

# **CONTROLLED LANDFILL PROJECT, YOLO COUNTY, CALIFORNIA A REVIEW OF RESULTS SINCE 1994<sup>1</sup>**

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## **ABSTRACT:**

An advanced landfill bioreactor approach termed “controlled landfilling” is continuing development at the Central Landfill, in Yolo County, California. Two test cells have operated at Yolo at a scale of 9,000 tons since 1994. Operations have recently started at fullscale in cells with a total of over 100,000 tons of waste. Expected benefits to waste managers include maximum methane energy recovery and substantial early waste volume reduction, with associated potentials for landfill life extension and more capacity. Expected environmental benefits include earlier waste stabilization and minimization of landfill-gas related emissions. Methane generation and waste stabilization have been accelerated in a 9,000 ton test cell through managed additions of supplemental water and leachate. The first-order rate constant for methanogenesis has been over 0.4 year<sup>-1</sup>, over fivefold “normal” for a waste mass of this size. A control cell has been operated in parallel. Methane capture is maximized, with emissions minimized, by surface membrane overlying a surface permeable layer operated at slight vacuum to conduct gas to collection. Cells have been intensively instrumented to determine performance. Corresponding to solids’ reduction to gas, there has been rapid waste volume reduction in the enhanced cell. Slow and controllable liquid additions have been successful in achieving good measured moisture distribution as well as the rapid waste decomposition. A scaled-up anaerobic bioreactor of 70,000 tons has been started and is in early monitoring. Details, and results obtained since 1994, are presented below.

## **INTRODUCTION**

The Yolo County, California, Department of Public Works has been testing an advanced bioreactor landfill strategy (“controlled landfilling”) at its Central Landfill site outside Davis since 1994. Support has come from multiple sources including the California Energy Commission, the US Department of Energy’s (DOE) National Energy Technology Laboratory (NETL), the California Integrated Waste Management Board, (CIWMB), IEM, Inc., and Yolo County itself. This paper presents a summary—necessarily abbreviated--of encouraging results that have been obtained since project inception. Readers desiring more detail may consult Yazdani, 1997 Augenstein et al. 1998 Augenstein et al. 2000 Yazdani and Augenstein, 2001.

## **BACKGROUND**

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<sup>1</sup> Presentation at the Third International Methane and Nitrous Oxide Mitigation Conference, Beijing, China November 17<sup>th</sup> to 21, 2003. Conference co-sponsored by the China Coal Information Institute, US Environmental Protection Agency, UN Development Program, International Energy Agency Greenhouse Gas R&D Programme, 15 other international co-sponsors.

Conventional or “dry tomb” landfill problems. With “conventional” sanitary landfilling as regulated until now, (United States regulations) landfilled waste can remain relatively dry for many years after placement. It is now recognized that past “dry tomb” landfill practices entail long-term risks and other problems. Problems include gas collection inefficiencies, and fugitive gas emissions before collection starts and after collection stops. Other problems and issues associated with long terms of landfilled waste decomposition include the needs undecomposed waste poses for ongoing operator attention. These are needs associated with ongoing landfill subsidence, gas system and containment maintenance needs, and the like.

Landfill related climate and energy issues: Landfill methane, by various accountings, may make a difference in, ie add, over 5% of the total increase in radiative forcing due to buildup of all greenhouse gases in the earth’s atmosphere each year. In simplified terms, landfill gas alone may add 5% or more to the “greenhouse effect”. The greenhouse potency of methane gas (tenfold that of CO<sub>2</sub> on a volume basis) is such that almost any strategy to recover more of landfill methane will be “greenhouse cost effective” relative to other greenhouse gas abatement strategies. (For a discussion of this greenhouse cost effectiveness see Nordhaus, 1991. For one discussion of greenhouse cost effectiveness of landfill gas recovery see Augenstein, 1992)

Landfill gas energy use also represents conservation of an energy resource otherwise normally wasted, and can contribute rather significantly to US and other nations’ energy security: Present failure to use methane (including flaring of collected methane, and uncollected methane fugitive to the atmosphere) represents a not-inconsiderable loss of fuel, even now equivalent to over 150,000 barrels of oil a day for the US. In alternate terms of electric generation, unexploited electric generation potential in the US can be estimated even now at between 4 and 7 GWe. (see Hughes et al. 1994) This much power could meet electrical requirements associated with all activities of 3 million or more US citizens. For many countries around the world, landfill gas fueling of electric generation to full potential could typically meet roughly 1% of electricity needs. Much of the failure to use methane to potential is due to the unpredictability, variability and low rate of recovery of landfill methane. Lower recoveries lessen economies of scale. Unpredictable gas recovery makes projecting of landfill gas energy equipment generally risky. Uncertainties bar much methane exploitation, or very often lead to undersizing of energy equipment and less-than-full energy use of recovered methane at given sites.

Landfill gas energy use also represents a return of otherwise unusable organic waste discards, albeit in the form of energy, to the economic mainstream. In allowing re-use of otherwise unusable waste components, the LFG energy use also comprises a form of recycling.

As noted by several workers, it should be possible to design and operate landfills to overcome many of the difficulties with present “conventional” landfills. In fact landfills are one type of “reactor” in which composting, defined as the managed biological decomposition and treatment of waste organics, can be made to take place in

controlled fashion. A recent, popular generic term for landfills managed to accelerate and control methane generation (and often, recovery) is the “bioreactor landfill” or “controlled landfill”. This idea has been proposed in some detail as far back as 1976 (for example Augenstein et al. 1976, and work by Robert Ham and his co-workers, notably Prof. M. Barlaz, and Fred Pohland and co-workers)

Waste decomposition and methane generation can be promoted by means including control of moisture, temperature, pH and nutrients. In particular, elevated moisture (by conventional landfill standards) is regarded as essential for accelerating methanogenesis (for example see Halvadakis, et al. 1983) It is less well recognized that temperature elevation can also provide major benefit (An activation energy  $E_a$  ca. 15 kcal/mol implies rate constant doubling for each  $\approx 10$  C temperature increase over a span of 10-50+ C [Ashare et al. 1977]). Generally, and for US use, a process must (a) pass regulatory scrutiny, (b) integrate easily with current landfill practice, and (c) conform to particular local regulatory requirements (in Yolo County’s particular case those of California as well as the US Federal code). With these in mind, water and temperature were the sole enhancement techniques used, although other enhancement strategies would have been possible.

#### YOLO COUNTY PROGRAM

For the present program, for which planning began in 1989, a variant of the controlled landfill approach was proposed in 1990 to the California Energy Commission for Yolo County, California. This proposed landfilling entailed a sequence of:

- 1...Place a high-permeability leachate collection and recovery system (LCRS) under the waste. Liquid drainage capacity of this LCRS was such as to allow drainage of any likely increased amount of leachate due to the supplemental liquid needed for bioreactor operation.
2. Fill the landfill cell to capacity while emplacing sensors. Use only permeable daily cover (no soil). In this case the cover was greenwaste.
3. Cover the top waste surface of the filled cell with a highly gas-conductive permeable layer, in this case tire shreds with permeability estimated at  $> 10^6$  Darcys. Then cap with geotextile and a gastight polyethylene geomembrane. The geomembrane prevents gas emissions to the atmosphere and confines gas to the permeable layer so as to allow very high efficiency gas recovery through the permeable layer. .
4. Introduce liquid through multiple, metered 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. The arrangement is similar in design (and in its low cost) to layouts for lawn and other controlled irrigation.

5. Add liquid slowly, to meet criteria including (a) elevated moisture sensor readings, (b) a planned waste moisture content (around 40%) and (c) cell outflow ratio of at least 50% of inflow. Recirculate liquid leachate outflow back through the waste. (Further discussions of liquid percolation rates are presented below)

6. Apply slight vacuum (< 0.5 in w. g.) from the collection system to the permeable layer to withdraw gas as it is generated. The slight vacuum beneath the geomembrane prevents essentially all gas emission to the atmosphere, otherwise possible through any fissures developing in the geomembrane

The produced gas, mixed with other gas from the “conventional” landfill areas, is used to supply the engine-generator system at the Yolo landfill.

The following provides an overview. Much more information is found in references cited above, particularly Yazdani 1997 and Augenstein, Yazdani et al. 1998.

Waste Selection and Placement. Waste was typical residential or commercial from packer truck collection routes serving households, small businesses, markets, etc. Tonnages were carefully logged. Loads that were inert were, however, diverted. The 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. The test cells were filled between late 1994, and early 1995.

Demonstration cells. Specific features of the test cells, 100 x 100 x 40 feet. are shown in the oblique view in [figure 1](#). Moisture and temperature sensors were located at 3 layers of the moisture added “enhanced” cell and 2 layers of the control cell (cross sections of cells shown in [figure 2](#)). Ambient temperature (running weekly average) at the cell site was also recorded by a small weather station of type used widely by the US Forest service.

Refuse temperatures. Multilevel temperatures recorded throughout the waste from April 1995-January 2003 are shown in [figures 3 and 4](#): (Also shown in these figures for comparison are ambient site temperatures, recorded in the lower line oscillating from each summer to winter throughout the 7+-year interval.) Both cells experienced very substantially elevated temperatures, ca. 45-55 C in the bulk of the waste on filling and thereafter. The waste temperature elevation is attributed to limited aerobic composting on waste placement and also to exothermic reactions including methanogenesis. Heat generation from methanogenesis is thought particularly important in the enhanced cell, which maintained its higher temperature while the control trended more rapidly to cooler temperatures. This elevated temperature is a welcome and clearly beneficial factor in enhancing methanogenesis. This is because of the rate acceleration, noted above, at elevated temperature.

Moisture flows and waste moisture retention from 1995 to 2002 .[Figure 5](#) shows cumulated moisture flows into, and leachate exiting the 9000 ton enhanced cell,

along with net liquid retention in the waste. Considerable modeling study has projected need for rapid liquid additions for optimal moisture distribution into bioreactors. But in this test the liquid additions and recirculation were relatively cautious. Liquid addition was “slow” in order to limit head buildup over the base liner and also to minimize waste instability effects due to liquid pore pressure (and limit moisture-related factors like side seeps and increased lubricity/plasticity from increased moisture). An added objective was to develop data necessary to reassure regulators. For initial moisture elevation, well water was metered in at modest superficial velocities (averaged over the whole cell and based on empty cross section) typically averaging about 0.2 to 0.6 gallons.ft<sup>2</sup>.day. This rather modest addition rate was estimated as adequate to elevate cell moisture to criteria in about 3 months, as did occur. Once moisture criteria (above) were met, all leachate exiting the cells was combined with entering well water and simply recirculated continuously at low rates.

An early concern was that moisture distribution and elevation with slow additions and the multipoint distribution system would be incomplete. However the moisture sensor readings quickly elevated at nearly all points in the waste, a first indication of good moisture distribution. Sensor moisture readings recorded in the interval from April 1995 to January 2003 are shown in [figure 6](#). It is important to note that the rates of moisture addition at 0.2-0.6 gal/ft<sup>2</sup> day were very easily manageable. Later moisture recirculation rates were slow by various standards. The maximum moisture infiltration rates during recirculation would be equivalent to precipitation of about 30 inches per year percolating through the waste.

Another concern of many, has been that moisture outflow might not be easily controllable under some circumstances. However, in later test, when moisture infiltration was stopped (between December 1998 and March 2000 as seen in [figure 5](#)) the outflow also fell quickly, within days, to almost negligible levels, under 10 gallons per day for the cell as a whole. This is seen in [figure 5](#) from the cumulated inflow and outflow (and other observations) in the interval of December 1998 to March 2000, which were essentially unchanged. This degree of manageability (for this or similar configuration) suggests an additional degree of controllability for the “bioreactor” landfill.

A phenomenon was observed in the enhanced cell in which the base hydrostatic head rose slowly from zero to a peak level equivalent to water level in a U-trap in the LCRS outflow, then dropped abruptly to zero. (Detail is omitted here) This result, initially surprising, is now thought to be due to air entrapment in the particular drainage line used. It is avoidable with straightforward design modifications.

At the 9,000 ton scale, the liquid infiltration posed no problem. No liquid level buildup was seen in the injection pits, so liquid entered the waste easily, and most of the necessary liquid infiltration was accomplished within 3 months. Liquid permeability of the waste of over  $3 \times 10^{-5}$  cm/sec is estimated from these moisture permeation results.

Methane generation enhancement was striking. Figure 7 (gas data from June 1996 to April 2002) shows the cumulated methane generation for the enhanced cell, the control cell, with both of these compared to the “normal” expected for this mass of waste (the “normal” from the 19-landfill study of Vogt and Augenstein 1997, and sources including EMCON). This is one of the most important findings of the project. The accelerated methane recovery rates have major implications for improved methane energy recovery and, with high efficiency gas capture as in this demonstration, emission and odor control.

The methane generation behavior of the control cell in figure 7 is quite interesting: The control cell also started with rapid methane generation. This rapid start is thought due to its initial elevated temperature (figure 4) in conjunction with its “as received” moisture around 18% (see later core sampling, below). However the methane generation came to a near-complete stop quite suddenly, somewhat over a year after gas collection started (the absence of methane generation was confirmed by auxiliary tests, detail omitted). This observation supports the often-discussed (but comparatively undocumented, at least by detailed field measurements) expectation for “dry tomb” landfills from which moisture is excluded. The slowing and limit to waste decomposition in the “dry tomb” is confirmed by these control cell results.

Rate constant for methanogenesis (ie decomposition to methane, figure 8). The rapid decomposition of the enhanced cell, as seen from 6 years’ results, indicates a k value over  $0.4 \text{ year}^{-1}$ , over fivefold the “normal” range of  $k = 0.04\text{-}0.08 \text{ year}^{-1}$ . For these first 6 years, a “standard” plot using assumed  $L_0$  of  $1.4 \text{ ft}^3 \text{ CH}_4/\text{lb}$  suggests an apparent k value of  $0.45 \text{ year}^{-1}$ . At the assumed  $L_0$  the remnant methane potential would already be down below 15% of the total. However remnant methane generation, and degree of stabilization needs more confirmation through future measurement. In any event this high rate constant is also encouraging and the rate constant may be the highest seen for such a large mass of waste. When plotted with the same assumed yield, the control cell failure to approach the control cell methane generation endpoint is clearly evident.

Volume reduction. The rapid conversion of solid material to gas is associated with rapid reduction in waste volume (Figure 9). This fractional volume reduction in the moist, enhanced cell corresponded closely to the fraction of solids converted to gas. (Data are only to 2000, and updated measurements are expected to show further volume reduction). What is also interesting from the moisture data and figure 9 is that solids conversion to methane alone gave little apparent volume reduction. Only the “enhanced” 9000 ton cell with moisture added showed the fractional consolidation expected based on the waste solids converted to gas. The beneficial effects of recirculation and its cost effectiveness have also been discussed by Harris and Shafer (2002) and Sprague (2002) among others.

Later core sampling. In October 1999, it became possible to take cores from the waste and sample for moisture. Details were presented elsewhere in Barlaz et al, 2000. In addition to results in Barlaz et al. a notable feature of this waste core analysis was the moisture distribution shown in figure 10. The core sample results

are plotted in similar form to a sieve analysis, with the fraction of core length, (i.e. normalized core length) above a given moisture content (expressed on wet basis) plotted from each cell. These core results suggest for the cored waste, that there was in essence a relatively uniform elevation of moisture content of about 15%-20% (wet basis) for the enhanced cell, relative to the control which had no liquid added. There is very little overlap between cores from control and enhanced cells. These core moisture readings, suggest that moisture permeated most of the cored sample in the enhanced cell and further support moisture sensor and other results.

Implications of results: surface moisture additions 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 elevation throughout the mass of waste. This good moisture distribution with slow moisture percolation occurred despite studies indicating that much more rapid additions should be required. The footprint (lateral width) of the landfill, 100 x 100 feet, is probably reasonable in terms of giving representative results for liquid distribution. The demonstration cell depth of 40 feet is on the "low end" for current landfills. The freely permeable greenwaste and similar daily covers, allowing greatest moisture permeability, should be quite practical for most landfills. It will be of great interest to see how liquid permeation behaves at greater waste depths and with other liquid introduction approaches. The liquid infiltration rates, even if infiltration should be slowed by compaction at greater depths, are still quite promising.

The findings indicate that moisture addition might be delayed, until after a surface or other efficient gas collection system is in place, as in the Yolo demonstration. This sequence, part of the original proposal in 1990, permits maximum energy recovery as well as gas emission and odor control.

#### OTHER ISSUES:

Regulatory : The Yolo County program has benefited from inclusion in the United States EPA's project XL, an EPA program which essentially allows for improved regulatory flexibility in return for environmental benefits (Yazdani and Augenstein, 2001). As part of this program, the Yolo demonstration and scaleup have undergone intensive review by the wide range of involved 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 IEM (detail omitted here). Examples of areas examined have been head buildup over base liner, containment, and likely local air emissions (including those from the added gas energy use). Some of the environmental implications are reported above (ie the greenhouse gas implications), and the project team will report other results of their work in the future.

#### FULLSCALE TESTS

The fullscale landfill bioreactor operations were initiated at Yolo in 2001. Fullscale cells include an anaerobic cell containing over 70,000 tons of MSW, and a 35,000 ton 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. 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 encouraging. Additional fullscale results, once obtained, will be the topic of future presentations.

Supervisory Control and Data Acquisition (SCADA) system. As in the 9,000 ton cell (refer to Augenstein and Yazdani, 1998) the collection of data from the new fullscale cells is automated. The data presented above for the 9000 ton demonstration cells illustrate the excellent performance of the early version of the system for automated data collection. At larger scale, this system has performed well, although there has been breakdown of some sensors (or most likely their leads) Even with the sensor loss (some loss was expected), the SCADA system performance has been meeting all expectations at the larger scale as well. This sensor system provides excellent feedback on bioreactor cells' performance and provides an avenue for the close control of the bioreactor.

#### CONTROLLED LANDFILL: GREENHOUSE AND CARBON SEQUESTRATION IMPLICATIONS

As operated at Yolo County, the controlled "bioreactor" landfill facilitates greenhouse gas abatement through three routes. The first is the close control and efficient capture, that prevents fugitive methane emissions that otherwise occur from landfills. The second is the use of the methane for energy, to offset fossil fuel use elsewhere. The third route for greenhouse gas abatement is via carbon sequestration.

It is worth emphasizing that one of the best possible avenues for present US carbon sequestration is the burial within the United States of over 150 million tons annually of waste. This waste is high (ca. 30+%) in photosynthetically fixed carbon. This in fact is what US landfills are doing now. However the controlled landfill can further improve the greenhouse benefits obtained.

The carbon entering landfills has two possible fates. One is the carbon conversion to methane in landfill gas, which can be recovered efficiently, and used as fuel. Methane from decomposition of wastes (nearly all decomposing waste carbon is photosynthetically fixed) has greenhouse benefit so long as the methane is used for energy. This energy use offsets fossil fuel combustion that would otherwise occur elsewhere. The controlled bioreactor landfill maximizes recovery of methane to full potential, for fuel. The second possibility is for the carbon to remain sequestered in the landfill. Much carbon including that of wood-based products (see for example Micales and Skog, 1997) does not decompose at all. An option providing further greenhouse benefit is to assure that the undecomposed carbon is kept sequestered by containment in the landfill. To maximize sequestration and offset fossil CO2 emissions elsewhere, waste containment should be for times of at least several hundred years. This is the time necessary for carbon dioxide from fossil fuel combustion, emitted contemporaneously with the waste landfilling, to partition into the ocean. This option (as opposed to composting, or the slow late-stage aerobic decomposition of waste) can be facilitated by long-term waste containment and carbon sequestration with the controlled landfill.

The greenhouse gas abatement from wide application of the controlled landfill to US waste has been calculated accounting for (1) likely extra (incremental) methane emission abatement and (2) the energy offsets from using a (presumed) 80% energy use of the extra gas obtained. Sequestration was not counted in the analysis. The estimated benefits are of the order of 50-100 million tons CO<sub>2</sub> equivalent per year with attractive costs, ranging from 1 to 5 dollars per ton CO<sub>2</sub> equivalent. (I E M, Inc. 1999). Experimental findings to date continue to support these potential climate benefits.

## OVERVIEW AND SUMMARY

The above discussion has been brief, due to space and other constraints. Much more detail on all aspects of the Yolo project will be available and the project team plans to present this information at SWANA and other symposia.

To summarize, controlled “bioreactor” landfill tests in Yolo County, California have had objectives including

1. Reduction to minimal levels of methane emissions of waste masses to which it is applied.
2. Near-complete elimination of Volatile Organic Compounds (VOC's) that are of concern as local air pollutants
3. Completion of decomposition over shorter terms, reducing risks to the environment and reducing long-term landfill gas and other management costs
4. Reduced costs for post-closure landfill care and landfill gas systems operations and maintenance due to earlier completion of landfill gas generation and waste stabilization.
5. Maximizing rate and yield of methane recovery. and completion of decomposition more predictably, so that landfill-gas-fueled energy equipment may be appropriately sized to make full use of the generated gas
6. Better economies of scale for energy use of greater quantities of captured gas
7. Leachate quality improvements, and correspondingly reduced threats to groundwater
8. Reduced or eliminated costs for off-site disposal or other treatment of landfill leachate

Some notable experimental conclusions and findings to date are

1. The demonstration accomplished a substantial acceleration of methane generation with an apparent rate constant of  $k = 0.045 \text{ year}^{-1}$ . This is over 5 times the “normal” usually seen (0.04 to 0.08 year<sup>-1</sup>). This is attributed to the combined effects of elevated temperature and the elevated moisture levels.
2. A slow, multipoint surface liquid addition approach gave well-distributed elevated moisture throughout the waste. This as evidenced by (a) moisture sensors, (b) the substantially accelerated methane generation, (c) the rapid volume reduction, and

(d) core samples. Slower liquid additions than recommended in several studies were very effective in this test.

3. The “dry tomb” behavior—an early cessation of methanogenesis at much less than full yield in dry control cell waste—has been confirmed experimentally in this demonstration

4. From comparing enhanced and control cell data, added moisture, along with waste conversion to methane, would appear necessary to give greatest volume reduction and associated potential for future landfill capacity gain.

5. From this and similar past trials (Mountain View, CA), it appears that helpful temperature elevation to accelerate methanogenesis and stabilization can be accomplished straightforwardly and at low cost. The temperature elevation is attributed in part to limited composting, easily accomplished by steps during filling of waste, combined with later exothermic reactions in the waste

6. The use of multiple sensors, in combination with an appropriate supervisory data acquisition and control system, allows close control and adjustments

Although there are multiple benefits, and encouraging findings, there are also areas that need to be addressed. These include in particular, the stability issues that occur with side slopes, and several design/operational factors such as those that relate to liquid addition.

In summary the Yolo Controlled Landfill program is meeting intended objectives. Industry and regulatory interest and potential environmental benefits have been high. Controlled landfill scaleup is under way at Yolo County, and similar efforts are under way elsewhere, including by Waste Management, Inc (see for example Hater and Barbush 2002). In addition, recent regulatory changes including greater flexibility can be expected to facilitate controlled landfills and related bioreactor technology.

## REFERENCES

Ashare, E. D. Wise and R. Wentworth, 1977 Fuel Gas Recovery from Animal Residue, Dynatech R/D, Available from the US National Technical Information Service (NTIS)

Augenstein, D. 1992 The Greenhouse Effect and US Landfill Methane. Global Environmental Change, p. 311-328 December

Augenstein, D., R. Yazdani, K. Dahl and R. Moore, 1998, Yolo County Controlled Landfill Project. Proceedings, California Integrated Waste Management Board (CIWMB) Landfill Gas Assessment and Management Symposium, Ontario, CA April. CIWMB, Sacramento, CA.

Augenstein, D. R. Yazdani, L. Sinderson, J. Kieffer M. Byars, 2000 Proceedings, Second International Methane Mitigation Symposium, US EPA and Russian Academy of Sciences Akademgorodok, Novosibirsk, Siberia, Russia. Available from EPA, Washington DC)

Augenstein, D. D. L Wise, R. L. Wentworth and C.L.Cooney 1976 Fuel Gas Recovery from Controlled Landfilling of Municipal Waste. Resource Recovery and Conservation 2 103-117

Barlaz, M. R. Mehta, D. Augenstein and R. Yazdani 2000 Comparative Assessment of Solids Excavated from Leachate Recycle and Control cells at the Yolo County, California Landfill. Proceedings, Solid Waste Association of North America [SWANA] 5<sup>th</sup> Annual Landfill Symposium

Halvadakis, C. A. Robertson and J. Leckie. 1983 Landfill Methanogenesis, Literature Review and Critique. Stanford Civil Engineering Department Report 271. Available from US National Technical Information Service

Harris, J, and A. Schafer 2002. Case History of Airspace Gain due to Recirculation. Proceedings, SWANA 7<sup>th</sup> Annual Landfill Symposium, SWANA, Silver Spring MD

Hater, G. and J. Barbush. Research and Design Issues for Data Collection in Landfill Bioreactors. Proceedings, SWANA 6<sup>th</sup> Landfill Symposium SWANA, Silver Spring, MD.

E. Hughes, J. Benemann and D. Augenstein, 1994 Electricity from Biogas. Proceedings, Bioenergy '94. US Department of Energy (US DOE) and US DOE Western Regional Biomass Program Sixth National Bioenergy Conference, Reno/Sparks NV October

IEM Inc Landfill Operation for Carbon Sequestration and Maximum Methane Emission Control. Cost Effectiveness and potential: Controlled landfilling for greenhouse gas abatement. January, 1999. Final Report under National Energy Technology Laboratory (NETL) of the US Department of Energy under contract DE-AC26-98FT40422, IEM, Inc. Palo Alto, CA, 94306. Don Augenstein, IEM Project Manager. Sean Plasynski, NETL Technical Manager.

Micales, J. and K. E. Skog 1997 The Decomposition of Forest Products in Landfills International Biodeterioration and Biodegradation 29 p. 145

Vogt, G. and D. Augenstein. 1997. A Comparison of Landfill Methane Recovery Models. A 19-landfill study. Prepared for the Solid Waste Association of North America (SWANA) and the National Renewable Energy Laboratory (NREL) of the USDOE. SWANA, Silver Spring MD.

W. D. Nordhaus, 1991, The Cost of Slowing Climatic Change, Energy Journal Vol. 12, no. 1

Yazdani, R. 1997 Methane Enhancement by Accelerated Anaerobic Composting at the Yolo County Central Landfill, Report to the California Energy Commission Sacramento, CA June.

Yazdani, R. and D. Augenstein, 2001 USEPA Project XL. 2001 Yolo County's Accelerated Anaerobic and Aerobic Composting [Full Scale Controlled Landfill Bioreactor] Project, Solid Waste Association of North America (SWANA) Landfill Symposium, June 2001, SWANA, Silver Spring MD.

# YOLO COUNTY BIOREACTOR DEMONSTRATION PROJECT

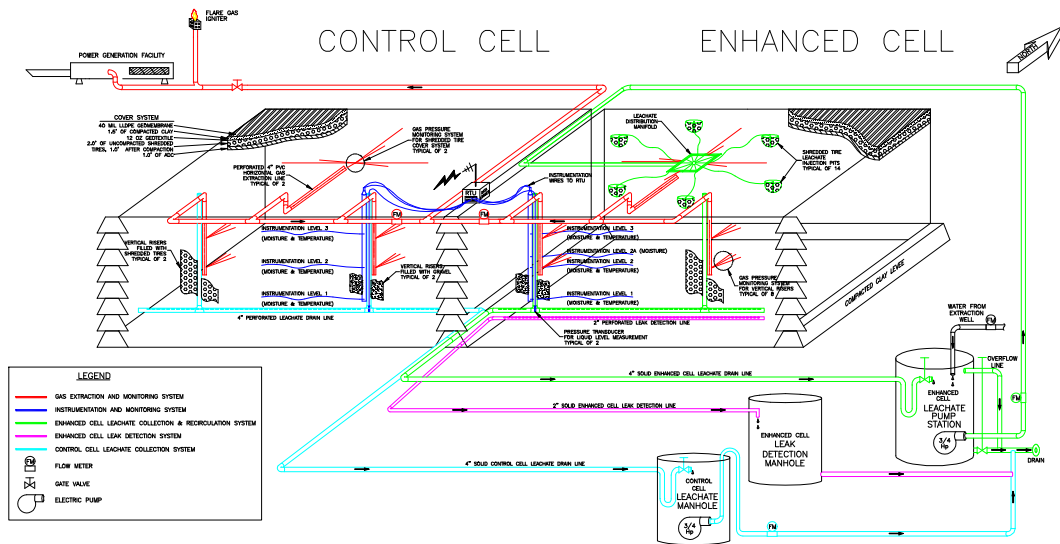


FIGURE 1- OBLIQUE VIEW OF 9000-TON SCALE DEMONSTRATION CELLS

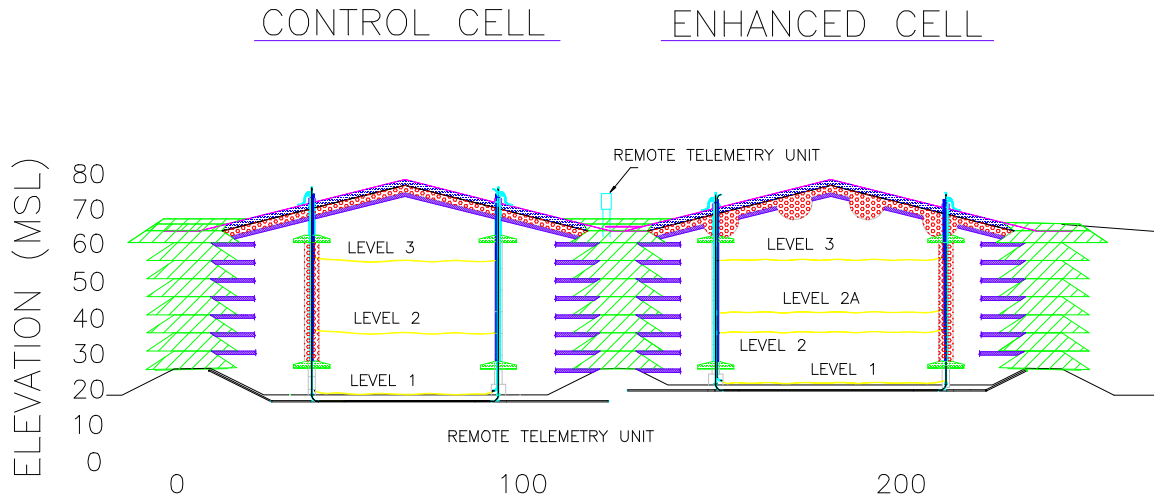
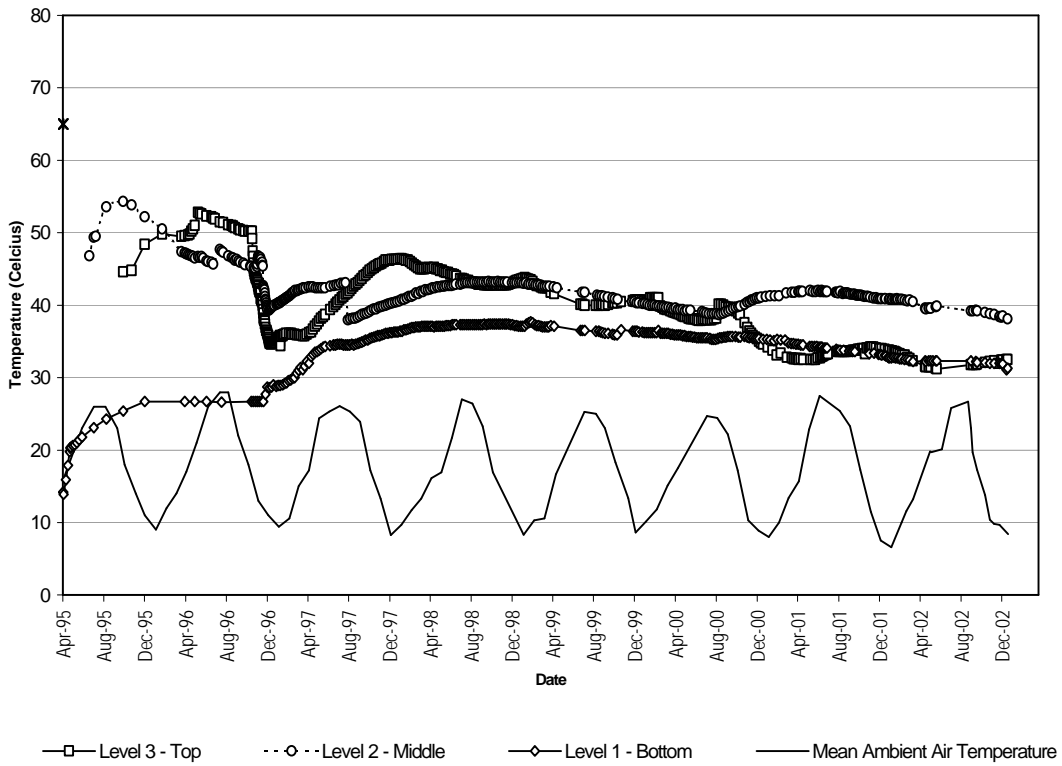
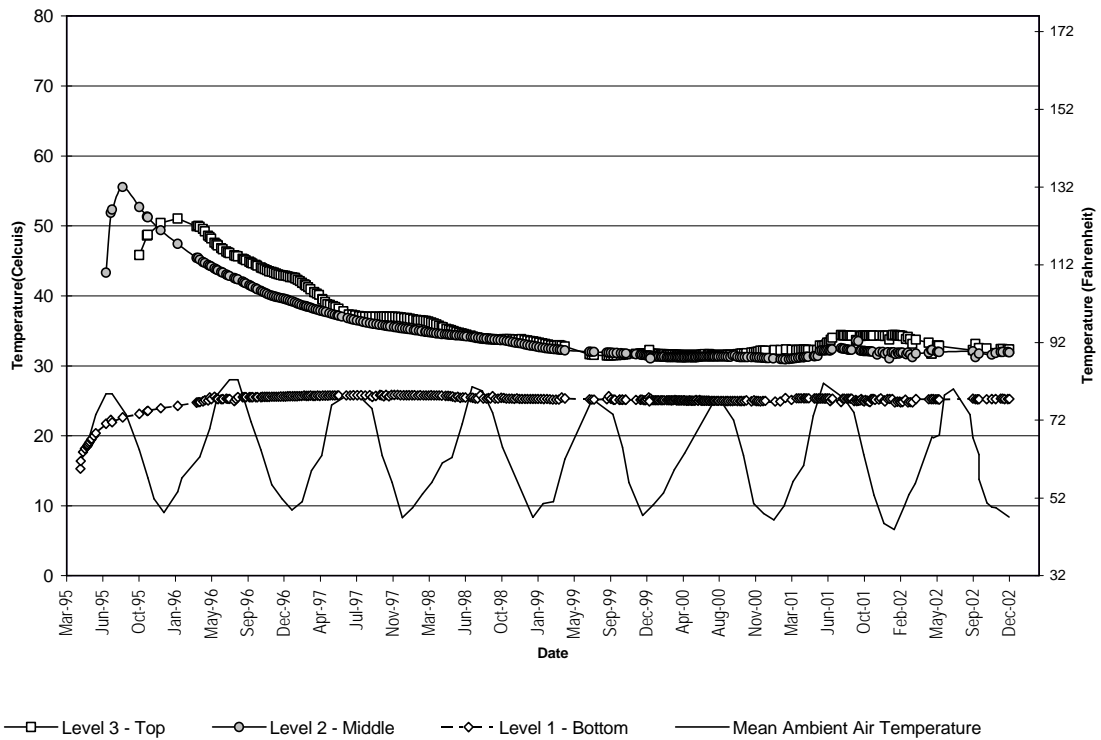


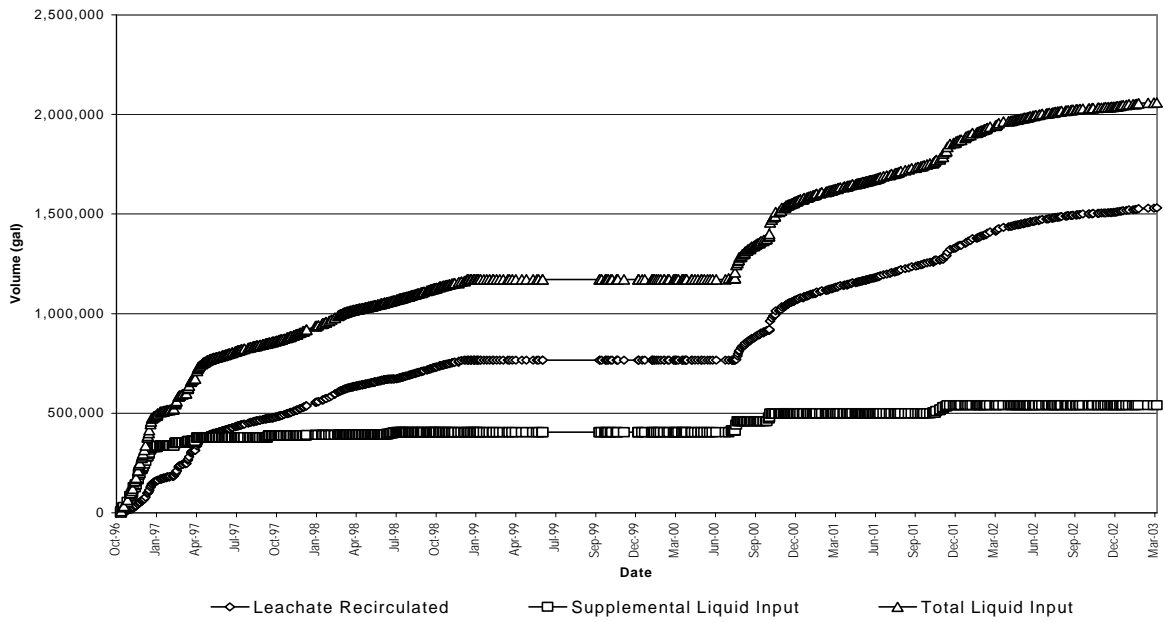
FIGURE 2- CROSS SECTIONAL VIEW OF 9000-TON DEMONSTRATION CELLS



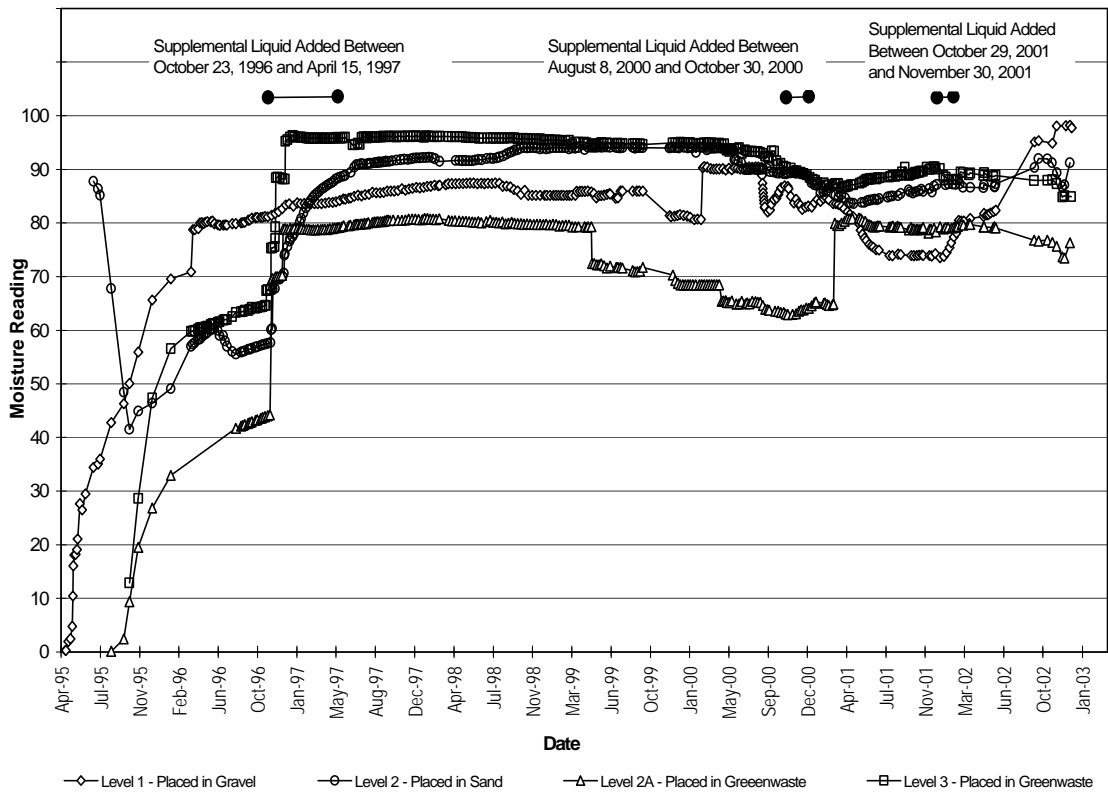
**FIGURE 3 ENHANCED CELL TEMPERATURE VS. TIME: Apr. 1995-Jan 2003**



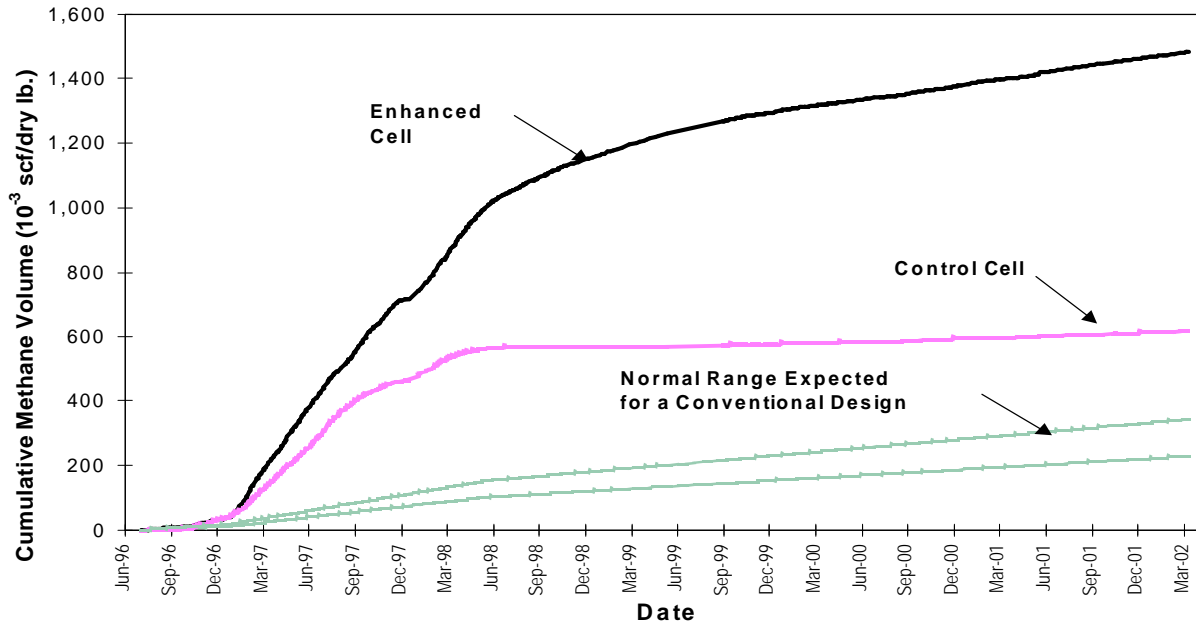
**FIGURE 4. CONTROL CELL TEMPERATURE VS. TIME Apr. 1995-Jan 2003**



**FIGURE 5. ENHANCED CELL MOISTURE INFILTRATION RATES VS. TIME: Oct. 1996-Mar. 2003**

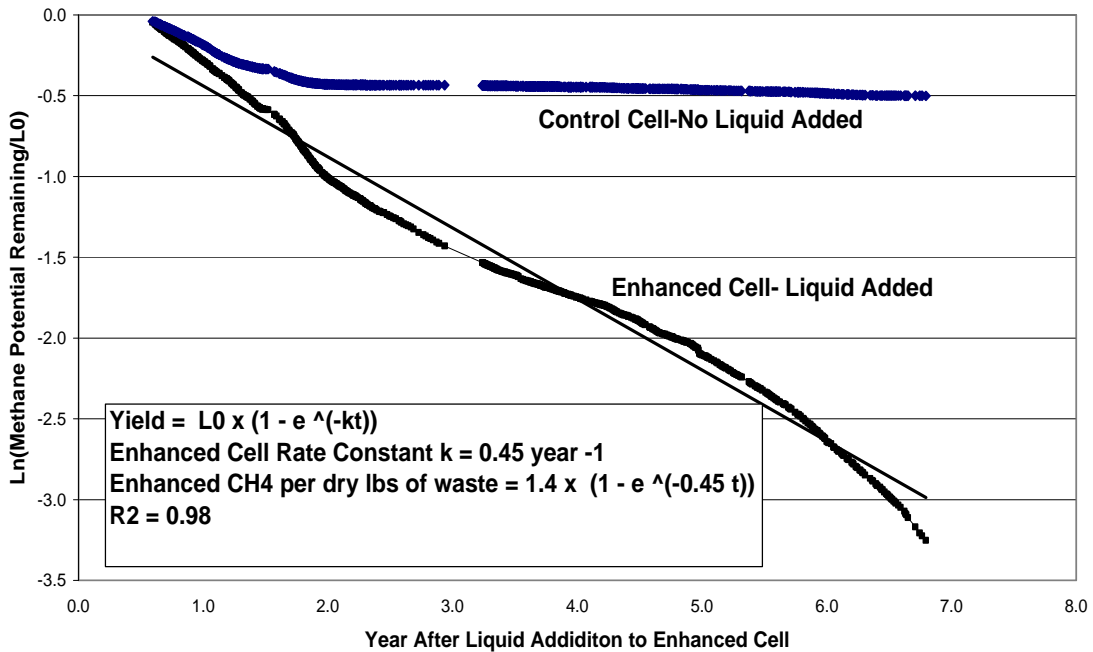


**FIGURE 6 ENHANCED CELL MOISTURE SENSOR READINGS VS. TIME Apr 95- Jan 03**



**FIGURE 7 ENHANCED AND CONTROL CELL CUMULATED GAS GENERATION VS. TIME 1996-2002. AND COMPARISON WITH “NORMAL”**

**Enhanced Cell Methane Generation Rate Constant  
 $L_0 = 1.4$  cubic feet per pounds of dry waste**



**FIGURE 8 RATE CONSTANT CALCULATION FOR CONTROL AND ENHANCED CELLS**

## Average Settlement over Time

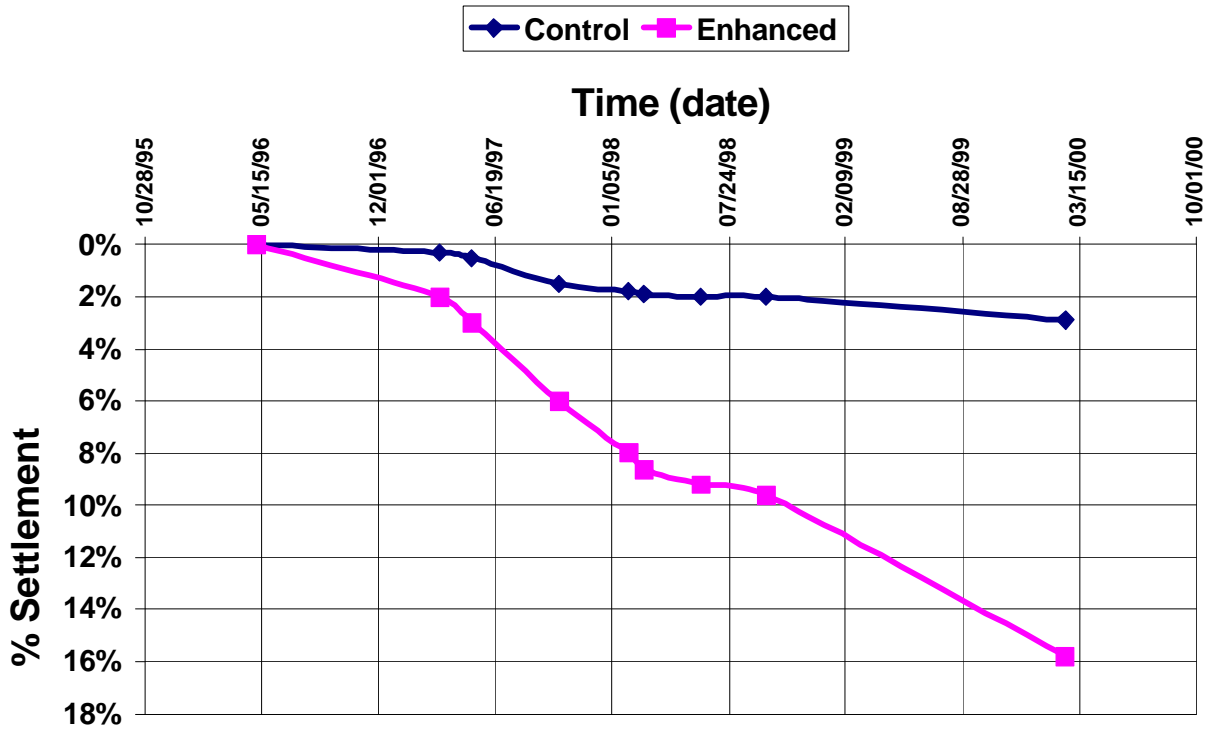


FIGURE 9. VOLUME REDUCTION VS TIME IN CONTROL AND ENHANCED CELLS Oct 1996-Mar 2000

## Waste Sample Moisture Distribution

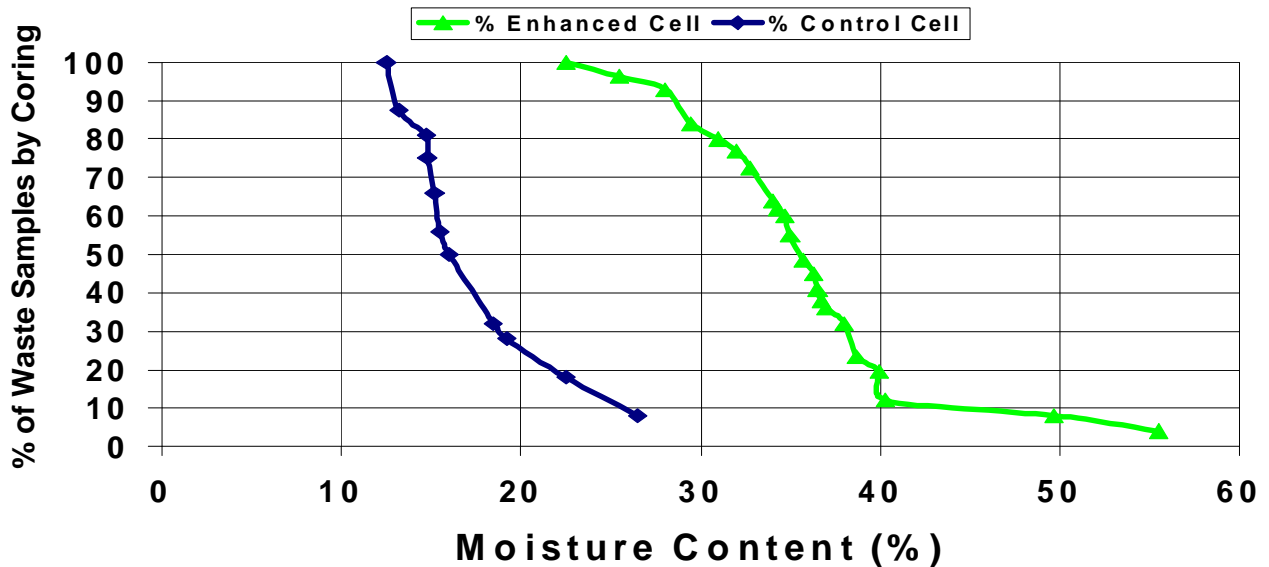


FIGURE 10: MOISTURE DISTRIBUTION IN CONTROL AND ENHANCED CELL CORE SAMPLES. SHOWN AS FRACTION OF CORE LENGTH ABOVE GIVEN MOISTURE