THE ANAEROBIC BIOREACTOR CONTROLLED LANDFILL TECHNOLOGY FOR SOLID WASTE MANAGEMENT AND GREENHOUSE GAS ABATEMENT

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ABSTRACT:

An advanced waste landfill bioreactor approach termed the ABC Landfill ("Anaerobic Bioreactor Controlled Landfill") technology has been under development at the Central Landfill in Yolo County, California for over ten years. Demonstration cells at a scale of 9,000 tons have operated at this site since 1994 and recently a full-scale landfill of over 100,000 tons has started operations. The ABC Landfill technology involves the controlled addition of moisture, increased temperatures and recirculation of leachate, to result in a greatly accelerated rate of waste decomposition and landfill gas production. Methane capture is maximized by surface membrane overlying a surface permeable layer operated at slight vacuum to conduct gas to collection. Expected environmental benefits include local air pollutant reductions, long-term sequestration of photosynthetic and other carbon sources, complete methane recovery and greatly reduced solid waste-related greenhouse emissions. The rapid (< 10 years) and substantial (20 –25%) reduction in landfill volume due to settling, can significantly extend landfill life, compared to current technology where waste decomposition typically extends over fifty years or more.

The ABC Landfill technology was demonstrated in a comparative study of two 9,000 ton test cells, one of which received carefully managed additions of supplemental water and leachate, while the control cell only used leachate recycling. The cells were intensively instrumented to determine *in situ* conditions, in particular temperatures and moisture levels, and overall process performance. The apparent first-order rate constant for methane production (bacterial methanogenesis, a direct measure of waste breakdown) was greater than 0.4 $year^{-1}$, over five-fold "normal" for a waste mass of this size. Along with rapid gas production there was also rapid waste volume reduction, as demonstrated by settling, in the enhanced cell. A scaled-up ABC Landfill of 70,000 tons has started operations and is in early-stages of monitoring. The ABC Landfill technology is based on the carefully managed addition of liquid to allow even moisture distribution and temperature increases throughout the waste mass, which in combination with gas capture designs to maximize gas recovery, can essentially eliminate fugitive methane emissions from solid wastes, a major global source of greenhouse gases (3 to 5% of total), while providing a renewable energy source and for the long-term sequestration of organic carbon.

INTRODUCTION

Since 1994, the Department of Public Works of Yolo County, California, has been testing at its Central Landfill site an advanced bioreactor landfilling process that we now term the "ABC Landfill" (Anaerobic Bioreactor Controlled Landfill") technology. Support for this project has come from multiple sources, including the California Energy Commission, the US Department of Energy's (DOE) National Energy Technology Laboratory (NETL) and Yolo County itself. This paper presents a summary—necessarily abbreviated--of encouraging results that have been obtained since project inception (see Yazdani, 1997 Augenstein et al. 1998; Augenstein et al. 2000, and Yazdani and Augenstein, 2002, for more detailed information).

BACKGROUND

Landfill methane may, by various accountings, contribute about 5% of the "greenhouse effect, that is the total annual increase in radiative forcing due to buildup of greenhouse gases in the earth's atmosphere. The greenhouse potential of methane from landfills is such that almost any strategy to recover landfill methane will be "greenhouse cost effective" (*sensus* Nordhaus, 1991) relative to other greenhouse gas abatement strategies, as pointed out over a decade ago (Augenstein, 1992). Landfill gas is also a renewable ("CO_2 neutral") energy resource, that presently has additional potential, if fully captured and utilized, to substitute for and displace fossil fuel equivalent to over 150,000 barrels of oil per day, or, depending on assumptions, an electricity generation potential of about 4 GWe (see Hughes et al. 1994), roughly 1% of US requirements. Further, landfills, if properly designed, will provide for the long-term sequestration (>1,000 years) of photosynthetic carbon and other carbon sources (plastics, carbonates, etc.), providing another route for greenhouse gas abatement.

However, at present only about 30 to 40% of the total landfill gas is recovered and less than half of that recovered gas is utilized for energy. The failure to recover and use a greater fraction of this fuel is due to the unpredictability, variability and low rate of recovery of landfill methane. These uncertainties result in undersizing of the generation equipment, poor economies of scale and, often, only flaring of any gas actually recovered. The main reason for this state-of-affairs is that in conventional (also referred to as "dry tomb") landfill designs, the current standard in landfill technology, landfilled waste remains relatively dry for many years after placement Thus, bacterial breakdown and methane production is to far less than full potential, with gas generation taking place over many decades in a relatively unpredictable fashion. Unpredictability of methane energy recovery leads to undersizing in energy equipment, or failure at many sites to utilize landfill methane at all. This approach to municipal solid waste management also exhibits many long-term environmental and economic problems, including gas collection inefficiencies, fugitive gas emissions before collection starts or after collection stops, and activation of the microbial process anytime in the future that water infiltration reaches the undecomposed wastes, with resulting uncontrolled methane emissions and settling. This requires the long-term (30 to 50 or more years) monitoring and management of such landfill sites, including their gas collection and containment systems.

As noted by several workers over the years (e.g. Augenstein et al., 1976), it should be possible to design and operate landfills to overcome many of these difficulties by greatly accelerating and controlling methane generation through the addition of moisture and nutrients, and control of pH and temperature, a concept now often referred to a "bioreactor landfill" or "controlled landfill". In particular, elevated moisture (compared to conventional landfill standards) is essential for accelerating methanogenesis (for example see Halvadakis, et al. 1983). It is less well recognized that in addition to moisture, temperature elevation will also accelerate waste decomposition, because the activation energy of about 15 kcal/mol implies a rate constant doubling for each $\approx$ 10 ^{o}C temperature increase over a span of 10-50 ^{o}C (Ashare et al. 1977). In the present project, carried out at Yolo County, California, due to regulatory and other constraints, only water and temperature were used as enhancement techniques.

YOLO COUNTY ABC LANDFILL PROJECT

For the present project, a variant of the controlled landfill approach was proposed in 1990, entailing the following designs and operational steps:

1. Placing a high-permeability leachate collection and recovery system LCRS) under the waste. Liquid drainage capacity of this LCRS was designed to allow for collection of any likely amount of the supplemental liquid needed for bioreactor operation.
2. Filling the landfill cell to capacity while emplacing sensors for temperature, moisture, pH and pressure within the waste mass. Use only permeable daily cover (no soil). In this case the cover was greenwaste.
3. Covering the cell with a highly gas-conductive permeable layer, in this case tire shreds, with permeability estimated at >106 Darcys. Then capping with geotextile and a then a geomembrane.
4. Introducing liquid through multiple surface addition points spaced on approximately 25-foot centers. This was in fact economic using a grid of 13 scrap tire filled "injection pits" served by a network of metered hoses, similar to layouts for lawn and other controlled irrigation.
5. Adding liquid to meet criteria including (a) elevated moisture sensor readings, (b) a waste moisture content (around 40%) and (c) cell outflow ratio of at least 50% of inflow.
6. Applying slight vacuum (< 0.5 in w. g.) from the collection system to the permeable layer to withdraw gas as it is generated.

7. Automating the sensor data collection systems (see Augenstein and Yazdani, 1998). This sensor data collection system along with the gas measurements provides excellent feedback on bioreactor cells' performance and an avenue for the control of the bioreactor.
8. Utilizing the produced gas, mixed with other gas from the adjoining (conventional) landfill, to supply the engine-generator at the Yolo landfill for electricity production.

The following provides an overview of the results obtained with this two cell demonstration project over the past nine years (see Yazdani 1997 and Augenstein et al. 1998).

1. Demonstration cells. Dimensions of the test cells were 30 x 30 x 13 meters (100 x 100 x 40 feet). Moisture and temperature sensors were located in 3 layers of the "enhanced" (moisture added) cell and 2 layers of the control cell. (See Fig. 1 and 2 for oblique and cross section views).

2. Waste Source and Placement. Waste was from truck collection routes serving households, small businesses, markets, etc. Tonnages were carefully logged. Loads that were mostly of an inert nature were, however, diverted. A most important variation from conventional landfill practice is that lifts were covered with greenwaste rather than more typical cover soil. This use of greenwaste for cover left waste permeable to later moisture additions, and allowed some limited initial composting which elevated startup temperature as well.

3. Refuse Temperatures. Both cells experienced substantially elevated temperatures, ca. 45-55 oC, in the bulk of the waste on filling and thereafter. Figures 3 and 4 show temperature from the start of measurements in April 1995, to January 2003. Temperature elevation is attributed to limited aerobic composting on waste placement and also to anaerobic exothermic reactions, including methanogenesis, particularly in the enhanced cell, where it is beneficial in enhancing methanogenesis due to the rate acceleration, already noted above.

4. Moisture Flows and Water Retention. Figure 5 shows moisture flows entering and exiting the 9000 ton enhanced cell, and net liquid retention in the waste from the beginning of moisture addition in October 1996, to March 2003. To increase moisture levels initially, well water was metered in at superficial velocities averaging over the whole cell about 8 to 24 liters/meter^2-day (0.2 to 0.6 gallons/ft^2-day), an easily manageable amount of water addition even for a full-scale system. Once moisture criteria (above) were met, all leachate exiting the cells was recirculated continuously at low rates, equivalent to a precipitation of about only 0.75 meters (30 inches) per year percolating through the wastes. No liquid level buildup was seen in the injection pits. Moisture sensor readings quickly increased at nearly all points in the waste (Figure 6), a strong indication of good moisture distribution and allying concerns that moisture distribution would be uneven or incomplete. When moisture infiltration was stopped (between December 1998 and March 2000) the outflow also fell quickly, within days, to almost negligible levels, under 40 liters (10 gallons) per day for the cell as a whole (See Figure 5). This allayed the concerns that moisture outflow might not be easily controllable, even after water additions are stopped. Most of the necessary liquid infiltration was accomplished within 3 months. Liquid permeability of the waste of over 3 x 10^{-5} cm/sec is estimated from these moisture permeation results.

5. Methane Generation Enhancement. This was the most striking and important result of this project: Figure 7 shows the methane generation for the enhanced cell, the control cell, and a "normal" gas generation range expected from this mass of waste having methane productivity characteristic of a conventional landfill. Both the enhanced and control cells started with rapid methane generation, attributed to elevated temperature for both cells (due to composting of the cover and waste) in conjunction with an "as received" moisture of around 18% (see below) . However, in the control cell, the methane generation came to a near-complete stop quite suddenly, somewhat over a year after gas collection started. This observation supports the expectation for "dry tomb" landfills, from which moisture is excluded, where landfill gas generation can slow or, as in this case, halt due to moisture limitation. Only additional moisture, if and when infiltrating, would result in continued gas production, that likely taking place over greatly extended periods of many decades.

6. Rate Constant for Methanogenesis (Waste Decomposition). The rapid decomposition of the enhanced cell indicates a k value of greater than 0.4 $year^{-1}$, over fivefold higher the "normal" range of k = 0.04-0.08 $year^{-1}$ (Figure 8). For measured gas recovery over the initial 6 year interval, a "standard" plot using an ultimate yield of 90 liters CH4/kg (1.4 ft^3 CH4/lb) of waste placed suggests a k value of 0.45. This may be the highest decomposition rate observed for such a large mass of waste. When plotted with the same assumed yield, the k of the control cell drops to near zero after the initial year, placing in stark contrast the effect of presence versus absence of moisture.

7. Volume Reduction. The rapid conversion of solid material to gas is associated with rapid reduction in waste volume for the enhanced cell, compared to the control. (Figure 9). What is also interesting from the moisture data and Figure 9 is that settling in the control cell was lower than expected from methane production data, suggesting that it was moisture addition combined with solids and not simply the conversion of solids to gas alone, that resulted in the large consolidation of waste noted in the enhanced cell.

8. Later core sampling. In October 1999, cores from the two cells were collected for analysis (see Barlaz et al, 2000 for details). A notable feature was the relatively uniform increase in moisture content of about 15-20% (wet basis) of the enhanced cell core relative to the control cell core, which had no liquid added (Figure 10). These core moisture readings suggest that moisture permeated most of the cored sample in the enhanced cell and further support sensor results.

DISCUSSION AND CONCLUSIONS

The sensor readings, core moisture results, methanogenesis and volume reduction all indicate that it was possible for a slow, multi-point surface moisture addition approach (without injection wells) to give good moisture distribution throughout the mass of waste. This good moisture distribution with slow moisture percolation occurred despite some prior modeling studies of moisture addition suggesting that much more rapid additions would be required. The footprint (lateral width) of the landfill, 100 x 100 feet, is probably sufficient in terms of giving representative results for liquid distribution. The demonstration cell depth of 40 feet is on the shallow end for current landfills. Liquid permeation with larger cells, of greater dimensions and depths is a major objective of future research. The liquid infiltration rates, even if infiltration were to be slowed by compaction at greater depths, are quite promising. These findings indicate that moisture addition can be delayed, until after a surface membrane or impermeable cover with an efficient gas collection system is in place. This sequence allows best possible energy recovery and greenhouse gas emission control, by avoiding major quantities of gas to be produced prior to landfill cell closure and initiation of gas extraction and utilization. Another concern, that moisture outflow might not be easily controllable under some circumstances, can also be allied from the results presented.

Perhaps the greatest impediment to the rapid adoption of the ABC Landfill technology, are the regulatory issues faced by any new landfill technology. As part of this program, the Yolo demonstration and scale-up have undergone intensive review by a wide range of California regulatory agencies, as well as the US EPA. Numerous issues have been studied for the benefit of the regulatory agencies by the County and also IEM (detail omitted here). Examples of issues addressed by the Project team have been head buildup over base liner, liquid containment, and local air emissions (including those from the added gas used in power generation). The Yolo County program has benefited from inclusion in EPA's "Project XL" Program, which essentially allows for improved regulatory flexibility in return for added environmental benefits (Yazdani and Augenstein, 2001). The ABC Landfill technology provides both a technological and a regulatory model for reducing greenhouse gas emissions from solid wastes, as one of the multiple benefits derived from such processes.

The success of the Yolo County Demonstration Project, allowed this project to advance to a full-scale ABC Landfill bioreactor operation, initiated in 2001. This project currently operates two full-scale cells, the first, and larger one, an anaerobic cell containing over 70,000 tons of municipal wastes, and a smaller (30,000 tons) aerobic cell.. For the anaerobic cell, moisture additions to the cells has been via gravel filled trenches extending horizontally at 3 levels within the waste. As for the smaller cells, this landfill is also instrumented with sensor and automatic data collection system. So far, it appears that moisture addition is slower because of lower permeability of the deeper, less permeable waste. Other results including methane generation are supportive of the demonstration project results. This work is ongoing, with initial data to be reported by the next Conference.

As already mentioned above, the ABC Landfill abates greenhouse gases through three routes:
1. Efficient and near-complete capture of methane emissions; and maximization of methane recovery in a short period (< 10 years).
2. Use of the methane for energy, in particular electricity generation, offsetting fossil fuel use elsewhere.
3. Carbon sequestration in long-term repositories, designed to remain stable for thousands of years.

These are listed in their relative order of importance, with the first, methane emissions reduction, representing a greater reduction in greenhouse forcing than the other two. Whatever carbon is not converted to methane (and a similar amount of CO_2) during methanogenesis, will remain in unaltered essentially indefinitely (hundreds of years), in particular the wood wastes which do not decompose (Micales and Skog. 1997). Presently, in the United States over 150 million tons annually of municipal solid wastes are buried in landfills, with a high content (ca. 30+%) of photosynthetically fixed carbon. This in fact is what US landfills are doing now. The ABC Landfill technology can increase the greenhouse benefits obtained from landfills, particularly by greatly reducing fugitive methane emissions and increasing energy recovery.

The greenhouse gas abatement from wide application of the ABC Landfill technology to US municipal wastes has been calculated accounting for (1) likely extra (incremental) methane emission abatement and (2) the energy offsets from assuming an 80% energy use of the extra gas obtained. Sequestration was not counted in the analysis. The estimated benefits are of the order of 100 million tons CO_2 equivalent per year with costs ranging from $1 to 5 per ton CO_2 equivalent. (I E M, Inc. 1999). Experimental findings to date continue to support these potential climate benefits. Carbon sequestration would add another 10 to 20% to this figure, depending on assumptions about alternative fates of carbon and other factors.

Alternative technologies to the management of solid wastes have been proposed but none appears as benign environmentally, both in the short and long-terms, as the ABC Landfills. Incineration with power generation (waste-to-energy) plants are well established technology, but the stack gas emissions controls are expensive and the residual ash (still a considerable fraction of the waste) must generally be buried in landfills. Composting does not produce power, results in a large volume of rejects (to be landfilled), and the compost is often difficult to market. In-vessel anaerobic digestion (methanogenesis) processes, popular in Europe, overall are over an order of magnitude more expensive than bioreactor landfills and do not actually recover as much methane gas and produce very little net power. In the longer-term, we can envision bioreactor landfills that can recover the degraded and stabilized waste for other applications, thus making the material flow in our societies truly renewable. This however, requires a commitment to avoid introducing into society and commerce materials and products not easily recycled.

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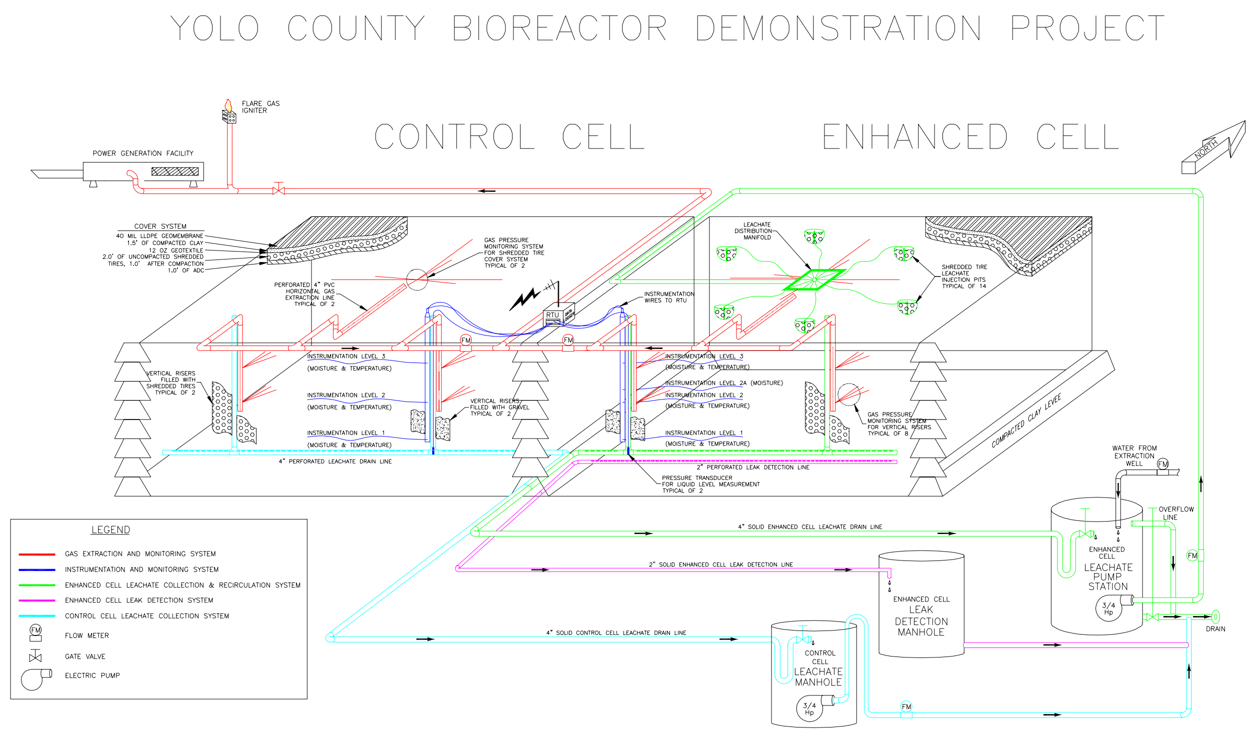


FIGURE 1- OBLIQUE VIEW OF 9000-TON SCALE DEMONSTRATION CELLS

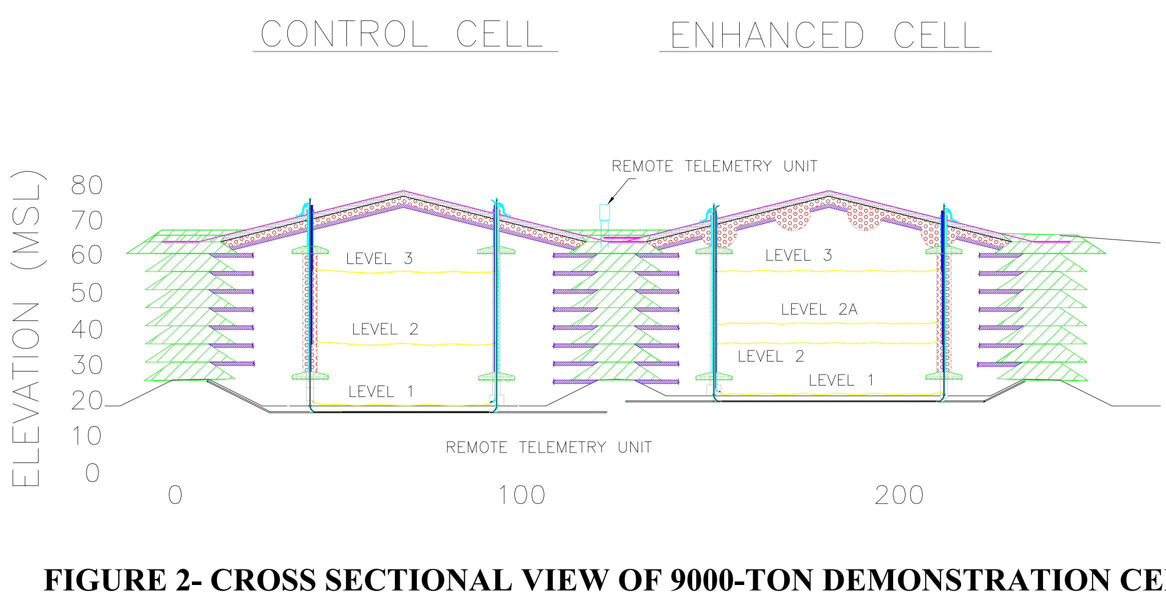
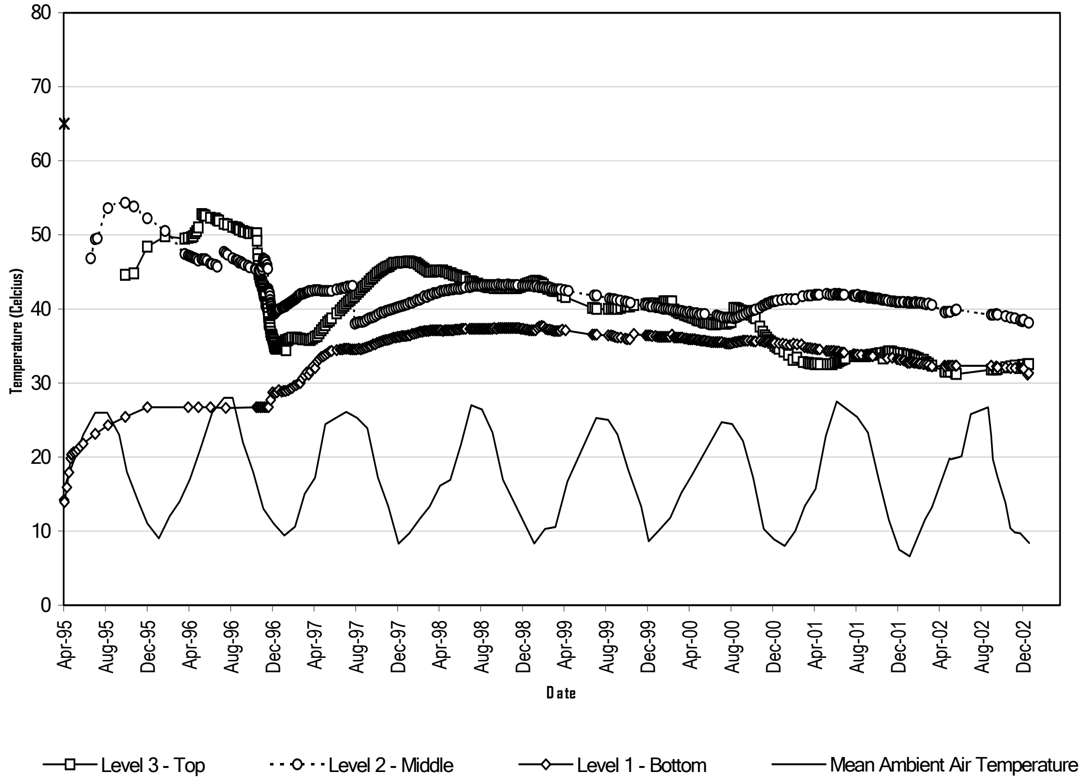


FIGURE 2- CROSS SECTIONAL VIEW OF 9000-TON DEMONSTRATION CELLS



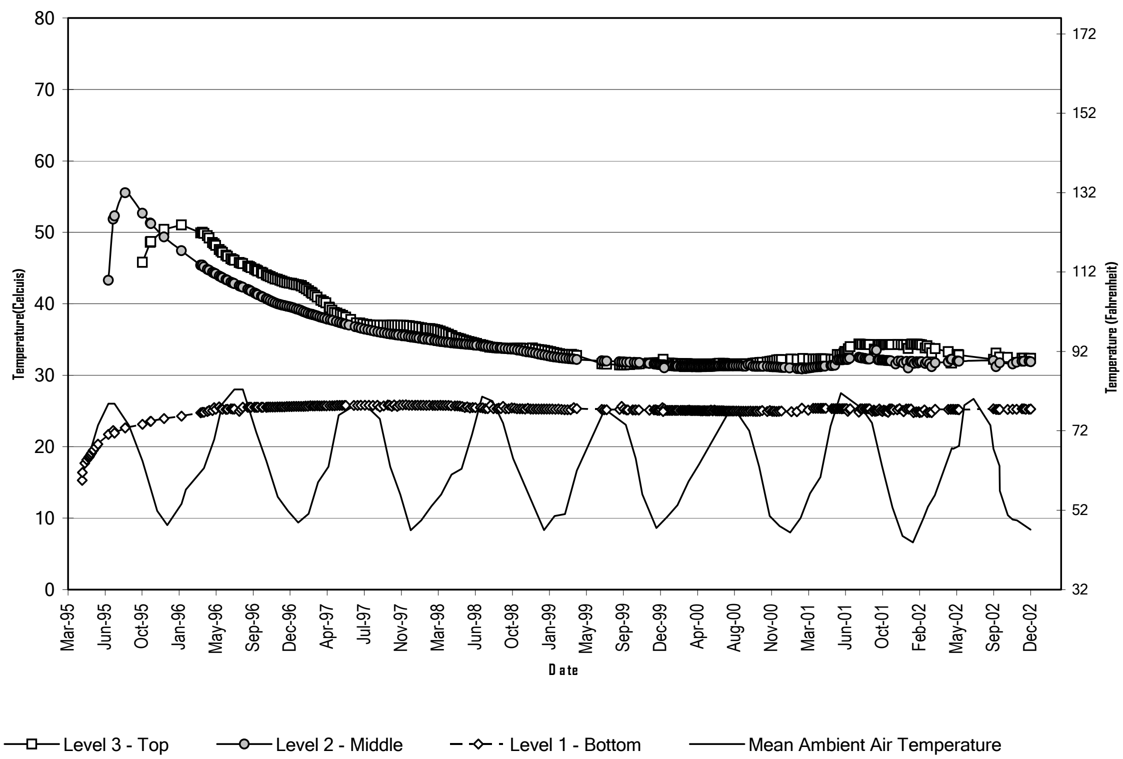


FIGURE 3 (TOP) ENHANCED CELL TEMPERATURE VS. TIME

FIGURE 4. (BOTTOM) CONTROL CELL TEMPERATURE VS. TIME

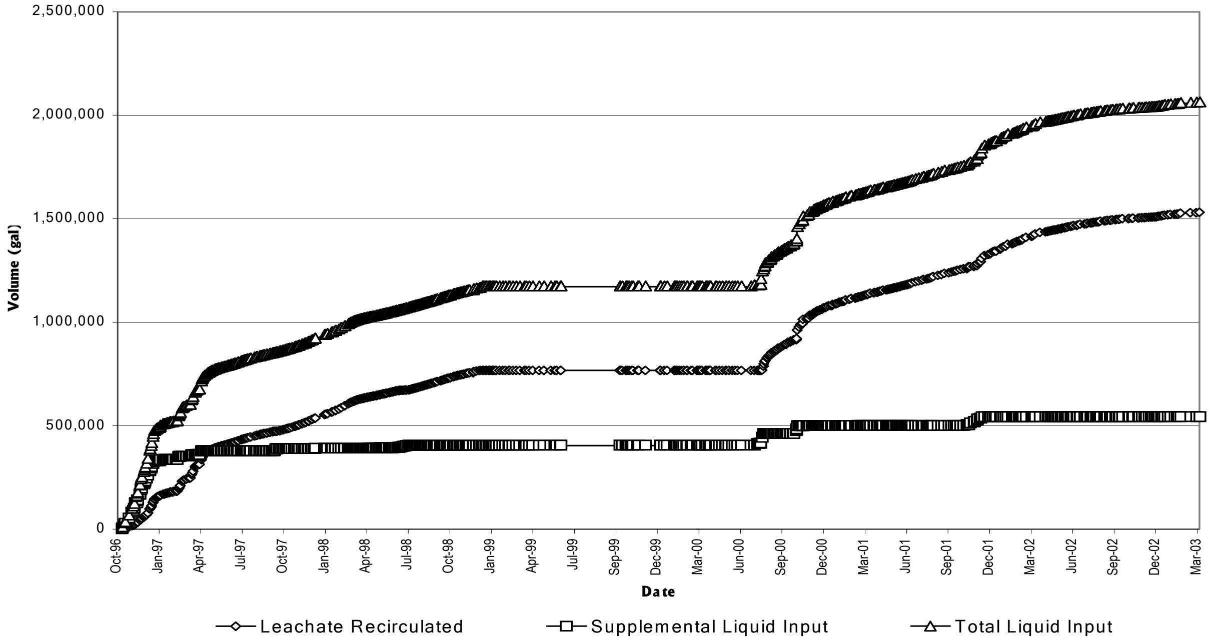


FIGURE 5. ENHANCED CELL MOISTURE INFILTRATION VOLUME VS. TIME

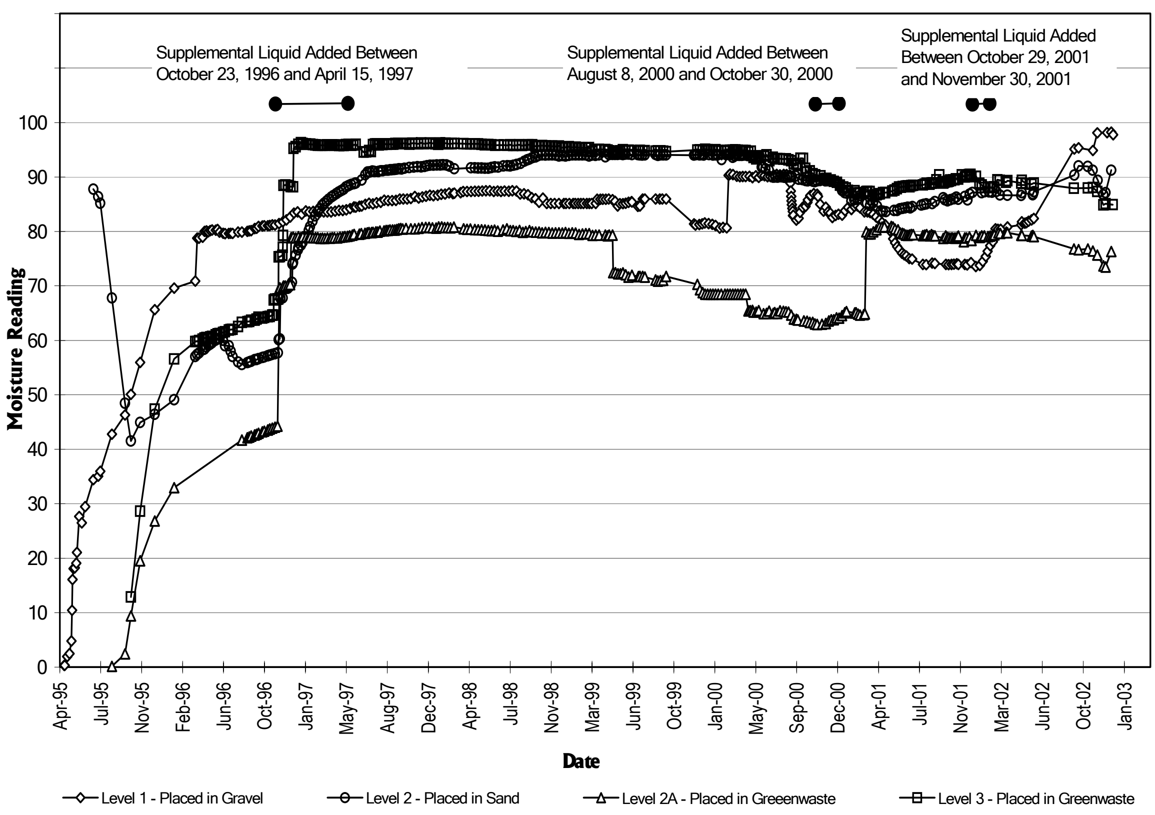


FIGURE 6 ENHANCED CELL MOISTURE SENSOR READINGS VS. TIME

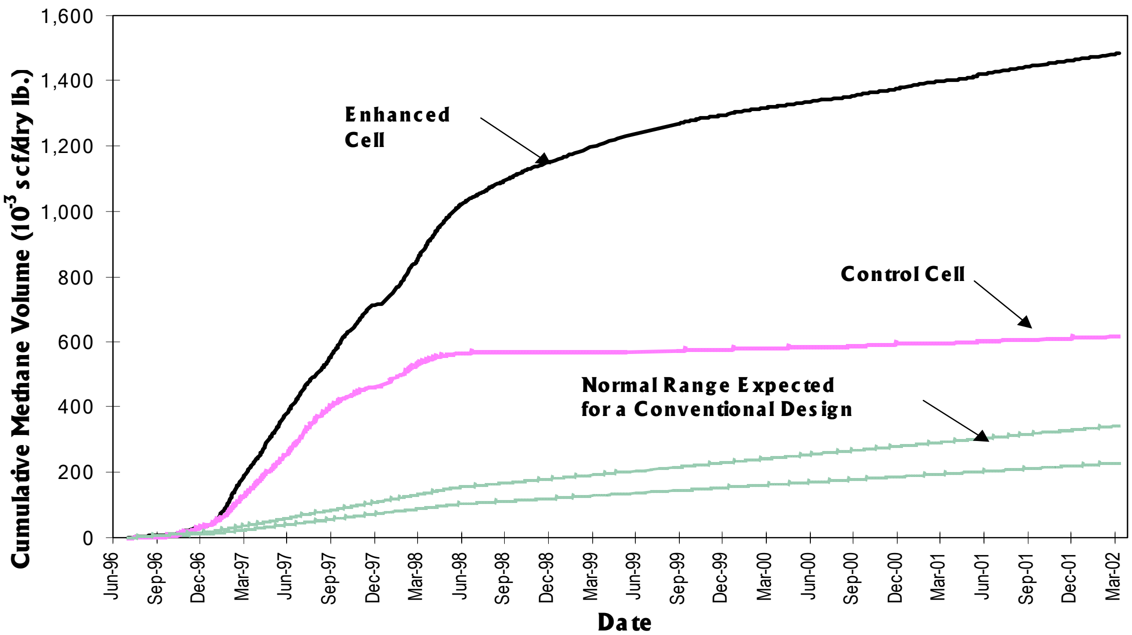


FIGURE 7 ENHANCED AND CONTROL CELL CUMULATED GAS GENERATION VS. TIME

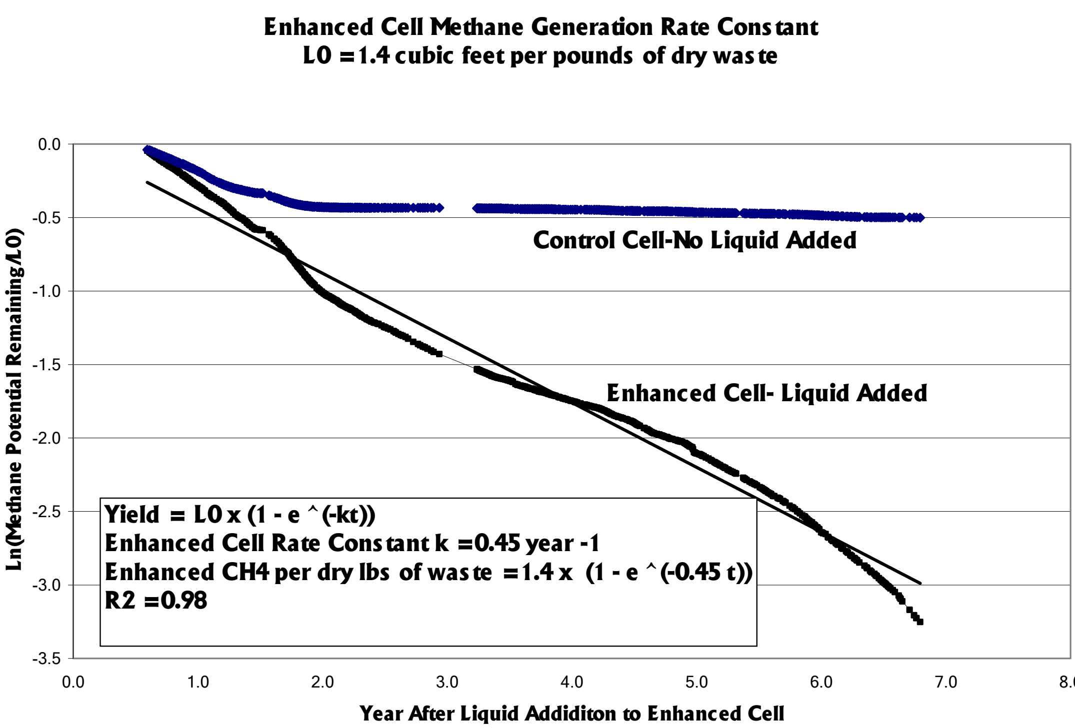


FIGURE 8 RATE CONSTANT CALCULATION FOR CONTROL AND ENHANCED CELLS

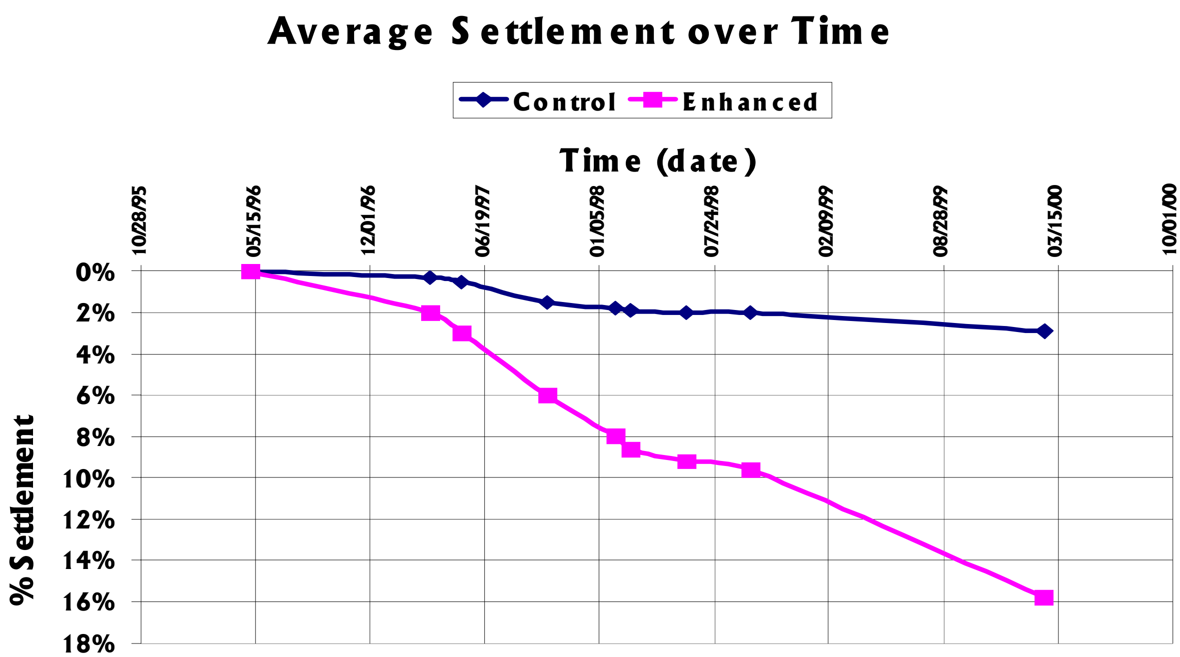


FIGURE 9. VOLUME REDUCTION VS TIME IN CONTROL AND ENHANCED CELLS

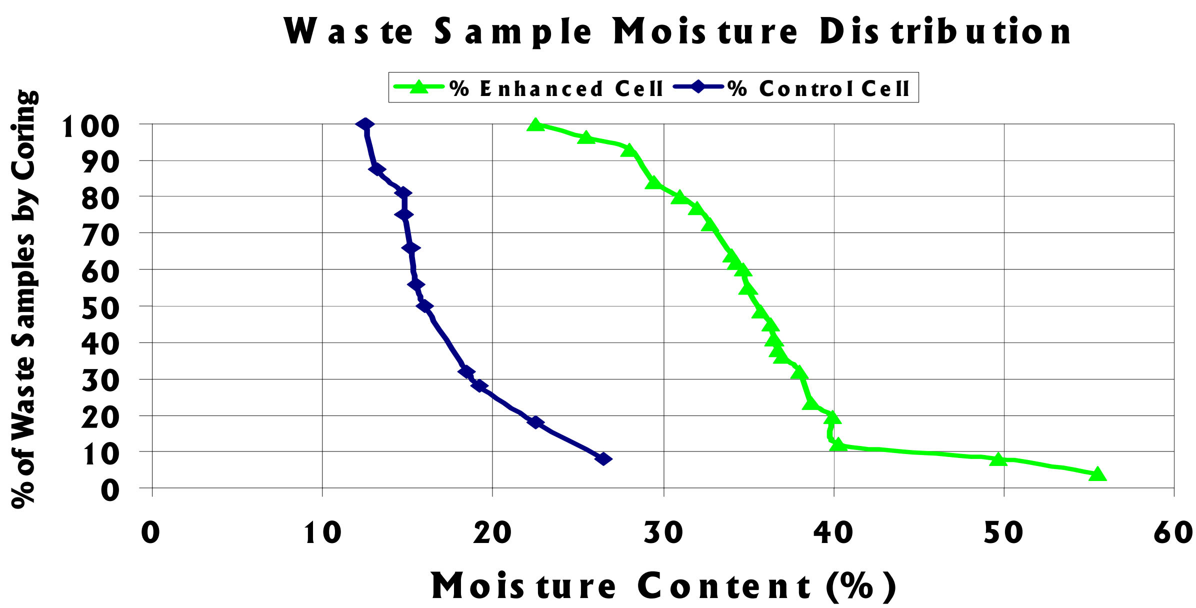


FIGURE 10: MOISTURE DISTRIBUTION IN CONTROL AND ENHANCED CELL CORE SAMPLES