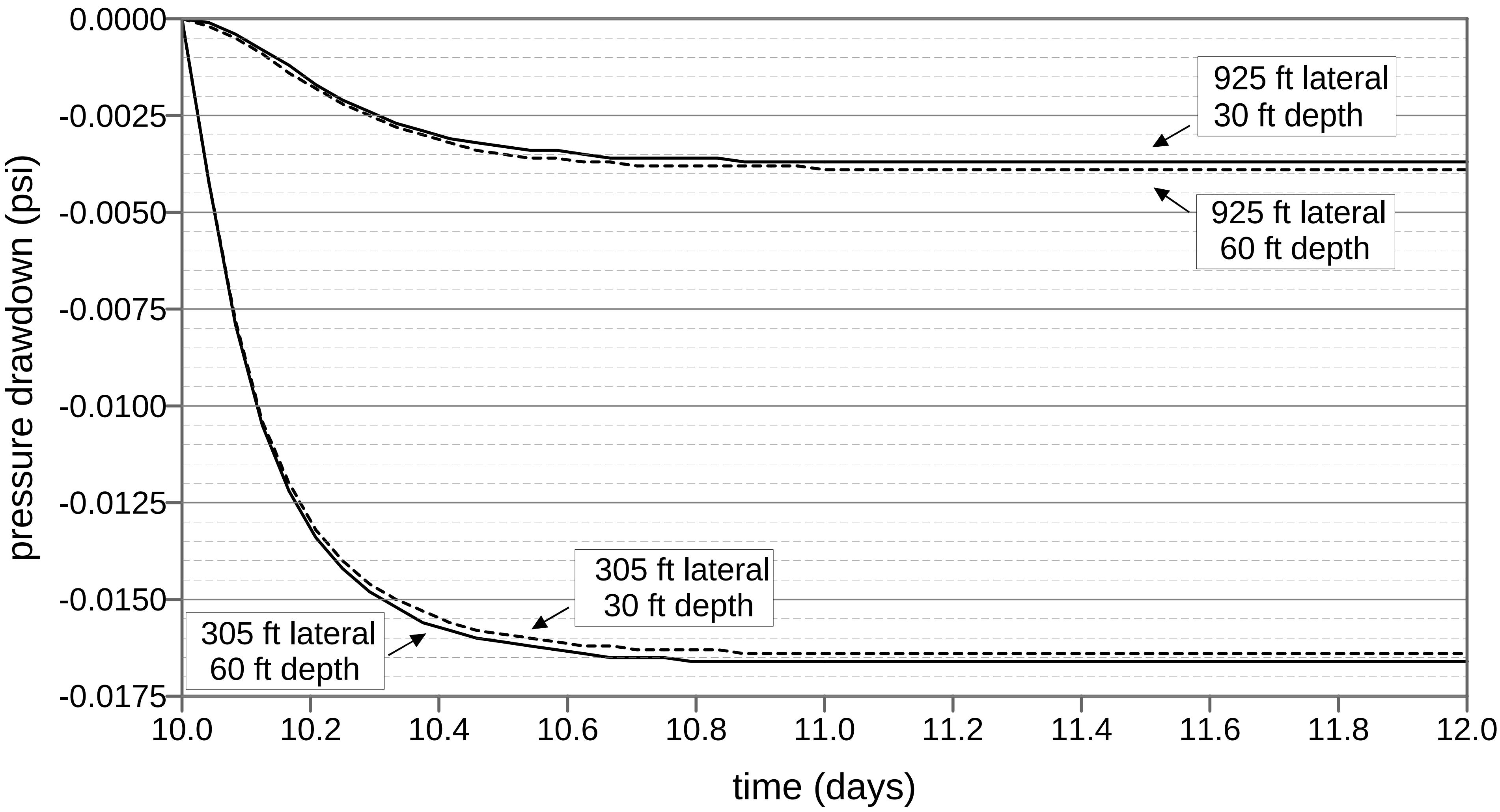
CASE 6
SIMULATED PRESSURES
AT 30 FT DEPTH AND 60 FT DEPTH PROBES

Approved	Date	Reference	Figure
			15



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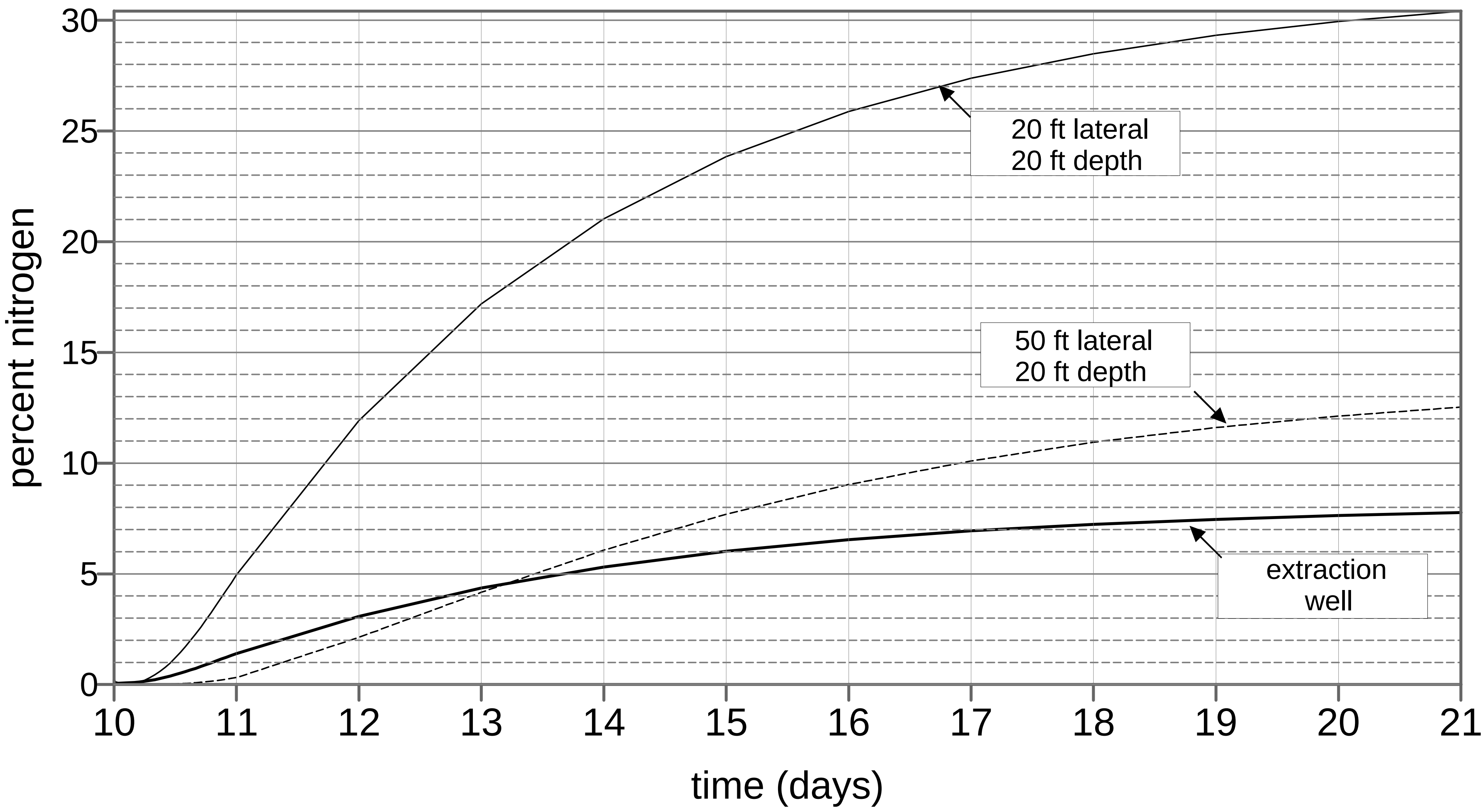
CASE 3
SIMULATED PRESSURE DRAWDOWNS WHILE EXTRACTING 100 SCFM

Approved	Date	Reference	Figure
			16



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CASE 1
SIMULATED NITROGEN CONCENTRATIONS
GAS EXTRACTION RATE = 100 SCFM

Approved	Date	Reference	Figure
			17