IMPROVING LANDFILL METHANE RECOVERY -- RECENT EVALUATIONS AND LARGE SCALE TESTS[1]

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ABSTRACT

Shortly after 1990, IEM, Inc of Palo Alto California, USA and the Public Works Department of Yolo County, California USA began a long-term collaboration, to test methods to improve landfill gas (LFG) recovery and advance landfill gas to energy (LFGTE). The collaboration started with the Yolo "Controlled Landfill" anaerobic bioreactor project. Both the scopes of work and collaborating team have expanded, to involve other parties and explore other promising avenues to improve LFGTE and landfill emission control. Along with IEM and Yolo, the collaborating team now includes the University of Delaware, North Carolina State University and HGC, Inc. Topics being investigated include

(a) The "controlled landfill" bioreactor
(b) Permeable layers to improve LFG recovery
(c) Use of subsurface gas probes.
(d) Approaches to help overcome "waterlogging" that can impede gas extraction
(e) Early stage measures to limit emissions during filling
(f) Advanced finite element analysis.
(g) Modeling, and use of pneumatic tests to project gas generation.

This presents an overview of this work. The rationale for projects and results of evaluations and field testing are presented.

INTRODUCTION

Landfill gas recovery and energy uses have been increasing for over 3 decades. Despite a steadily growing experience base, there are remaining issues with current practice, that can often limit landfill gas (LFG) recovery and emission control and that interfere with

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[2]

landfill gas to energy (LFGTE). A list of some often interrelated problems that can crop up is shown in Table 1

Table 1

Frequently encountered problems and limitations with landfill gas recovery:

1. Inefficiencies of collection, and problems with air entrainment, and maintaining constant methane content in extracted gas
2. Difficulties in extraction due to water buildup in wells ("waterlogging")
3. Fugitive methane emissions and losses in early stages of filling when extraction is relatively inconvenient and often inefficient (or absent)
4. Tedious and slow iterations of monitoring/adjustment/control when basing such control on "typical" indicators like wellhead gas composition
5. Predicting most effective designs for gas recovery
6. Predicting and assessing methane recoverability at a given site, where misses in predictions lead to performance shortfalls relative to expectations

As background to further discussion it is useful to review some issues that remain concerns with “state of the art”

Conventional Landfill Gas recovery The conventional LFG recovery technologies are described in references including EMCON, 1982, *Methane Generation and Recovery from Landfills*, and documents such as the SWANA-NREL 1997 *Landfill Gas Operation & Maintenance Manual of Practice*. LFG is predominantly extracted from the landfills using subsurface wells or trenches. A typical vertical extraction well, along with arrows denoting gas flows, is shown schematically in Figure 1

Extraction rates are adjusted so that on average air entrainment is limited while maintaining extracted methane content at levels often near 45-50% .

Some of the drawbacks with the well/trench approaches can be seen from Figure 1. They include

(a) air entrainment into the landfill that can tend to a maximum over the locus of extraction
(b) emission of fugitive methane at points distant from the well.
(c) Irregular variation of gas flux over the landfill surface.

Item (c) the irregularities of surface gas flux – both areas of gas out and air entrainment in – are understood to exist. One past study measured gas fluxes in and out of landfills’ surfaces and presented these as visually informative “topography” of areas of LFG emission and air entrainment. (Dr. Stanley Zison, various personal communications 1992-2005 with permission -see notes with reference).

Although Figures 2 and 3 are judged to have uncertainties of possibly as much as +/- 30%, Figure 2 and 3 (along with 1) illustrate important points. Clay and similar covers invariably have some degree of permeability in practice. With conventional or "standard" extraction approaches, the gas flow patterns are such that surfaces have irregular pressure gradients. These in turn result in regions of significant methane emission and air intrusion. Both of these are detrimental to LFGTE.

Other factors can also influence and reduce LFG recovery. There are inevitably variations over time in total flux (as distinguished from spatial or point to point variation over the landfill footprint as in figures 2 and 3). Fugitive methane emission and air entrainment will not only vary from point to point but over time from causes including (a) barometric fluctuations which have surprisingly large effects (b) mis-adjustments of extraction compared to "optimal" extraction rates and (c) purposeful variations in extraction rate which might be carried out to fuel peak energy demands . Relevant discussion is provided in Young, 1991 and Augenstein et al., 2007a and 2007b.

Actual fractional capture probably varies widely depending on individual landfill features, and over time. The preceding simply points out that there is room for improving conventional LFG recovery/ control efficiency. This is true even in landfills of the most developed countries, ie, the US, and OECD countries, as in the EU and in Australia and Japan. The problems can be more serious in developing countries, as discussed in a recent World Bank workshop "Landfill Gas Capture: Project Design vs. Actual Performance and the Future for CDM Projects". Washington, DC, - April 19 2007. In that workshop, most of the problems and limitations in Table 1 were encountered in one or another of the World Bank funded projects.

As of the present time, conventional strategies to increase landfill gas collection efficiency and improve methane content of collected gas may include

--Thicker clay caps on landfills, for better barriers to LFG emissions/losses and prevention of air entrainment
--Closer spacing of underground wells or trenches
--More frequent monitoring
--"Overpull" or use of extraction rates greatly in excess of generation

These and other related strategies (detail omitted) can lessen surface emission (to extents somewhat difficult to measure and quantify) and achieve better gas recovery and quality (more easily quantified). However they can reach points of diminishing returns. In the case of increasing extraction or "overpull" relative to generation, air entrainment inhibits methane generation. And with overpull, dilution of landfill gas with air can limit certain energy uses.

In summary, the commonly practiced strategies have their limitations.

Measured and/or estimated collection efficiencies

A recent study (Spokas et al.) calculated extraction efficiencies of over 90% for a set of landfills during active gas collection post-closure. The US EPA had used a default collection efficiency of 75% (USEPA 1990) Recent work in Sweden Borjesson, et al. 2007 determined recovery efficiencies from below 30% to over 60%.

It must be emphasized that such recovery efficiencies in the literature are "points in time" values measured over very small intervals compared to decades of gas generation and recovery. Recovery efficiencies change over time and the aggregated recovery efficiencies from placement to completion of generation have not been determined. The field studies above did not examine early emissions of methane during filling, or at long terms. Significant methane may be generated slowly at long times after closure – for example at a rate constant k of 0.04 year-1 over 30% of waste methane can be generated more than 30 years after filling.. At long terms diffusional losses and other inherent difficulties with slowly generated gas render capture less efficient than in the initial few years shortly after closure.

Whatever the actual efficiencies at given sites, "conventional" LFG collection efficiency varies over time and can often be less than desirable. Based on published values, and considering losses in the beginning and at long terms after closure it is judged that fractional collection of the total generated methane for most US landfills may lie between 60-85%.

What might be done to improve LFG recovery and LFGTE?

Shortly after 1990, the Institute for Environmental Management (hereafter IEM,, Inc.), a not-for-profit organization, joined with the Yolo County, California, USA Department of Public Works, to address issues above and explore methods to improve LFG recovery. The number of topics has expanded well beyond the initial "Controlled Landfill" anaerobic bioreactor project. The project team has expanded to include academic and private organizations: IEM, Inc., Yolo County, the University of Delaware, North Carolina State University and Hydro Geo Chem, Inc.

With recognition that work is still in progress, it is appropriate to present some of the ongoing work. Practical (as well as scientifically interesting) approaches have been sought not only for the US but also the developing world. Next are presented overviews -- highlights and conclusions -- from various evaluations and field tests that help address issues above.

I. THE BIOREACTOR "CONTROLLED" LANDFILL.

This is the long-running Yolo County, California USA Controlled Landfill project/program. As conducted at Yolo, this approach entails, in essence, enhancement of landfill methane and capture by steps including

(a) Filling with waste as rapidly as practical under a given landfills' circumstances

(b) Coverage with permeable layer (optional) and geomembrane
(c) Only after means for gas capture are in place, enhancement of rapid methane generation by liquid (leachate and other) addition

The program has given very encouraging results and many insights since planning began over 15 years ago. This project is to be separately covered by the presentation of. Mr. Ramin Yazdani of Yolo County at this Beijing, China Methane to Markets Expo. Details are also posted, respectively, on the World Bank, Washington DC and Yolo County California websites. The World Bank and Yolo links are

http://siteresources.worldbank.org/INTUSWM/Resources/Angenstein_controlledlandfill.pdf

and the Yolo County, California Website

http://www.yolocounty.org/recycle/bioreactor.htm

Some relevant details of the Controlled Landfill project relevant to methane energy and the US EPA Methane to Market program by IEM, Inc are found at the link http://www.osti.gov/energycitations/purl.cover.jsp?purl=/795745-EMfXDz/native/ Some findings include

--Substantial acceleration of methane generation to maximum yield. Acceleration of fivefold to tenfold "normal" in theYolo tests was attainable via management of moisture and temperature.

-- Efficient capture of the rapidly generated methane was shown possible (estimated over 90% of total methane potential with proper setup sequence, and ongoing control. Geomembrane cover greatly reduces both fugitive LFG and air entrainment that were evident in figures 1-3.

The controlled landfill approach offers large prospective benefits to landfill energy operators including the EPA MTM program partners. However it must be emphasized that the controlled landfill approach at Yolo is demanding. The setup and operation require skill, and care. It is suggested that this type of project should be implemented by personnel with extensive experience.

This text's figures 4 and 5 exemplify important findings.

--Figure 4, compares accelerated methane recovery in an enhanced cell, versus a control
--Figure 5 illustrates how more rapid conversion to methane reduces waste volume.

Mr. Yazdani's presentation provide much more detail

II. PERMEABLE LAYERS

The Controlled Landfill above addresses issues and limitations with conventional landfill gas recovery. However the controlled landfill is relatively demanding of technical expertise, operational care, and infrastructure. On top of that, geomembrane cover can be quite expensive.

Permeable layers. The project team has been evaluating a simpler approach for improving LFG recovery and LFGTE. Thin (≤ 30 cm) permeable (highly gas conductive) layers can be emplaced during filling slightly below the landfill surface. Such layers could be made of any of several widely and economically available materials, e. g. shred tires and/or rubble or wood chips. Layers of such materials within landfills, can provide more desirable of gas flow patterns than those of figure 1, enabling substantially increased LFG recovery efficiency while reducing air entrainment. Associated measurement and control strategies can be straightforward.

An example application of permeable layers is shown in the schematic cross section of the landfill in figure 6. Gas flow is denoted by arrows. Operating principles and features of the permeable layer approach include

1. Under conditions of landfill operation, permeable layer conductivities for LFG are from 10^3-10^6 (ie a thousand-fold to a million-fold) greater than surrounding waste or soil. With this extremely high permeability the LFG pressure within the near-surface permeable layer will be essentially constant throughout the layer

2. Since the LFG pressure differential between the permeable layer and the atmosphere is essentially constant, the irregular pressure gradient and surface fluxes associated with conventional extraction is (see figure 1) are "evened out". With constant "draw" over the entire permeable layer footprint, the Figure 2 "hills and valleys" of fugitive emission (gas loss) and air entrainment are greatly reduced.

3. The very high conductivity of permeable layers relative to surrounding material provides an LFG flow path enabling more effective capture of gas distant from deep wells. To put things another way, a higher fraction of LFG can be made to go where LFGTE operators want it to go.

4. Close and rapid control of extraction is possible from sampled composition of gas from appropriate locations in the cover and permeable layer.

Thus, permeable layers offer advantages to facilitate higher fractional LFG recovery with less entrained air. Other advantages include (a) relatively constant methane content for LFGTE providing deep wells are used and (b) that tolerance to mis-adjustments and easier control are expected (detail omitted here but available in Augenstein et al. 2007a).

Other factors relating to permeable layer use are:

--Constructability
--Results of performance modeling
--Dealing with potential prolems
--Field performance testing

--Potential applications (particularly developing countries)

Constructability

Permeable layer construction at large scale has proven relatively straightforward. Construction of surface permeable layers was accomplished at Yolo County as early as 1994 (Augenstein et al 1998). Most recently, a test area of subsurface permeable layers has been constructed in a test section of Yolo County. Figures 7 and 8 show a permeable layer under construction. In this case the layer is made of shred tires. The use of shred tires takes care of the very common (worldwide) problem of waste tire disposal. However other large pore size materials such as rubble, wood chips and gravel would be equally suitable.

Modeling permeable layer performance by finite element analysis

LFG recovery using permeable layers was initially modeled by IEM, Inc. and then Hydro Geo Chem of Tucson, AZ. More extensive modeling by finite element analysis is now under way by graduate students and faculty of the University of Delaware, including Yoojin Jung, Professor Paul Imhoff and Liquin Li.

Figure 9 illustrates the permeation of air into a landfill first without and then with permeable layers present (findings by University of Delaware). Figure 10 shows fractional methane capture improvements for one set of modeled conditions. In figure 10 fractional methane capture is shown as a function of assumed horizontal/vertical permeability ratio and extraction rate relative to generation. It should be remarked that figure 10 results cover one specific set of assumptions and other scenarios can give higher augmentation of capture efficiency (ie that fugitive emissions could be dropped by >50% among other things). These results are quite encouraging.

One conclusion from all analyses is that permeable layers as envisioned will always improve fractional capture and reduce air entrainment compared to “conventional” recovery using wells or trenches alone. In most case the improvement would be considerable, ie fugitive CH4 and air can be reduced by the order of 50% (range 25-75%) This would provide major benefits for LFGTE

Modeling also suggests another very pronounced benefit for certain common landfill situations around the world: Performance improvement with permeable layers will be greatest with more heterogeneous landfills where cover soil use is less, or is haphazard. This type of situation is very common in the less prosperous developing countries of the world (where IEM, Inc has been examining applications). An example of a likely level of benefit to capture efficiency occurs where the ratio of horizontal to vertical gas permeability is low, a likely feature of developing world landfills. Benefit can be seen by comparing the higher fugitive emission curve marked “without tire layer” in figure 10 to lower curves “with tire layer” .

Dealing with potential problems

Wider application of permeable layers as envisioned here would be relatively new in LFG recovery. When considering any newer approach to improve LFG recovery it is important to anticipate and address possible problems. The most serious problem envisioned is LFG/air "leaks" by channeling through low permeability cover zones or fissures. The effectiveness of permeable layers has in fact been evaluated in the presence of likely degrees of fissuring. The situation where fissures are present has been analyzed by graduate student Yoojin Jung of the University of Delaware. Results of one of her analyses are shown in figure 11. In essence modeling shows that permeable layers retain effectiveness for gas collection even if there should be some (moderate) fissures in landfill cover overlying the layers. This is another important benefit

Permeable layers can help substantially reduce gas recovery problems with fissures in the cover. In addition they would be synergistic with a parallel strategy to deal with "leaks" from fissures. The fissures and breaches in the cover can be dealt with by turning off recovery and tracking down "hot spots" with combustible gas detectors. The hot spot can then be sealed with material such as clay (a standard procedure at landfills).

As an example of another problem, portions of permeable layer porous material could be blocked or interruptions could be created by "scarps", ie settlement of waste in such a way as to create discontinuities. Settlement over time is common. Problems of this sort can be lessened by closer spacing of deep well or trenches, and by using thicker permeable layers (although involving a tradeoff, meaning some loss of fill capacity)

All other potential operational problems that could be envisioned to date have solutions (discussion omitted).

Field- scale construction and recent performance testing

Field tests of permeable layers are ongoing in an approximately 2-acre test section of the Yolo County landfill (Figure 12). This test area is highly instrumented to allow measurements of gas compostion in (a) the extracted gas (b) the permeable layer (c) multiple levels of the cover.

Figure 13 illustrates some initial results. These results illustrate ability of the sampling and analysis system to monitor gases of concern at locations and levels of interest, particularly, within the permeable layer. Extraction rates were varied in this test. (The extraction rate variation can be considered a stringent test of permeable layer use.) By limited, spot tests, surface emissions were close to negligible at all points tested by flux box. Emissions amounted to a level estimated less than 3% of the amount of methane extracted. However it should be noted biocover was present in this case. Low surface emissions are attributed to a combination of (a) a methane/air interface that remained below the surface as can be inferred from behavior of the air/methane interface within the cover, combined with (b) efficacy of the biocover in abating methane leaving the soil surface.

The data are preliminary and more tests are ongoing and planned. Based on all results and encouraging indicators to date, IEM and the project team consider the permeable layer approach to be well worth continued exploration. .

Potential applications in developing countries.

Permeable layers are adjuncts or simply “add-ons” to conventional gas recovery. Based on field experience they are relatively easy to emplace and use in operation. Being relatively low-tech, the permeable layer approach could be helpful in addressing the range of problems listed above, not only for developed but also developing countries Benefits could be substantial for reasons noted earlier and there would seem little risk, in terms of potentially adverse effects. IEM and the project team have been seeking appropriate situations in and outside the US where the approach can be applied.

III. SUBSURFACE GAS PROBES.

This topic first requires a brief background of how “conventional” LFG extraction wells around the world are generally adjusted or “tuned” to optimum flows for extraction

Gas extraction system based on wells (as in figure 1) must be adjusted (“tuned”) to maximize recovery. Typical tuning may gradually increase extraction rates from wells over time, until falling extracted methane levels at the wellhead indicate that air entrainment through the landfill surface, and into the collected gas, is too high. If methane content falls too far, the well must be throttled down.

However the wellhead gas compostion is a “lagging indicator” on which to base control. This is because of the very large volume of deep gas relative to extraction rates, and imprecision and lags of feedback. The time constant for adjustments is long and the total time for wellhead compostion to reflect adjustments can be weeks to months. Also, in this situation it is often not clear a priori how much or how often extraction flows should be changed. Furthermore, continuing adjustment, adjusting wells for changing generation or other factors is a tedious complex process and feedback is likewise slow.

Because of these factors, control of extraction to proper rates often presents difficulties, particularly in developing countries.

Probing subsurface gas composition for control.

As gas collection occurs, the actual situation in the interior of the waste is one where a diffuse boundary will exist between LFG and entrained air beneath the landfill surface. The project team has had good experience for several years in delineating subsurface gas compositions via simple gas sampling probes. These can locate regions of LFG, intruding air, and key factors such as the boundary between these. Such information can provide early indications of air intrusion (ie overpull) or, alternatively, show when circumstances will allow for increased methane extraction (“underpull”). An example of results from such probes for sampling at strategic locations was shown above in figure 13

Such probes give faster feedback than wellhead gas analysis to allow extraction adjustments

Gas probes have also been used by others, notably in the work of Dr. Jean Bogner. They have also been used in this work in the assessment of biocover performance by the project team (detail omitted). However the simplicity and ease of use suggests that they could find even more application in LFGTE.

IV. AVOIDING “WATERLOGGING” OF LFG WELLS.

Soil cover is routinely used to quickly cover waste after filling, for sanitation and to prevent waste access by birds, rodents, etc. Layers of cover soil remains embedded in the landfill. Even if a landfill’s soil cover may be initially permeable to liquid, precipitates can form and block pores in soils used for daily cover. An example involves calcium acetate (commonly at high levels in leachate) which can react to calcium carbonate.

$$\underset{\text{Calcium acetate}}{Ca^{++}(CH_3COO\text{-})_2} + \underset{\text{Water}}{H_2O} \rightarrow \underset{\text{Calcium carbonate}}{CaCO_3} + \underset{\text{methane}}{2CH_4} + \underset{\text{carbon dioxide}}{CO_2} \quad \text{(Eq. 1)}$$

The precipitated calcium carbonate product of eq. 1 – basically “limestone” – can seal off pores in soil layers. The blockages in geotextile are also well documented in publications of the Koerners and others at the Geosynthetic Institute (GSI). A result of blocked pores can be blockage of infiltrating liquid and excessive liquid accumulating in some landfill zones and wells. (The blocked liquid is referred to as “perched” liquid.) Once filled with liquid, wells or trenches obviously cannot collect LFG. In addition liquid that builds up in the landfill can ultimately exit the landfill in “side seeps” The problems with liquids buildup in deep wells have been detailed, or example, at workshops such as that of the World Bank of April 19, 2007 and side seeps seen in many situations including Yolo bioreactor tests (discussed in some detail below).

Permeable layers discussed earlier in II offer one solution for LFG collection in the presence of moderate liquid buildup. As long as the interstices of a permeable layer remain gas-filled, ie do not fill with water, LFG will find a way to the layer (bubbling through or bypassing liquid saturated zones). A permeable layer will function as shown in figure 6. In this respect the permeable layer can be one solution to the problem of “waterlogging”

A second approach is to substitute more porous material for the usual soil cover. Soil pores are small and easily clogged with the precipitates that form from leachate. In place of soil cover, compost and other liquid-permeable "alternative daily cover" materials with high porosity and large interstitial passage (pore) size has helped avoid such problems by allowing unimpeded liquid percolation and drainage from the landfilled waste.

In bioreactors, accelerated liquid infiltration is applied to “jump start” methane generation. Consequently bioreactor cells are good “test systems” for evaluating various cover materals’ effects in avoiding or creating liquid buildup. Figure 14 documents how liquid rapidly permeated waste in operation of a test cell in Yolo County when compost (alternative daily cover) was used. Liquid permeated readily, at about 1-3 cm/day. (This rate would correspond to infiltration of heavy rain at 0.5-1-inch per day.) A contrasting result was obtained with a larger bioreactor cell which had some unplanned remnant soil cover (left inadvertently). Permeation was much slower. Results with the larger cell are shown in figure 15 When rapid liquid addition was attempted, side seeps and other problems were encountered. To avoid further problems, infiltration had to be reduced to a level under 5% of that in the cell with ADC. Even with the reduced infiltration in the test cell, perched liquid was found repeatedly when sample cores were drilled.

For a number of reasons (much detail omitted here) it seems best when possible to use alternative daily covers such as composted waste or greenwaste rather than soil.

V. EARLY STAGE MEASURES TO PREVENT FUGITIVE EMISSIONS DURING FILLING.

There are significant fugitive LFG emission and losses during initial waste filling, and these emissions have long been concerns. These early emissions can be lessened with simple designs and strategies, including not only early gas extraction from the drainage layer but by interspersing permeable layers as wastes are placed. Detail on use of permeable layers to limit early emissions is omitted here but is found in proceedings of the recent ICLRS International Solid Waste Conference held in Gallivare, Sweden under the auspices of Sweden’s Luleå Technical University. Summaries were assembled by Prof Anders Lagerkvist of Lulea Technical University at

epubl.ltu.se/1402-1536/2006/05/LTU-TR-0605-SE.pdf. Pages 43-44.

VI. ADVANCED FINITE ELEMENT ANALYSIS.

Computer programs involving finite element analysis can be used to optimize LFG recovery, (for example see Waineo, 1999). In conjunction with work at Yolo, modeling is being conducted by the University of Delaware using Tough2 codes from US Department of Energy (Los Alamos National Laboratory) reservoir fluid flow models, as adapted to gas flow in a landfill Similar work is being performed by HGC, Inc, some of that work cooperatively with the University of Delaware. Such programs become more accurate and less costly as the programs evolve and parameters are refined. They are expected to be very useful adjuncts to landfill gas recovery worldwide, particularly in developing countries.

Several interesting results of the Delaware finite element modeling work for this program have been shown here in figures 9,10 and 11.

VII. INITIAL GAS GENERATION ASSESSMENT – LIMITATIONS OF MODELING, AND USE OF PNEUMATIC TESTS AS ADJUNCTS TO MODELING.

Throughout the history of LFGTE in and outside the US, there have been uncertainties in abilities to predict gas generation and assess recoverability. Errors in LFG recovery prediction commonly lead to oversizing (thus idle equipment) or undersizing of energy equipment (thus wastage of gas). Gas recovery models can help, but have remaining and to some extent unavoidable uncertainties because of site features that increase or decrease experienced generation compared to "default" model projections. Extraction tests using vertical wells are if anything, demonstrably more uncertain. Uncertainties with models would be expected even greater in developing countries because of the wider spectrum of site and waste features along with other confounding variables.

Uncertainties with models are illustrated by findings from a 19-landfill study in the US. (Vogt and Augenstein, 1997). In that study under the best of circumstances, about 80% of experienced gas recoveries fell within 60 and 180% of the "best" calibrated model's projections. Figure 16 shows the "spread" of experienced landfill gas recovery versus the "best fit" model. Figure 16 provides a guide to what models can and cannot do in terms of precision, and uncertainties are large.

To supplement models, pneumatic methods for assessing gas generation rates can be applied to assess gas recoverability and reduce uncertainties at candidate sites. These are variations on the earlier work by Zison. Improved model tests are being applied now by Hydro Geo Chem. Such methods would lessen the frequent mismatches and gas shortfalls relative to needs of energy equipment installed to use the gas.

CONCLUSION

The presentation has presented overviews of some promising newer approaches with potential to improve conventional landfill gas extraction The straightforward nature of many approaches, requiring only moderate personnel skills, suggests that several strategies are well worth continued exploration for wider application, not only in the United States and OECD but in poorer countries of the world.

REFERENCES

Augenstein, D 2007a. Variable Rate Landfill Gas Recovery for "Peaking energy". Background document for panel discussion, Proceedings, SWANA Wastecon, 2007

Augenstein, D. J. Benemann and R. Yazdani (2007b) "Landfill Design and Method or Improved Gas Capture" USPTO 7,198,433

Augenstein, D. Yazdani, R. R. Moore and K. Dahl. 1998 Yolo County Controlled Landfill Project. Presentation paper at CIWMB Symposium on Landfill Gas Assessment and Management, Ontario, CA

Borjesson, G.; Samuelsson, J and J. Chanton 2007 Methane oxidation in Swedish Landfills quantified with the stable carbon isotope technique in combination with an optical method for emitted methane. Environmental Science and Technology published on web, August 2007.

Borjesson, G.; Svensson, B. H., Seasonal and diurnal methane emissions from a landfill and their regulation by methane oxidation. *Waste Management & Research* **1997,** *15*, (1), 33-54.

Spokas, K. J. Bogner, J.P.Chanton, M. Morcet, C. Aran, C. Graff, Y. Moreau le Galvan, I. Hebe “Methane mass balance at three landfill sites: What is the efficiency of capture by gas collection systems?” Waste Management, July 2006

USEPA, 1990, Radian Corporation publications for EPA. Also S. A. Thorneloe, personal communications between 1989 and 2007.

Vogt, W. G. and D. Augenstein. 1997. Comparison of Models for Predicting Landfill Methane Recovery: A 19-landfill study. Report prepared for Solid Waste Association of North America and National Renewable Energy Laboratory

Waineo, D. (GC Environmental, Inc) 1999 LFG system design using the finite element method. Journal reprint available on the GC Environmental web site http://www.gc-environmental.com/

Young, Alan. 1991 The Effects of Fluctuations in Atmospheric Pressure on Landfill Gas Migration and Composition. Water, Air and Soil Pollution vol. 64 p.601.

Zison, Stanley, Ph. D.. Personal communications between 1990 and 2005. The surface emission work by Dr. Stanley Zison was performed for Getty Synthetic Fuels (GSF, which later became Pacific Energy).

<u>Notes on Zison work:</u> Dr. Zison basically used the surface of the landfill as a “flux meter”. He determined pressure drop through surface layers of laboratory calibrated permeability (flux vs. pressure drop) and translated these into 3-dimenstional plots These show emissions fluxes as elevations and air entrainment as depressions (ie hills and valleys) on a grid representing the landfill footprint. Figure 2 and 3 showed this “topography” of emission and entrainment flux determined by Zison at the Penrose and Toyon landfills in the Los Angeles, California area. Although this and related plots have their“error bars” with accuracy probably +/- 20% such accuracy is more than sufficient to make the important point. Basically, the “hills and valleys” of fugitive emissions and air entrainment in Figure 2 represent the likely situation with most landfills worldwide that use conventional extraction.

Information excerpted from work for GSF and Pacific Energy is used here with permission of Mr. Zison.

FIGURES FOLLOW

Figure 1. The gas flow pattern with use of a vertical gas well

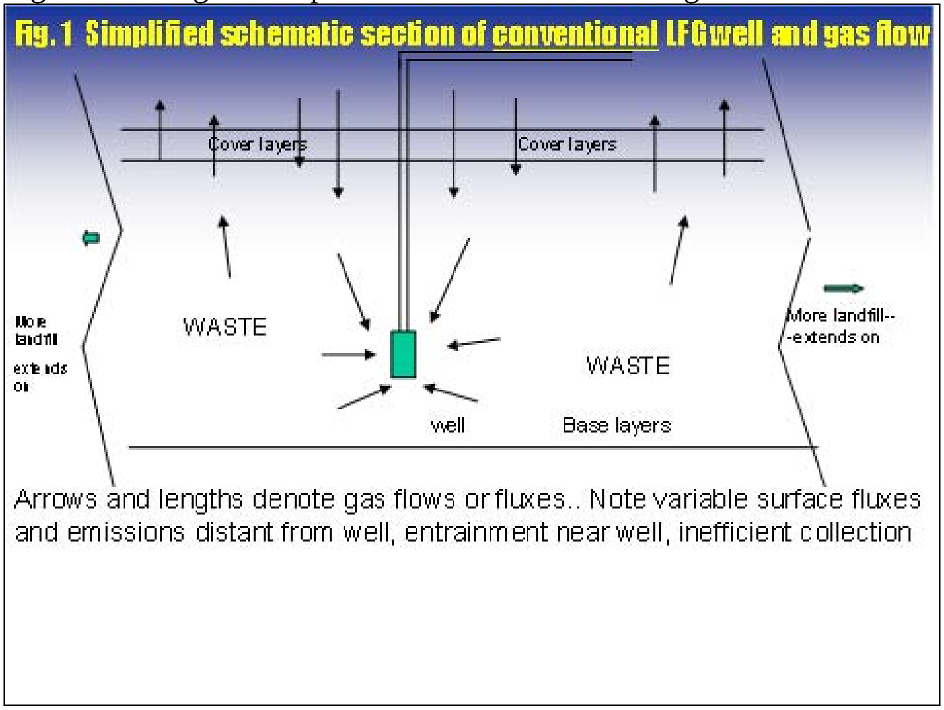


Figure 2. Surface fluxes of gas at the Southern California USA Penrose landfill showing fugitive emission ("peaks") and air entrainment ("valleys"). Work by Dr. Stanley Zison

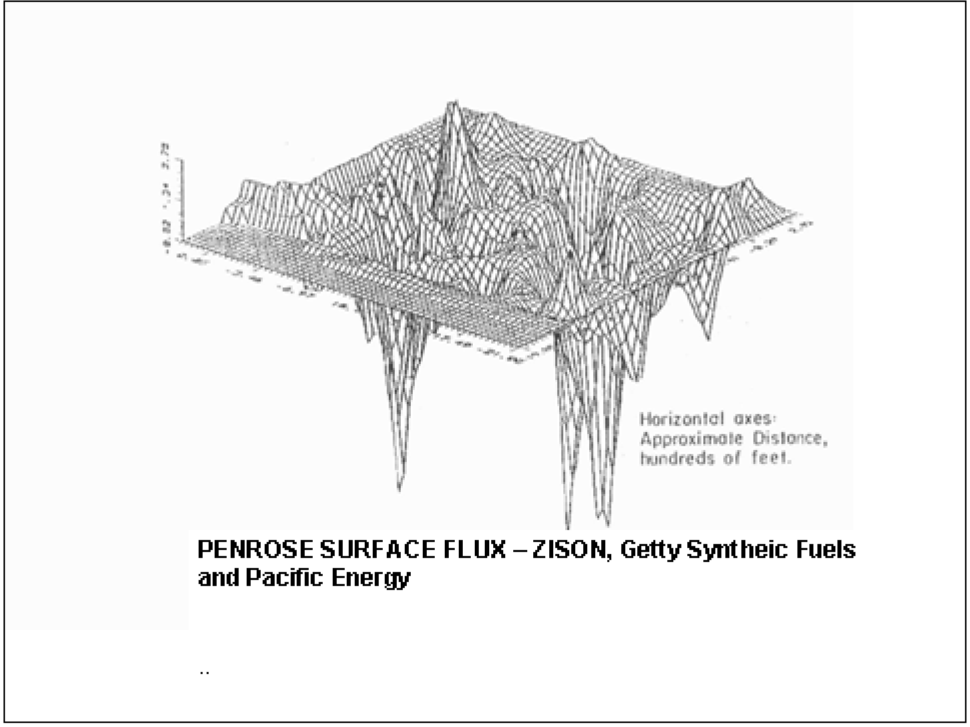


Figure 3. Surface gas flux profile of Sheldon Arleta Landfill, Southern California USA

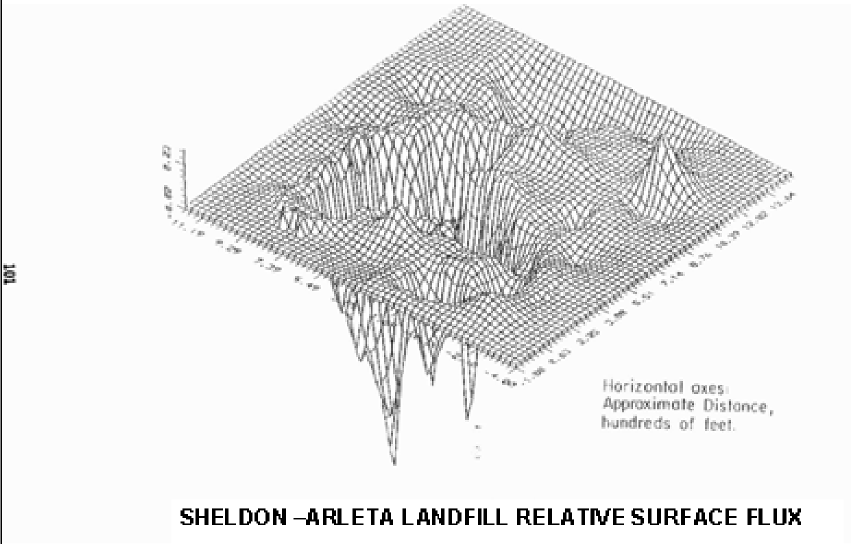


Figure 4. Comparison of methane generation enhancement in “enhanced” cell with control and conventional practice in the Yolo County, California USA Controlled Landfill program

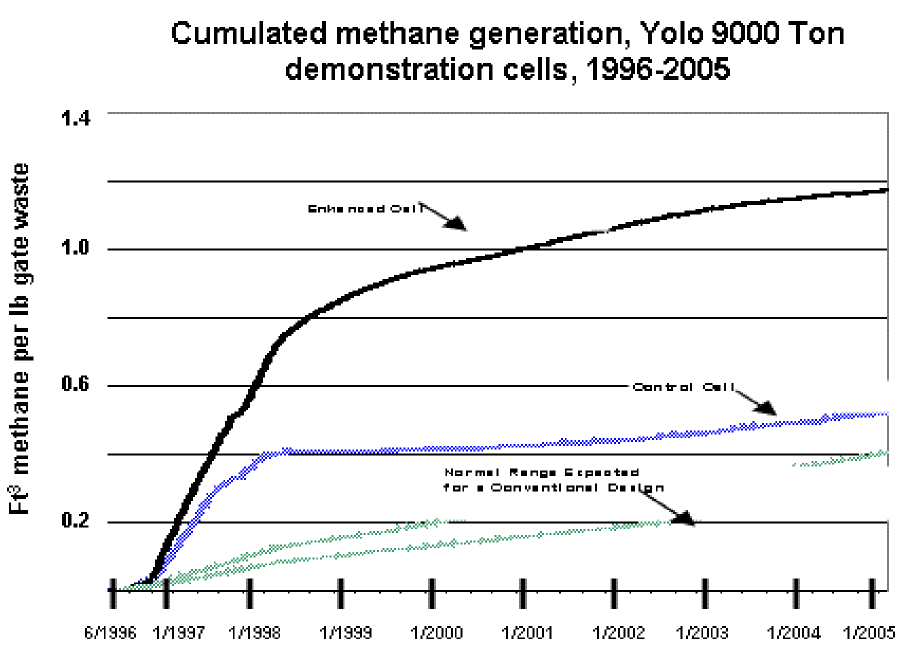


Figure 5. Comparison of enhance cell with un-enhanced control illustrates how conversion of solids to gas reduces waste volume (and can increase landfill life)

Comparison of surface profiles--enhanced vs. control cell

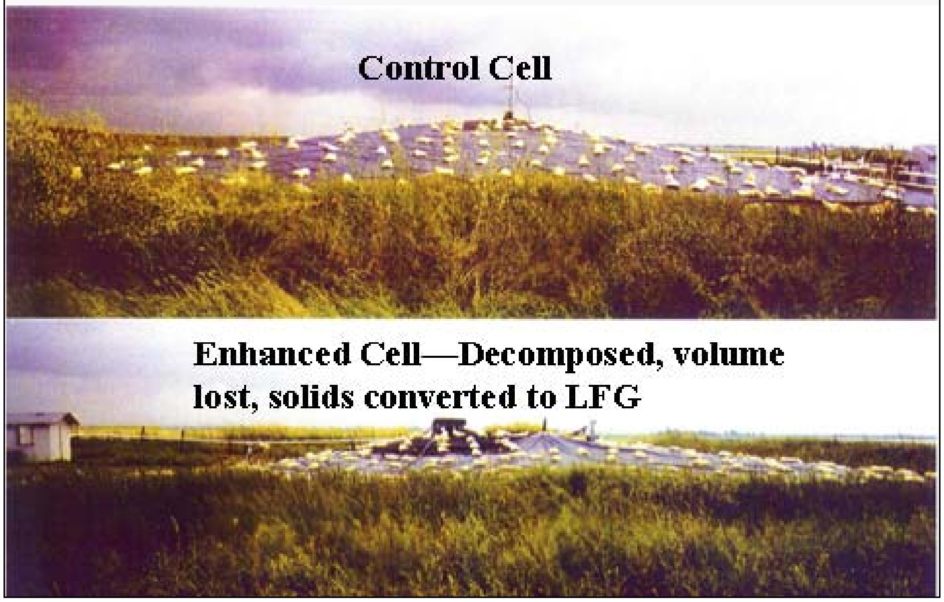


Figure 6. Schematic showing functioning of permeable layer

Simplified schematic section LFG extraction via permeable layer under low permeability cover, in combination with deeper subsurface extraction_ Arrows and lengths denote gas flows or fluxes.. Note capture of LFG emissions by permeable layer and re-entrainment of emitted LFG with consequent recovery efficiency increase.

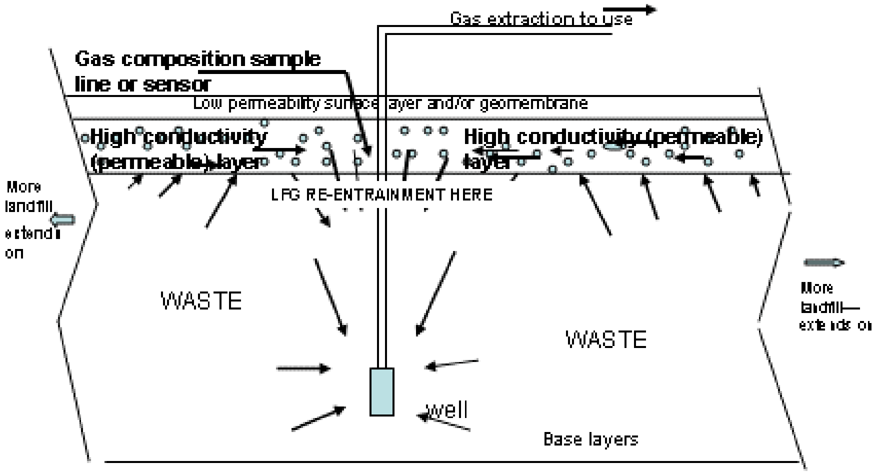
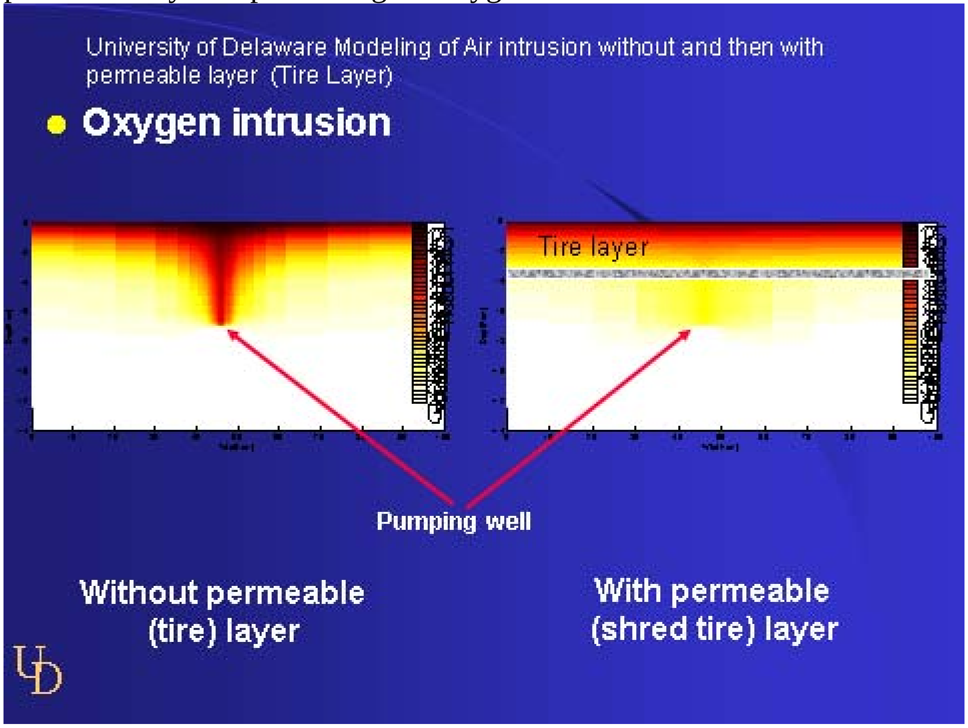


Figure 7. Photo of extensive layer of shred tires which will form permeable layer.

Figure 8. Construction of permeable layers at the Yolo County Central Landfill, California, USA. Photo shows placement of lower waste layer, shred tire permeable layer and top waste layer

Figure 9. University of Delaware modeling result showing bemefit of permeable layer in preventing air/oxygen intrusion.



University of Delaware Modeling of Air intrusion without and then with permeable layer (Tire Layer)

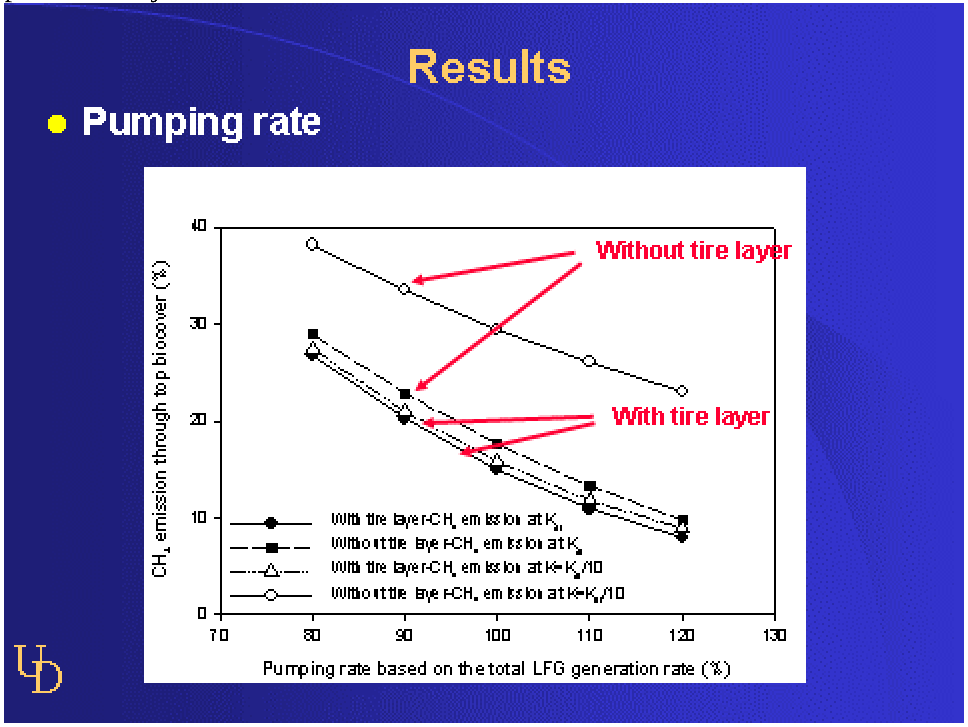
- **Oxygen intrusion**

Pumping well

Without permeable (tire) layer

With permeable (shred tire) layer

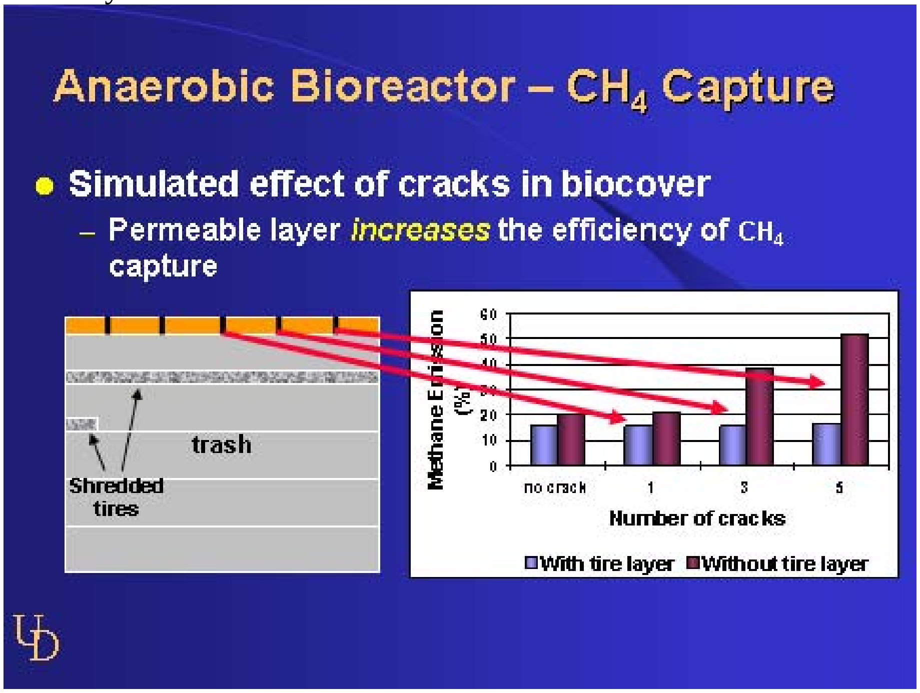
Fig. 10 University of Delaware modeling result showing permeable layer benefit in inceasing LFG capture efficiency at various horizontal/vertical permeability ratios



Results

- **Pumping rate**

Figure 11. University of Delaware modeling result showing how permeable layer maintains high LFG capture efficiency even with breaks or fissures in the soil/ clay cover



Anaerobic Bioreactor – CH_4 Capture

- Simulated effect of cracks in biocover
  - Permeable layer *increases* the efficiency of CH_4 capture

Figure 12: Schematic top view – layout of permeable layer test area at the Yolo County Central Landfill in California, USA

Figure : Top view of plan permeable layer test area, showing (at lower left) conductive layer textured ▨) footprint and well.

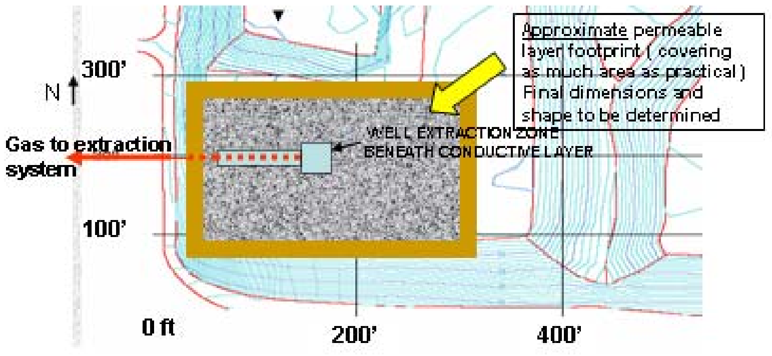


Figure 13. Log of results: Continuous gas sampling at multiple levels of permeable layer test area at the Yolo county Central Landfill. Barometric pressure, an important variable, is also shown

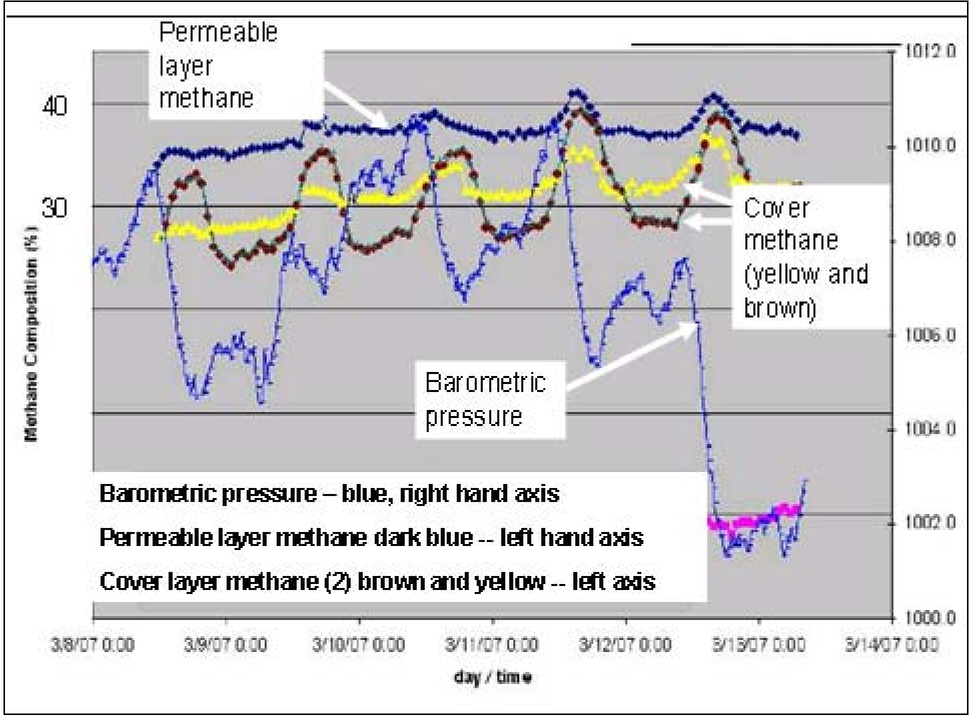


Figure 14: Rapid moisture permeation observed in a landfill test cell with highly liquid –permeable alternative daily cover (greenwaste as opposed to soil cover).

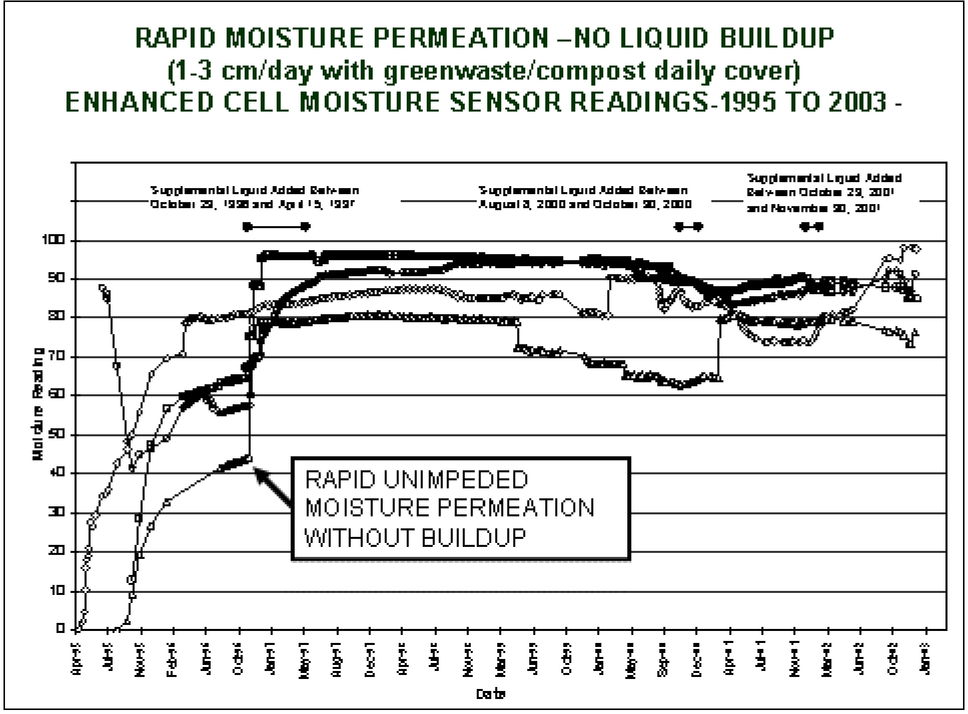


Figure 15. Experience with a bioreactor test cell where cover soil remained in the cell. Basically, permeation was retarded to less than 10% of the rate seen in figure 14 above Side seeps and gas well blockage occurred

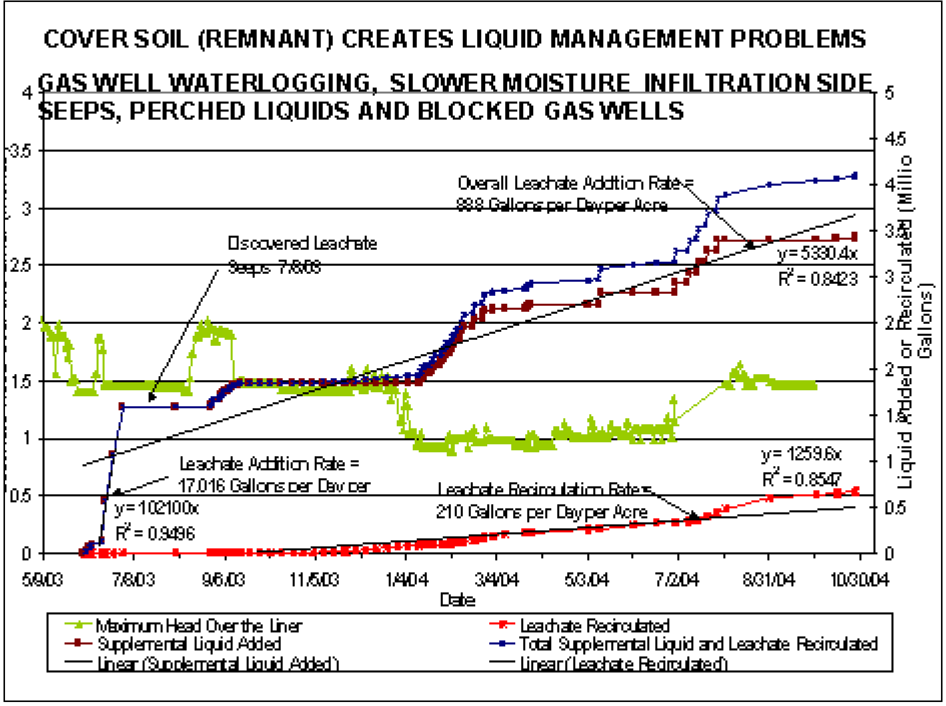


Figure 16. The “spread” of experienced gas recoveries versus “best fit” model projections obtained in a 19-landfill study for the Solid Waste Association of North America (SWANA). Vogt and Augenstein, 1997