VERTICAL LANDFILL GAS EXTRACTION WELLS - THE SCS MODEL

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ABSTRACT
Since the beginnings of the landfill gas (LFG) industry in the late 1960s to early 1970s, the vertical extraction well has been the most commonly used LFG collection device. Because of its wide-spread use, its design is almost always accepted and never questioned. This has lead to "cookie cutter" approaches to well designs and wellfield layouts. Fundamentals sometimes are overlooked, and new costly systems have not performed as expected. As such, a step back to the basics is warranted.

Our literature review on this topic uncovered that the basis for well designs has been mostly either proprietary and unpublished or based on empirical observations. This paper presents SCS Engineers' mathematical model for the LFG vertical extraction well. It provides the design engineer with a theoretical basis for establishing the key system parameters. Our model addresses radius of influence and its relationship to landfill permeability, flow rate, well depth, applied vacuum, and other parameters. Combining this theoretical basis with empirical knowledge, the design engineer can develop a sound, practical, and cost-effective design for any landfill.

To demonstrate the validity and use of the model, the paper presents a case study of a recent pump test. Using field data for model calibrations, we established and verified parameters such as required well head vacuum, landfill permeability, well depth, well radius of influence, and well spacing.

INTRODUCTION
Vertical LFG extraction wells are the most commonly used collection device in the industry, dating back over 35 years to the beginning of the LFG industry. With a mature industry, typical well construction details have become available, and we have found that some designers are simply using these typical details without tailoring them to their particular sites, leading to costly systems that do not perform as expected.

The purpose of this paper is to review the fundamentals of the vertical LFG extraction well. An extraction well operates under the basic principle that LFG generated within the landfill moves towards the well due to a pressure gradient created by vacuum applied to the well.

We present a simple mathematical model for a full-depth extraction well, the evolution of which dates back to a concept presented in a 1983 report, prepared by Dr. Dallas E. Weaver. The model gives an understanding of flow dynamics around the well and indicates how various landfill properties like permeability, waste density, LFG generation rate and well design affects the dynamics around the well.

A recent pump test case study is presented to demonstrate use of the model and to establish design parameters. Finally, we present typical design parameters for extraction wells and suggest ways they should be tailored to specific site conditions.

MATHEMATICAL MODEL
Our mathematical formulation is based on the simple extraction well model presented in Figure 1. Several parameters are introduced in this figure and are defined below:

D	=	Well depth,
H	=	Maximum depth of influence,
S	=	Length of gravel pack around the well screen,
R_I	=	Radius of influence,
r	=	Radial coordinate (centered on the well), where $0 < r \le R_I$,

$h(r)$ = Height of the influenced volume at radius, r,

$Q(r)$ = Flow rate to the well at radius, r, and

R_w = Borehole radius.

We assume that the induced well vacuum causes the formation of concentric, cylindrical isobars (i.e., surfaces of equal pressure) centered on the well and that LFG flows into the well in a radial and horizontal manner. As landfills are filled in lifts, it is typical of them to exhibit macroscopic heterogeneity, i.e., their horizontal permeability relative to LFG flow is substantially greater than their vertical permeability. Recognizing this, we assume that the volume of influence takes the shape of the upper half of an oblate or ellipse, such that

$$h = \frac{H}{R_I}\sqrt{R_I^2 - r^2} \qquad (1)$$

The volume of influence, V,

$$V = \int_0^{R_I} 2\pi r h\, dr \qquad (2)$$

Substituting Eq. [1] into Eq. [2] and integrating, we get

$$V = \frac{2}{3}\pi R_I^2 H \qquad (3)$$

Assuming that the pressure head is the main driving force for LFG movement through the waste, we have from Darcy's equation that

$$Q = Av = -2\pi r h K \frac{\partial \psi}{\partial r} \qquad (4)$$

where

K = Horizontal or radial landfill permeability with respect to LFG,

v = Average LFG velocity to the well,

A = $2\pi r h$ = Cross-sectional area,

ψ = Vacuum head (P/γ),

P = Vacuum,

γ = Specific weight of the LFG,

and the other parameters are as previously defined. Note that change of velocity and elevation heads with respect to radial distance is negligible and is ignored in Darcy's equation, Eq. [4]. LFG compressibility is ignored since

the vacuums in the waste mass are typically relatively low (less than 1 psig range). The flow is assumed to be laminar.

Let's introduce another parameter, G_V, the LFG generation rate per unit volume. Now Q is a function of r and represents the amount of LFG generated outside r but within V, or

$$Q = G_V \int_r^{R_I} 2\pi r h\, dr \qquad (5)$$

Substituting Eq. [1] into Eq. [5] and integrating, we get

$$Q = \frac{2\pi}{3}\frac{G_V H}{R_I}\left(R_I^2 - r^2\right)^{3/2} \qquad (6)$$

Substituting Eqs. [1] and [6] into Eq. [4] and integrating from r_1 to r_2 (where r_2 is greater than r_1), we get

$$\int_{\psi_1}^{\psi_2} \partial \psi = -\frac{1}{3}\frac{G_V}{K}\int_{r_1}^{r_2}\frac{R_I^2 - r^2}{r}dr \qquad (7)$$

$$\Delta\psi = \psi_1 - \psi_2 = \frac{1}{3}\frac{G_V}{K}\left(R_I^2 \ln\frac{r_2}{r_1} - \frac{1}{2}r_2^2 + \frac{1}{2}r_1^2\right) \qquad (8)$$

but

$$G_V = G_M \rho_w \qquad (9)$$

where

G_M = LFG generation rate per unit mass, and

ρ_w = Waste density.

From Eqs. [8] and [9],

$$\Delta\psi = \frac{1}{3}\frac{G_M \rho_w}{K}\left(R_I^2 \ln\frac{r_2}{r_1} - \frac{1}{2}r_2^2 + \frac{1}{2}r_1^2\right) \qquad (10)$$

Eq. [10] is the general mathematical form of our model. It states that vacuum is a complex logarithmic function of distance from the well, proportional to ρ and G_M or Q, and inversely proportional to K.

Eq. [10] is a powerful tool for the design engineer. It tells the story of what happens to the LFG in the vicinity of the well. For given or reasonably assumed landfill properties, the engineer could use Eq. [10] to select suitable design

parameter combinations, i.e., applied vacuum/flow rate/well spacing combinations.

Eq. [10] is derived for an almost full depth extraction well (i.e., the well is installed to almost the full depth of the landfill). Interestingly, the mathematical model for a partial depth extraction well, where the volume of influence takes the shape of a full oblate, yields a similar equation.

Model Analysis/Parameter Investigation

To help understand our model, let's consider an example. An extraction well is drilled to about the full depth of a landfill; R_w, the borehole radius is 1 foot. Table 1 lists the combination of waste parameters or scenarios analyzed. For comparison purposes, a K of 5E-4 cm/sec is typical of a sand soil type; 5E-3 is typical of gravel; and 5E-5 is typical of silty sand (*Dillah et al.*, 2001).

TABLE 1. WASTE PROPERTIES

Waste Type	K (cm/sec)	ρ_w (lb/yd³)	G_M(cf/lb/yr)
Typical	5E-4	1,500	0.1
Higher ρ_w	5E-4	2,000	0.1
Higher G_M	5E-4	1,500	0.2
Higher K	5E-3	1,500	0.1
Lower K	5E-5	1,500	0.1

In order to investigate ψ relative to R_I, we will set r_1 at 1 foot (radius of the borehole) and r_2 at R_I. Thus, Eq. [10] is simplified to

$$\Delta \psi = \frac{1}{3} \frac{G_M \rho_w}{K} \left(R_I^2 \ln R_I - \frac{1}{2} R_I^2 + \frac{1}{2} \right) \quad (11)$$

For our example, we use Eq. [11] to calculate the results presented in Figure 2. For example, for typical waste as defined in Table 1, it is estimated (see Figure 2) that an applied vacuum of about 5 inches of water column (in.-wc) (i.e., the vacuum applied to the gravel pack) should cause a radius of influence of about 155 feet.

Figure 2 also plots curves for the other waste types presented in Table 1. For a given $\Delta\psi$, R_I increases for either a higher K, a lower ρ_w, or a lower G_M, and vice versa: R_I decreases for either a lower K, a higher ρ_w, or a higher G_M.

From the curves, it is clear that ψ–R_I relationship is most-impacted by K. For example, for an applied vacuum of 5 in.-wc, as K changes by one order of magnitude, from 5E-4 cm/sec to 5E-5, R_I changes from about 155 feet to about 55 feet. Differences in G_M and ρ_w have much less of an

impact as these parameters usually do not change by orders of magnitude.

Care should be used when interpreting the results of the model. For example, Figure 2 suggests that for high permeable waste, R_I has the potential to be much greater than 300 feet for a relatively small applied vacuum, about 2 in.-wc. This would be valid only if there exists an ideal case that perfectly fits our model assumptions. Consideration should be given to real situations such as atmospheric short-circuiting (i.e., vertical flow), preferential movement, and other subsurface complexities that may exist, and adjustments should be made as appropriate. Similar to this, other real and practical considerations are discussed later in the paper.

CASE STUDY

As part of a landfill gas collection system expansion project at a landfill in the Northeast United States, a regulatory agency requested that the landfill owner conduct a field test to confirm that the selected R_I was appropriate. As such, the landfill owner undertook a field test program to evaluate the capability of the LFG collection system to influence the landfill mass. The objective of the field test program was to evaluate the zone of influence of a representative group of selected vertical wells.

Pump Test Layout

For the pump test, four clusters of three vertical extraction wells each were evaluated. At each well cluster, seven test probes were installed to monitor vacuum in the landfill. One of the test clusters, which included wells EW-108, EW-109 and EW-402, is selected for presentation here. Figure 3 shows a site plan, and Figure 4 shows the relative location of the wells and test probes. Note that test probe P-108-C is common to the three wells and the suction of each well might influence this probe.

The test probes were installed at locations, radiating out from each of the three test wells as shown on Figure 4. The probes were installed at the following approximate distances from each test well:

- "A" probes, closest to the extraction well: 1 to 3 feet.

- "B" probes: about 25 feet.

- "C" probes: equidistant from the three extraction wells, approximately 110 feet.

Each test probe was installed approximately 25 feet below grade, so the bottom of each probe is at about the same elevation.

The test probes were installed with a hollow-stem auger, 6-inch diameter. One foot of ¾-inch crushed stone was placed at the base of each boring. One-inch Schedule 40 PVC or 2-inch HDPE pipe with a 5-foot perforated section was placed in the borehole and backfilled with ¾-inch crushed stone to 1 foot above the screen. Geotextile fabric or liner was placed over the stone, followed by 1 foot of sand backfill and a 2-foot thick bentonite seal. General backfill was used to bring the borehole up to grade. Each monitoring probe was equipped with a quick connect fitting for pressure monitoring.

The depths and configuration of EW-108, EW-109, and EW-402 are presented in Table 2.

TABLE 2. WELL DEPTHS AND CONFIGURATION

	EW-108	EW-109	EW-402
Well Depth (ft)	94.9	92.3	92.5
Depth to Gravel Pack (ft)	18.9	16.3	19
Waste Depth (ft)	103	108	108

Field Activities and Data
The field activities are summarized below:

- Since the test wells are part of a comprehensive LFG collection system, all extraction wells in the vicinity of the pump test location were closed off.

- Upon closure of these wells, static measurements were taken at the test wells and probes until steady state was apparent.   They all showed positive pressure readings at this point.

- The test wells were reactivated and adjusted to minimize air infiltration.   The test wells were operated for at least two weeks to achieve steady state prior to beginning test probe measurements for the active portion of the test.

- During the active portion of the test, measurements were recorded in the morning and afternoon for 6 consecutive working days. The data consists of the following:
  - Vacuum at all test probes and wellheads.
  - Methane, oxygen, carbon dioxide, and balance gas at all test wellheads.
  - Differential pressure across the orifice plate at each test wellhead.
  - Temperature the test wells.

Vacuum data for the test probes and wellheads during the active portion of the test are presented in Table 3.

Parameter Estimation
Off-the-shelf statistical programs are not readily available to compute the parameters found in the non-linear logarithmic equation, Eq. [10]. As such, we developed a FORTRAN program to evaluate R_I and K using a best-fit analysis; i.e., values are selected such that the sum of the square of errors (*SSE*) between the actual data and the model output are minimized.

$$SSE = \sum_{i=1}^{n} \sum_{j=1}^{p} \left[\psi_a(i,j) - \psi_m(i,j) \right]^2 \quad (12)$$

where

$\psi_a(i,j)$	=	actual vacuum at probe j during event i,
$\psi_m(i,j)$	=	modeled vacuum at probe j during event i (as calculated from Eq. [10]),
n	=	Number of events, and
p	=	Number of probes.

The program was run for each well, varying K for the well and R_I for each event while computing *SSE*. The values of K and R_I which minimize *SSE* are selected.

Table 4 presents the K and R_I estimates for our three test wells. The calculations were based on the following:

- R_I is estimated to be at the point along r where the vacuum is zero inches of water column (in.-wc), gauge. This results in a lower estimate than if R_I were defined as the point where the difference in static and active pressures is zero.   Note, however, that the model also could estimate this other definition of R_I.

- G_M and ρ_w was assumed to be constant for the test area.   The product of the two variables was assumed to be 200 as background information on the site suggests that G_M was 0.1 ft³/lb waste/year and ρ_w was 2,000 lb/yd³.

- The wellhead vacuum was not considered in the parametric estimation as headlosses between the wellhead and borehole/waste interface were uncertain.

- Adjustments were not made for overlap between each well's radius of influence.

Comparison to Model
Figure 5 shows a comparison of the actual probe vacuum data and the model results for each of the three wells for the March 30, 2005, morning event. An almost perfect fit is indicated. The other events also showed similar results. Furthermore, a calculation of an overall coefficient of determination, R^2, was made for each well, which incorporates all events into the calculation.

$$R^2 = \frac{SSY - SSE}{SSY} \qquad (14)$$

where

SSY	=	Sum of squares of deviation between the actual vacuums and its mean, and
SSE	=	Sum of squares of errors between the actual vacuums and the model.

Table 4 shows the overall R^2 for each well: with each at or over 0.99, again supporting an almost perfect fit to the data.

DISCUSSION
The primary goal of the pump test described in this paper was to demonstrate that a spacing of about 200 feet between wells was appropriate for the landfill. Thus, the pump test was setup in a triangulated manner, and it focused on subsurface pressures or vacuums within the triangle. Reviewing the results shown in Figures 4 and 5 and Table 4, we note the following:

- The triangular region between the wells was under influence, satisfying the main goal regarding proper spacing between wells. Note that all test probes within the area were under vacuum.

- The wells are spaced only about 200 feet apart, but the variability in R_I and K is significant, demonstrating the inherent nature of variability in landfills.

- For a well spacing of 200 feet, the average R_I should be about 120 feet for wells located/spaced in a triangulated manner; i.e., well spacing equals $2R_I\cos30$. From Table 4, the average R_I for the three test wells is 180 feet.

- Figure 4 shows perfect circular influenced areas around each well, corresponding with our idealistic and simple model. In reality, these influenced areas are irregularly shaped, depending on varying parameters like landfill waste types and permeabilities. If additional test probes were installed around each test well radiating outwards from each well in different directions, R^2 would have not been as perfect.

Design Parameters
Based on this and other pump tests performed by SCS and our design, construction, and operational experience gathered over the years, we typically select the following general design parameters for vertical extraction wells:

- Typical well spacing of 200 feet. If the landfill was not very well compacted or is lined and capped, this spacing could be increased. Well spacing is decreased in shallow waste areas, side slopes, or if the overall landfill permeability is low.

- Well depth, D (refer to Figure 1), to about 15 feet off the landfill bottom or 100 feet maximum. Particularly in a lined landfill, well depths of 100 feet are sufficient as LFG in the lower regions of the landfill finally makes its way into the influence zone of the wells. If the leachate collection piping or sumps show the presence of LFG, these devices are connected to the LFG collection system.

- Solid pipe length, D-S, is typically set at 20 feet, recognizing that landfills are filled in lifts and typically exhibit high horizontal to vertical permeability ratios (e.g., 6:1). Because of air intrusion, this design limits R_I to about 120 feet (i.e., 20 times 6), but is consistent with the recommended spacing of 200 feet. The solid pipe length may be increased to further limit the potential for air intrusion, particularly at sites that have utilization projects that cannot handle air intrusion and the resulting degradation of LFG quality.

  The designer should investigate how the landfill was filled. If an alternative daily cover like a tarp is utilized, the horizontal to vertical permeability ratio may decrease, and the solid pipe length or well spacing should be adjusted.

  Solid pipe lengths may also be adjusted for high leachate levels. When the solid pipe is shorter, recognize that R_I and the well spacing also decrease. In severe cases, consider using leachate pumps in the wells or using horizontal collectors (*McCarron et al.*, 2003).

- Extraction blowers, header pipes, and laterals are sized such that the vacuum available to the wellhead is about 15 in.-wc. If landfill permeability is suspected to be low, such as in the test case presented in this paper, the design wellhead vacuum is increased.

- Well casings are typically constructed of 6-inch diameter PVC. We prefer PVC over HDPE because during differential settlement of the landfill, PVC typically shears and either cracks or breaks. When this happens, LFG extraction from the well is still feasible if shearing occurs in the gravel pack. If HDPE is used, the casings may pinch off, reducing the wells' effectiveness. Consideration should be given to 4-inch diameter casings if flows are anticipated to be low, due to minimal headlosses in the casing.

The model presented herein is for a full-depth vertical extraction well. Adjustment to the model is required for partial-depth wells. If the interest exists, we may publish this adjustment in the future.

REFERENCES
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Dillah, D. D., E. R. Peterson and S. G. Lippy, 2001, "Air Injection to Control Off-Site Landfill Gas Migration: Design Parameters, Mathematical Model, and Case Study," WasteCon 2001 Proceedings.

McCarron, G. P., D. D. Dillah and O. R. Esterly, 2003, "Horizontal Collectors: Design Parameters, Mathematical Model, and Case Study," SWANA 26th Annual Landfill Gas Symposium Proceedings.

**TABLE 3. VACUUM AT THE THREE WELLHEADS AND SEVEN TEST-PROBES (in.-wc)**

Date	Time	EW-108	P-108-A	P-108-B	EW-109	P-109-A	P-109-B	P-402	P-402-A	P-402-B	P-108-C
3/30/2005	10 AM	19.2	3.26	0.35	8.2	4.48	2.31	1.0	0.37	0.24	0.15
3/30/2005	2 PM	19.1	3.26	0.32	8.1	4.47	2.26	2.8	0.95	0.54	0.16
3/31/2005	10 AM	19.7	3.30	0.34	8.3	4.62	2.34	3.5	1.27	0.69	0.20
3/31/2005	2 PM	18.9	3.31	0.31	7.8	4.20	2.10	3.2	1.00	0.54	0.14
4/1/2005	10 AM	18.7	3.20	0.33	7.8	4.30	2.20	3.0	1.07	0.59	0.17
4/1/2005	2 PM	18.4	3.00	0.07	7.7	4.10	0.52[*]	2.9	0.24	0.12	0.03
4/4/2005	9 AM	18.9	3.10	0.34	7.8	4.30	2.20	3.1	1.09	0.61	0.21
4/4/2005	2 PM	18.9	3.10	0.31	7.8	4.30	2.10	3.1	1.10	0.61	0.20
4/5/2005	10 AM	20.0	3.30	0.38	8.6	4.70	2.40	3.6	1.20	0.75	0.30
4/5/2005	2 PM	20.9	3.50	0.33	8.6	4.80	0.24[*]	3.5	1.10	0.61	0.34
4/6/2005	10 AM	21.0	3.50	0.40	7.8	4.20	2.20	3.8	1.30	0.76	0.25

* suspect data removed from analysis.

TABLE 4. R_I AND K ESTIMATES

Parameter	Date	Time	EW-108	EW-109	EW-402
K (cm/sec)			1.72E-5	3.87E-4	1.44E-2
R_I (feet)	3/30/2005	10 AM	57	146	238
	3/30/2005	2 PM	57	146	345
	3/31/2005	10 AM	57	148	388
	3/31/2005	2 PM	57	142	350
	4/1/2005	10 AM	57	144	362
	4/1/2005	2 PM	56		190
	4/4/2005	9 AM	56	144	366
	4/4/2005	2 PM	56	132	367
	4/5/2005	10 AM	57	149	388
	4/5/2005	2 PM	58		371
	4/6/2005	10 AM	58	143	397
Average R_I			56.9	143.8	342.0
Overall R^2			0.9991	0.9878	0.9909

Note: Average R_I for EW-108, EW-109 and EW402 = 180.9 feet.
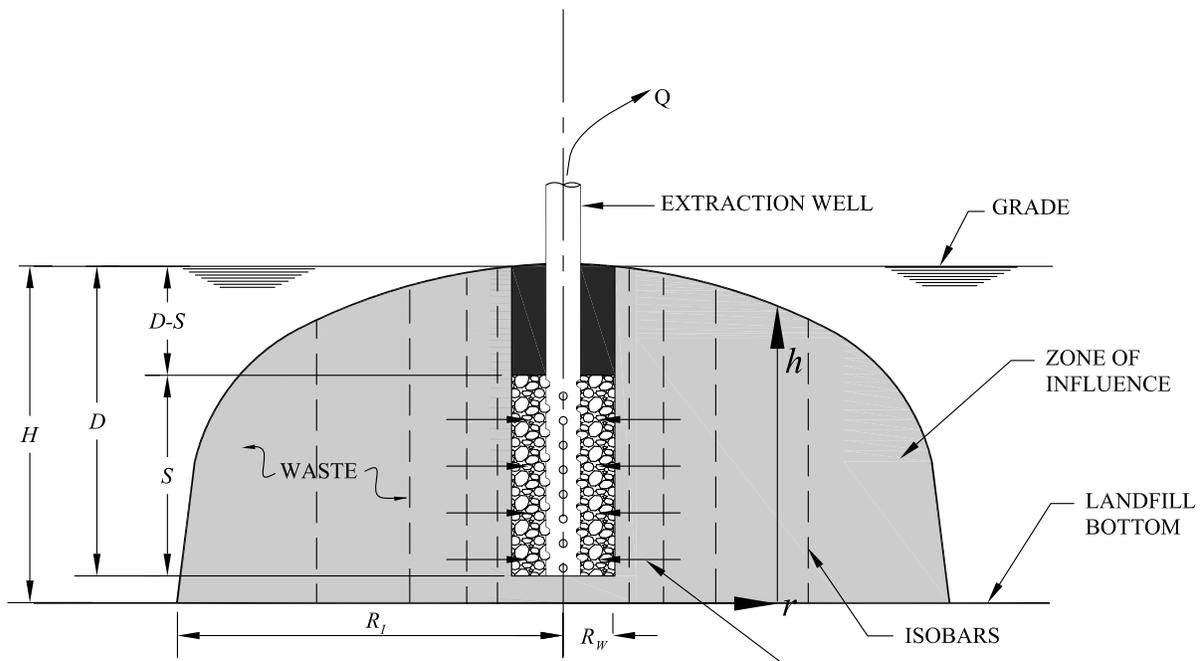
VERTICAL SECTION
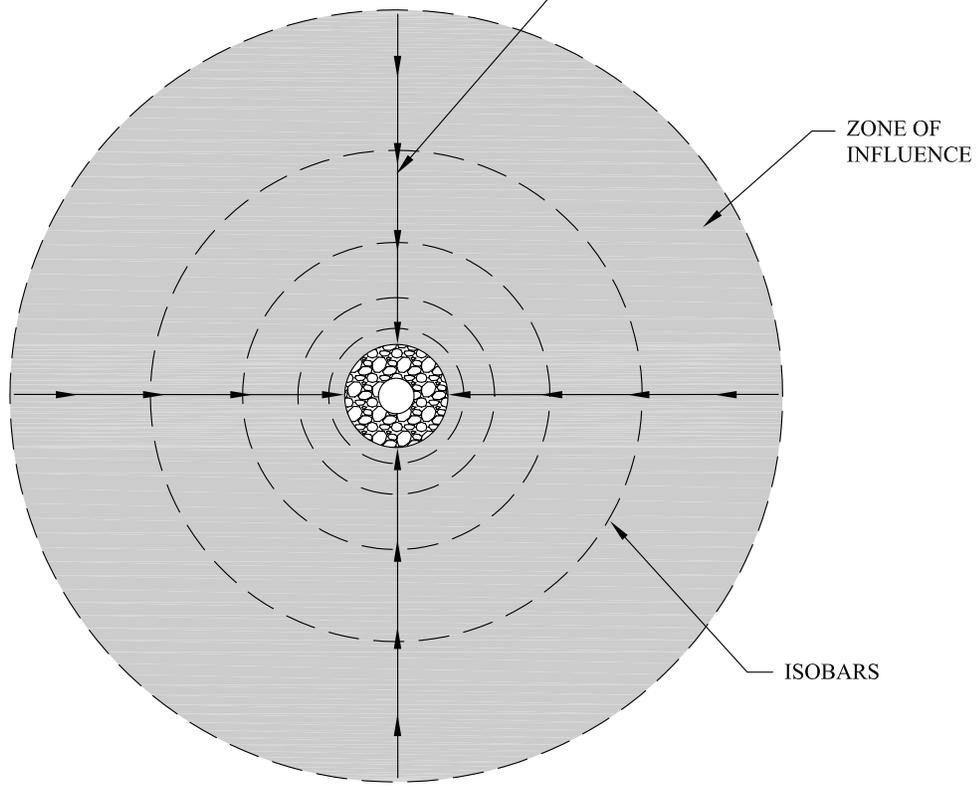
HORIZONTAL SECTION
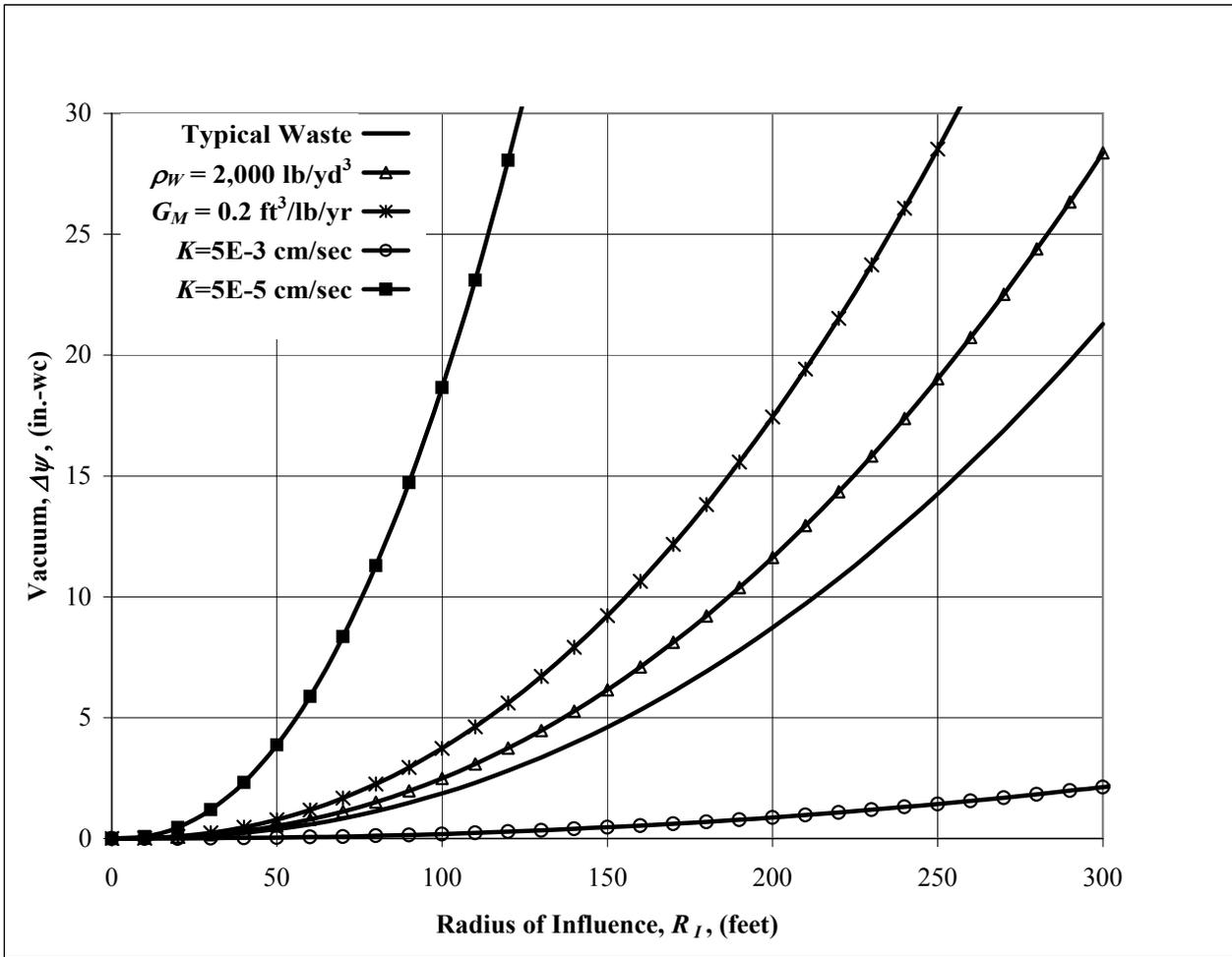
FIGURE 1. VERTICAL LFG EXTRACTION WELL MODEL

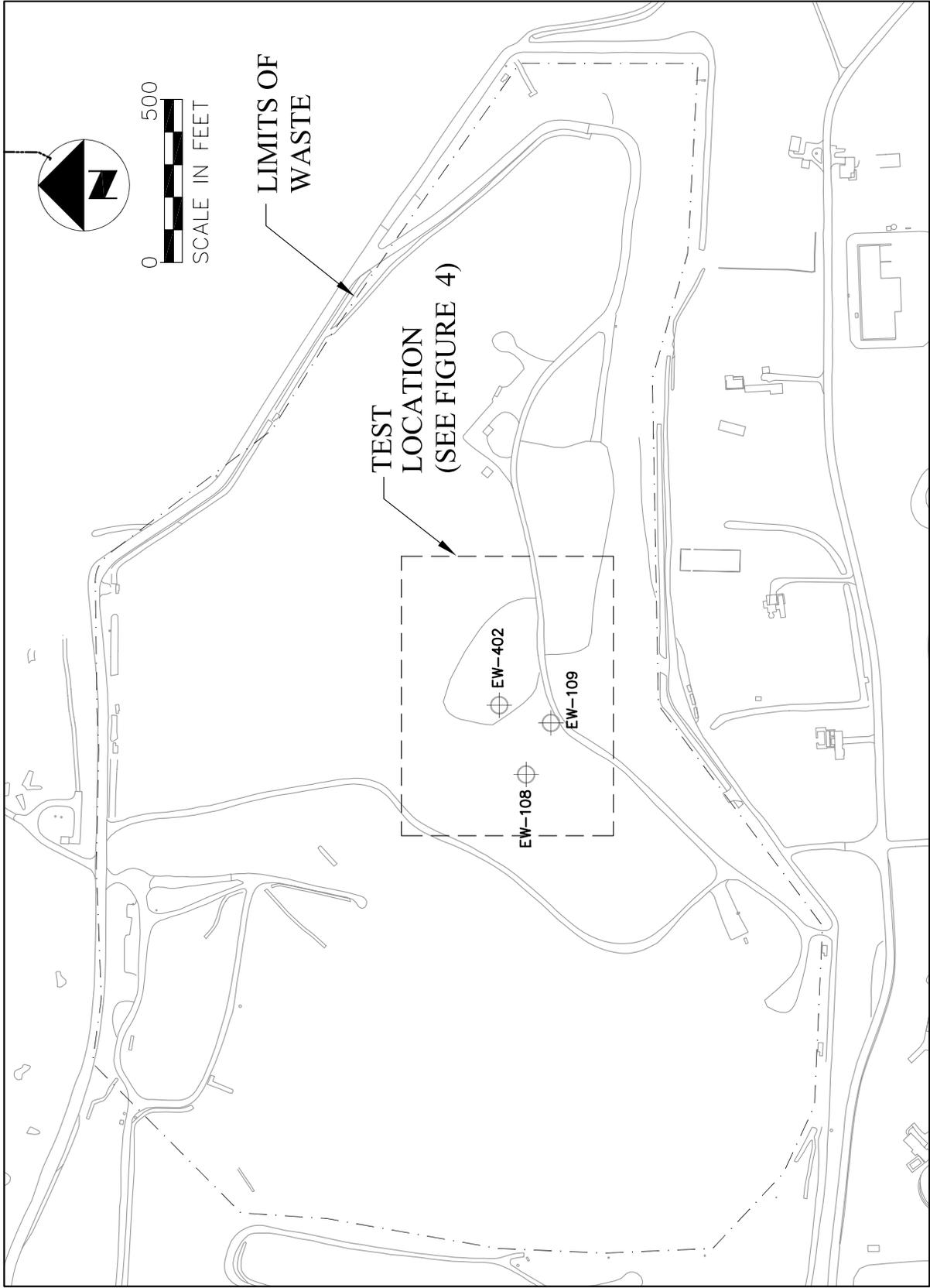**FIGURE 2.** $\Delta\psi$ **VERSUS** R_I **FOR VARIOUS WASTE TYPES**

LIMITS OF WASTE

TEST LOCATION (SEE FIGURE 4)

SCALE IN FEET

0   500

EW-402

EW-109

EW-108

FIGURE 3 - SITE MAP

SCALE IN FEET

EW-108 ⊕ VERTICAL EXTRACTION WELL

P-108-A ▲ TEST PROBES

RADIUS OF INFLUENCE - MODELED

EW-402
P-402-A
P-402-B
P-108-C
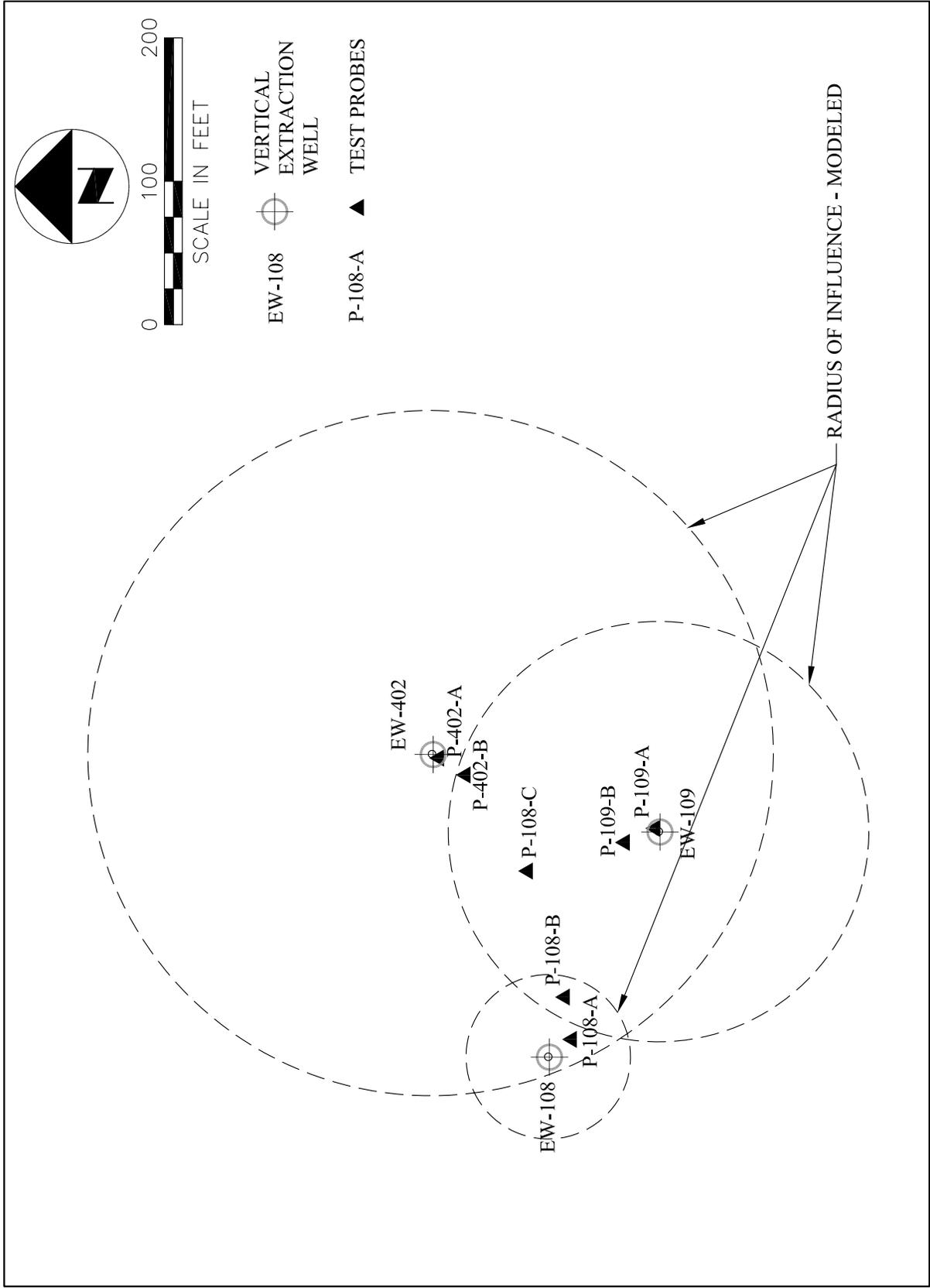P-109-B
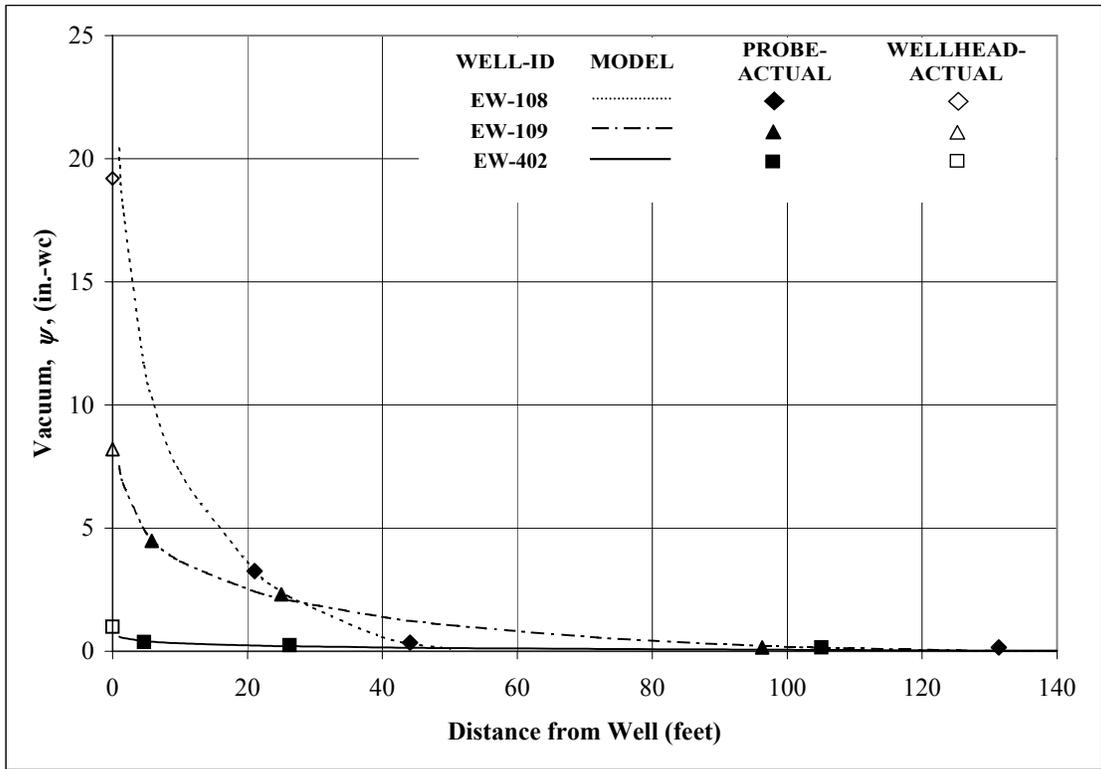P-109-A
EW-109
P-108-B
P-108-A
EW-108

FIGURE 4 - TEST LOCATION

FIGURE 5. COMPARISON OF ACTUAL DATA TO MODEL FOR MARCH 30, 2005, 10 AM