MONITORING THE PERFORMANCE OF ANAEROBIC LANDFILL CELLS WITH FLUIDS RECIRCULATION

Final Project Report

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FINAL PROJECT SUMMARY REPORT

MONITORING THE PERFORMANCE OF ANAEROBIC LANDFILL CELLS WITH FLUIDS RECIRCULATION

Objective:
Monitor the performance of anaerobic landfill cells with fluids recirculation

Key words/phrases: Landfill, Landfill gas, Biogas, Bioreactor landfill, Composting, Anaerobic Digestion

Approach/background
In a Bioreactor Landfill, controlled quantities of liquid (leachate, groundwater, gray-water, etc.) are added and recirculated in waste to increase the moisture content of the waste. This process significantly increases the biodegradation rate of waste and thus decreases the waste stabilization and composting time. The waste decomposes (ie, is composted) in the absence of oxygen (anaerobically), to landfill gas (biogas) in a shorter time (5 to 10 years) relative to what would occur within a conventional landfill (30 to 50 years or more). The biogas from anaerobic landfill waste composting is a substantial renewable energy resource that can fuel electricity or other uses. Other benefits include increased landfill waste settlement and a resulting increase in landfill capacity and life, and abatement of greenhouse gases through highly efficient methane capture.

To reach these objectives and potential benefits, the Yolo County controlled landfill project has entailed operation since 1993, of two demonstration cells containing approximately 10,000 tons of waste each. Most recently, the project has scaled up (in 2001-2002) two anaerobic cells, together containing over 200,000 tons of waste. This WRBEP contract has supported continued monitoring of the 10,000 ton demonstration cells, and of initial operation of the two new anaerobic cells.

STATUS/ACCOMPLISHMENTS

Monitoring and testing of liquid leachate (Full-scale project, Task 1): This task has been carried out for the two scaled-up cells with waste totaling over 200,000 tons. The fullscale cells are in early monitoring and the leachate COD levels are still high (ca. 10,000 ppm) but leachate data will provide a baseline against which future pollutant abatement can be evaluated.

Field sampling and testing of landfill gas (Full-scale project, Task 2): The field sampling and testing of landfill gas from the scaled-up cells has generally shown a composition near the 50 percent methane and fifty percent carbon dioxide, typical of landfill gas. Landfill gas generation is already being accelerated in the two scaled-up cells; but the gas generation, under 10% of potential, is at a stage too early to allow more than limited conclusions.

Field sampling/testing of leachate (Pilot scale project, Task 3): Sampling and testing shows that leachate has reached low and stable leachate pollutant loads as evidenced by COD level between 2,200-2,800 mg per liter and by several other standard indicators. This confirms value of bioreactors in leachate pollutant abatement.

Landfill gas monitoring (Pilot scale project, Task 4): Over the past seven year, landfill gas monitoring has shown greatly accelerated methane generation, with a rate constant over fivefold that seen from conventional landfills. This finding amply confirms the hoped for acceleration of methane generation and waste stabilization, with important implication for both increased renewable energy capture from landfill methane, and for earlier stabilization of the landfilled waste and lessened aftercare.

Project management, data management—Analysis and interpretation, Task 5: The instrumentation of all aspects of pilot and fullscale cells has allowed extremely detailed picture of cell performance. Analysis and interpretation of findings are summarized in the report that follows.

Operations and Maintenance, Task 6: Operation and maintenance entailed fixing or addressing a number of minor problems. No major problems were encountered. The operation and maintenance issues are presented in the main report.

Final Report, Task 7: The final report is attached.

Project Location: Yolo County, Woodland, CA.

Publications and Presentations: None during the contract interval.

Summary date: Initially submitted March, 2003. Revised July, 2003.

ABSTRACT

This project involves a key portion of the development of the bioreactor “controlled” landfill through operation of cells at scales ranging from 10,000 tons to over 70,000 tons. The overall purposes of this project are twofold: (1) to maximize energy potential of municipal solid waste by accelerating landfill methane generation along with waste stabilization, and (2) simultaneously, accomplishing highly efficient capture of the generated landfill gas. In anaerobic bioreactor “controlled” landfills, controlled quantities of liquid are added and recirculated through the waste to accelerate the natural biodegradation of solid waste components. Methane capture is facilitated by a surface membrane over a permeable layer atop the waste. The work that is the subject of this report includes evaluation of this approach with a pilot scale (10,000 ton) demonstration with two cells, and operation of two newly-constructed larger cells containing a total of over 200,000 tons of waste between them. The cells for both the pilot and fullscale operations are extensively instrumented for all major parameters of interest. The purpose of this contract with the Western Regional Biomass Energy Program has been to carry out operation and monitoring of the pilot scale and the newer scaled up cells, and to assess and document their performance in detail.

Key words/phrases: Landfill, Landfill gas, Biogas, Bioreactor landfill, Composting, Anaerobic Digestion

MONITORING THE PERFORMANCE OF ANAEROBIC LANDFILL CELLS WITH FLUIDS RECIRCULATION

EXECUTIVE SUMMARY

Introduction:
This executive summary gives an overview of the objective and approach of the project. It then summarizes the project findings and conclusions.

Objectives:
The Yolo County Department of Planning and Public Works is demonstrating new bioreactor landfill technology ("controlled landfilling") to manage landfilled solid waste. The overall objective of this work is to manage landfilled solid waste for rapid waste decomposition, maximum landfill gas generation and capture, and to minimize long-term environmental consequences of landfilled waste management Additional objectives include development of data to address regulatory concerns, establish performance, and provide information so that this technology can be widely applied to benefit solid waste landfill operators, and the public.

Approach/Background:
In a Bioreactor Landfill, controlled quantities of liquid (leachate, groundwater, gray-water, etc.) are added to increase the moisture content of the waste. Leachate is then recirculated as necessary to maintain the moisture content of the waste at or near its moisture holding capacity. This process significantly increases the biodegradation rate of waste and thus decreases the waste stabilization and composting time (5 to 10 years) relative to what would occur within a conventional landfill (30 to 50 years or more). If the waste decomposes (ie. e., is composted) in the absence of oxygen (anaerobically), it produces landfill gas (biogas). Biogas is primarily a mixture of methane, a potent greenhouse gas, carbon dioxide, and small amounts of volatile organic compounds (VOC's). This by-product of anaerobic landfill waste composting can be a substantial renewable energy resource that can be recovered to fuel electricity or other uses. Other benefits of a bioreactor landfill composting operation include increased landfill waste settlement and a resulting increase in landfill capacity and life, improved opportunities for treatment of leachate liquid that may drain from fractions of the waste, possible reduced landfill post-closure management effort, possible landfill mining, and abatement of greenhouse gases through highly efficient methane capture over a much shorter period of time than is typical of waste management through conventional landfilling.

The Yolo County controlled landfill project has entailed operation since 1993, of two demonstration cells containing approximately 10,000 tons of waste each. Most recently, the project has scaled up (in 2001-2002) two anaerobic cells, together containing over 200,000 tons of waste. This WRBEP contract has supported continued monitoring of the 10,000 ton demonstration cells, and construction and initial operation of the two new anaerobic cells.

Work accomplished and conclusions are described in terms of the tasks in the WRBEP contract as follows.

STATUS AND ACCOMPLISHMENTS OF CONTRACT TASKS

Task 1. Monitoring and Testing of Leachate (Full Scale Project)
Liquid and leachate were added to the northeast fullscale cells through horizontal trenches. Liquid addition started at the bottom lift of waste as part of a plan to moisten waste upward from the base. One initial finding has been that added liquid appears to permeate the waste in the larger cell more slowly than with the 10,000 ton cell, which is thought due to greater compaction and associated lower permeability of the waste.

The quality (pollutant load) of leachate liquid draining from waste is of interest environmentally, and to agencies that regulate waste. Leachate from the newly filled northeast and west anaerobic cell, was monitored for field chemistry and sampled for laboratory analysis. Monitoring began prior to the start of liquid addition and was then at intervals (monthly or quarterly) as specified in the contract. In general, highest leachate pollutant load is expected early and before liquid addition, and to fall with time as pollutants were reduced by bacterial action. This favorable behavior has been amply confirmed with the 10,000 ton demonstration cells. The west and northeast Anaerobic cells are to date in stages that are too early to show leachate pollutant changes. However their monitoring establishes a useful baseline against which to assess future changes

Task 2. Field Sampling/Testing and Laboratory Testing of Landfill Gas (Full Scale Project)
Landfill gas composition and flow have been monitored for methane, carbon dioxide and oxygen and nitrogen from the northeast cell. After a brief early “burst” of relatively high carbon dioxide to methane ratio generation, gas composition has ranged from about 55% methane and 45% carbon dioxide. This composition is after compensation for entrained air. Such methane to carbon dioxide ratio is normal for decomposing wastes. The northeast cell has shown accelerated methane generation but is very early in the methane generation cycle. The west cell did not receive enhancement by liquid addition in the contract interval. As of the end of 2002, northeast cell cumulated methane yield estimated at 10 % of the potential yield of 1.4 cubic feet of methane per dry pounds of waste and the west side cell at under 1 % of the estimated yield of 1.4 cubic feet of methane per dry pounds of waste.

Atmospheric emission of landfill gas from the new northeast cell was also tested using the integrated surface scan as specified by EPA. Such scans showed emissions were close to negligible, with surface methane concentrations under 10 PPM being less than 0.02% of the federal statutory limit of 500 PPM. Thus one major objective, reduction of greenhouse methane emissions to levels that are essentially insignificant, is being demonstrated.

Task 3. Field Sampling/Testing and Laboratory Testing of Leachate (Pilot Scale Project)
The 10,000 ton pilot scale cells have been operating for 8 years. Leachate bioremediation (minimization of leachate pollutants) was essentially completed by the first year of operation (1996-97.) Pilot scale leachate from the enhanced cell has shown little change over the recent contract interval, during which more recirculation occurred. Stable, low pollutant load was indicated by chemical oxygen demand (COD) remaining between 2,200-2,800 mg per liter and BOD values generally below 150 mg per liter. The control cell did not generate leachate. This behavior at long terms confirms value of this technology in facilitating bioremediation of

leachate components and achieving stable, low leachate pollutant load. This benefit is also widely confirmed in literature by other investigators.

Task 4. Field Sampling/Testing and Laboratory Testing of Landfill Gas composition /flow (Pilot Scale) Field monitoring of landfill gas was performed weekly. Landfill gas was monitored for methane, carbon dioxide, and oxygen, This monitoring confirmed a methane to carbon dioxide ration remaining near 50% methane and 50% carbon dioxide by volume. In addition to landfill gas constituents, the cumulated methane generation is confirming an extremely encouraging and high rate constant for the enhanced cell of 0.45year^{-1}, over fivefold the "normal" range of 0.04-0.08 year^{-1}. This important and encouraging finding confirms that major objectives of the controlled landfill approach, acceleration and better control of methane generation timing, have been met at the 10,000 ton scale.

Task 5. Project Management, Data Management-Analysis, and Interpretation. These test cell operations are long-running projects by their nature. The projects were monitored and assessed for biological conditions, gas generation, leachate recirculation as an effective leachate treatment strategy, and the reduction of constituent concentrations in landfill gas. Additional monitoring and analysis for the full-scale project included assessing the performance of the horizontal pipe and shredded tire system for landfill gas recovery and leachate injection, assessing the effectiveness of gas capture through shredded tire media on the surface of the landfill, and assessing the effectiveness of the base liner system at preventing liquid buildup.

Task 6. Operations and Maintenance
The main operational and maintenance issues for the projects are summarized below.

Pilot Scale Project
Liquid additions. As an overview, a total of nearly 539,500 gallons of supplemental liquid was added to the enhanced cell and 1,517,176 gallons of liquid recirculated since the start of liquid addition in October 1996. :

Liquid addition and further recirculation. Although the pilot scale data from 1996-1999 showed that liquid distributed reasonably well, some relatively dry zones were present in the waste based on sensors (2001) and analyses on earlier core samples. Accordingly from January 1, 2002 through March 17, 2002, liquid was again recirculated through the enhanced cell, with additions through the multiple liquid injection points serving the cell. Liquid was also added preferentially where data previously indicated driest waste, including waste surrounding a bore hole located on the northeast corner of the enhanced cell. Between September 9, 2002 and December 31, 2002, more liquid recirculation was conducted distributed equally into all injection locations of the waste. This has resulted in uniformly elevated liquid sensor readings, considered a best indication of uniform liquid distribution, as of the end of calendar 2002.

Datalogger In June 2002, the pilot scale datalogger malfunctioned in its automatic transmission of data to the Woodland, CA office. The datalogger malfunction was circumvented by connecting a laptop computer directly to the datalogger, a satisfactory method but somewhat more labor intensive approach. In another instrumentation problem, the control cell gas flowmeter malfunctioned on several occasions due to mechanical problems. During these times, the gas flow from the control cell was calculated by difference between the total gas flow (combined gas flows from the enhanced cell and control cell) and the enhanced cell meter, and interpolation. Other minor problems included a rip in the control cell liner around the penetration boots that was also found and fixed.

Full-Scale Project
Leachate addition to the Northeast cell began in March 2002. A total of 1,009,643 gallons of supplemental liquid (groundwater and leachate) was added and 466,940 of leachate recirculated to the northeast anaerobic cell through December 2002. To the end of 2002, the overall picture from sensors showed that the waste moisture, as indicated by sharply elevated readings as the waste "front" reaches each sensor, was elevated in close to 50% of the waste.

Liquid and leachate addition issues. In August 2002, leachate injection laterals in the northeast anaerobic cell were found to have calcium carbonate scale buildup, which was significantly affecting flow in the injection lines. This may be a problem site-specific to this project because of high-calcium leachate from the leachate reservoir. A satisfactory solution was developed based on injection of dilute citric acid into the piping system, then flushing remaining scale from, the injection lines. Also during leachate addition and liquid circulation to the landfill, several of the gas collection lines on Layer 1 and Layer 2 became liquid-full and were closed. When liquid addition to these areas was reduced, the addition trenches drained and the wells were reopened. This strongly suggests that the deeper, more compacted waste is less permeable to liquid.

Several leaks were located at saddle fittings that connected the individual injection lines to the main header line. The fittings were repaired and no leaks have since been detected. As liquid has been added to the fullscale cells, the sensors are providing valuable feedback and currently show that about half the waste is moistened (as indicated by elevated sensor readings).

CONCLUSIONS AND SUMMARY FROM TASKS 1-6

The controlled bioreactor landfill, in contrast to "conventional" landfills, treats waste more actively within the landfill. Work before and within this contract period illustrates the need for added management over and above that required for "conventional" landfills. However in return, the bioreactor is giving benefits of greater methane energy, emission reduction and the (quite valuable) airspace gain to operators. Among important conclusions are:

1. Ongoing pilot scale work at the 10,000 ton scale has continued to establish a baseline of operational experience. The 10,000 ton enhanced cell has verified the advantages sought, of accelerated methane energy recovery, methane emission reduction, and volume loss, and low and stable leachate pollutant load.

2. For the pilot scale work, initial liquid recirculation in 1996-1999 gave good, but not perfect, moisture distribution results, with moisture elevated in "most" (estimated > 85%) of the waste. The pilot results (after 8 years) suggest some continuing moisture supplementation may be helpful to maintain elevated moisture and to elevate moisture in remaining dry spots.

3. The permeability of the deeper, larger cells to added liquid may be somewhat lower than for the smaller cells. However the desired liquid elevation is still attainable within two years.

4. An integrated surface scan of methane has been conducted for the scaled up cells, showing that methane concentrations over the cell surface are essentially negligible. This confirms that another objective, greatly reduced landfill “greenhouse” methane and VOC emissions, is being met.

5. This is a long-term several (5+) year program. Initial operations of the new scaled-up cells, is helping to develop the experience necessary to allow wide application in the US and eventually worldwide. The project is proceeding according to plan. Importantly, no major problems or barriers have been encountered.

FUTURE APPLICATION

This bioreactor “controlled” landfill program has had high interest from several entities with its potential for energy, environmental and waste management benefits. The state of California continues its interest in facilitating application the technology to increase the amount of renewable electricity generated, as part of its state program to diversify electricity supplies and increase renewably based electricity generation. Recently, a local waste management jurisdiction in an adjacent county is examining application of the same technology, and discussions are ongoing.

Project Location(s): Woodland, California

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Key words/phrases: Landfill, Landfill gas, Biogas, Bioreactor landfill, Composting, Anaerobic Digestion

1 PREFACE

This report represents a major body of work, and itself is condensed from material in even more detailed reports for other project sponsors. The more detailed reports have been submitted to the Sacramento Municipal Utility District (SMUD) and the National Energy Technology Laboratory (NETL) of the US Department of Energy. The NETL report is the final report submitted under NETL contract DE-AC26-99FT40613 and additions thereto. The report can be obtained by contacting Ramin Yazdani, Principal Investigator.

2 INTRODUCTION

Sanitary landfilling is the dominant method of solid waste disposal in the United States, accounting for about 217 million tons of waste annually (U.S. EPA, 1997). The annual production of municipal solid waste in the United States has more than doubled since 1960. In spite of increasing rates of reuse and recycling, population and economic growth will continue to render landfilling an important and necessary component of solid waste management.

In a Bioreactor Landfill, controlled quantities of liquid (leachate, groundwater, gray-water, etc.) are added to increase the moisture content of the waste. Leachate is then recirculated as necessary to maintain the moisture content of the waste at or near its moisture holding capacity. This process significantly increases the biodegradation rate of waste and thus decreases the waste stabilization and composting time (5 to 10 years) relative to what would occur within a conventional landfill (30 to 50 years or more). If the waste decomposes (ie. e., is composted) in the absence of oxygen (anaerobically), it produces landfill gas (biogas). Biogas is primarily a mixture of methane, a potent greenhouse gas, carbon dioxide, and small amounts of Volatile Organic Compounds (VOC's). This by-product of anaerobic landfill waste composting can be a substantial renewable energy resource that can be recovered for electricity or other uses. Other benefits of a bioreactor landfill composting operation include increased landfill waste settlement (ie waste volume loss) and a resulting increase in landfill capacity and life, improved opportunities for treatment of leachate liquid that may drain from fractions of the waste, possible reduction of landfill post-closure management time and activities, landfill mining, and abatement of greenhouse gases through highly efficient methane capture over a much shorter period of time than is typical of waste management through conventional landfilling.

2.1 Overview of The Project

Between 1993 and 1996 two 10,000 square feet test cells (Pilot Scale Project) were constructed, These were an enhanced (bioreactor) cell that received leachate and groundwater recirculation along with a control cell that received no liquid. In addition the County of Yolo Planning and Public Works Department (Yolo County) is operating its next 20-acre landfill module near Davis, California as a controlled bioreactor landfill to attain a number of additional environmental and cost savings benefits. In the first phase of this 20-acre project, a 12-acre module was constructed. This 12-acre module contains a 6-acre cell and a 3.5-acre cell, which are operated anaerobically, and a 2.5-acre cell, which will be operated aerobically. Only the anaerobic cells will be discussed in this report to WRBEP. The County began construction the second phase of Module 6D in Fall 2002 and, depending on the results of the first phase of Module 6D, Yolo County may operate the second phase either anaerobically or aerobically.

Two new cells were operated anaerobically and one aerobically (Detail 1-1). We have designated the three bioreactor cells as the west-side anaerobic cell, the northeast anaerobic cell, and the southeast (aerobic) cell. This configuration allowed the northeast anaerobic cell to be constructed and operated prior to completion of the west-side anaerobic cell. By separating the anaerobic bioreactor into two separate cells, experiences gained from construction of the northeast cell were incorporated into the west-side anaerobic cell.

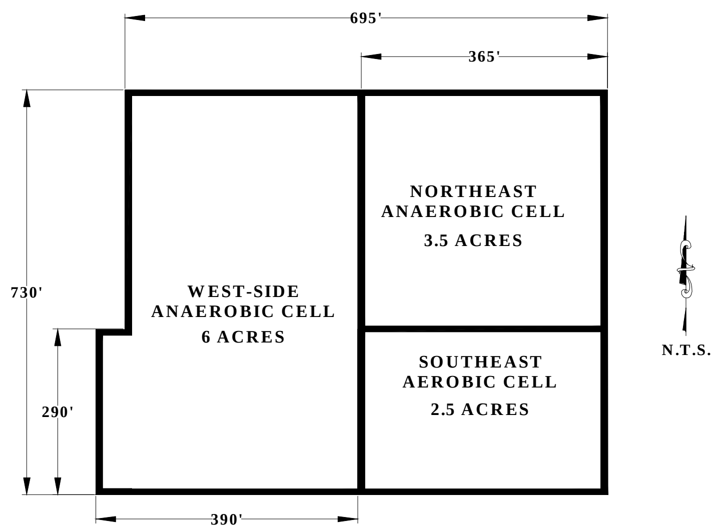

Figure 2-1. Overview of Module D Bioreactor Cells

Waste placement and the installation of instrumentation, leachate injection, and gas collection systems have been completed in the northeast anaerobic cell and the west-side anaerobic cell. A total of 65,104 tons of waste was placed in the northeast anaerobic cell and 166,294 tons of waste was placed in the west-side anaerobic cell.

2.2 Purpose of the Work

The primary purpose of this work is to maximize the energy potential of municipal solid waste by accelerating waste stabilization and biogas generation while demonstrating improved landfill gas collection efficiency.

2.3 Summary of Goals and Objectives

The Yolo County bioreactor cells were designed to test the operation of a landfill as a biological treatment system. By adding and recirculating liquid, the internal environment of the waste is optimized to achieve rapid biological stabilization and maximum landfill gas generation. The objectives of the project are listed below.

- Demonstrate substantially accelerated landfill gas generation and biological stabilization while maximizing gas capture.
- Demonstrate that the recirculation of leachate is an effective leachate treatment strategy.
- Measure and track the movement of moisture through landfills.
- Monitor the biological conditions within the landfill cells.
- Assess the performance of horizontal pipes embedded in shredded tires for liquid addition and landfill gas recovery in the Full-Scale project (the use of shredded tires as leachate injection and landfill gas recovery media were tested in the pilot scale project).
- Assess the correspondence of gas generation observed in the pilot scale project to gas generation in the full-scale project.
- Assess the effectiveness of gas capture through shredded tire media located near the landfill surface.
- Demonstrate no liquid buildup on the base liner.

2.4 Activities Performed

This project involved the following activities: monitoring and testing of leachate, monitoring and testing of landfill gas, project management and data analysis and interpretation, and operation and maintenance.

2.4.1 Major Tasks – Methodology

A comprehensive monitoring plan was developed to assess all aspects of the projects related to waste decomposition. Major tasks performed and the monitoring schemes are described below. A comprehensive discussion of the monitoring equipment is presented in the “monitoring” sections of the report. The outcomes of these tasks are presented in the “results” sections of the report.

2.4.1.1 Task 1 and Task 3. Monitoring and Testing of Leachate

Leachate composition is one parameter used to evaluate the rate and progress of waste decomposition. Therefore, leachate analyses were performed throughout the pilot scale project and full-scale project. Waste decomposition and landfill gas generation occur in five sequential phases. These phases are I) Initial, II) Transition, III) Acid, IV) Methane Fermentation, and V) Maturation. In phase I, air is still trapped within the waste allowing biological decomposition under aerobic conditions, as evidenced by the initial elevated waste temperatures. In the second phase (Transition Phase), oxygen is depleted and anaerobic conditions begin to develop, resulting in the start of the Acid Phase. At this stage, the pH of the leachate drops to a value of six or lower, heavy metals are solubilized, and the chemical oxygen demand (COD) increases significantly due to the dissolution of the organic acids in the leachate. In phase IV, both methane and acid formation proceed simultaneously, although the rate of acid formation is considerably reduced. Waste decomposition and landfill gas production both continue until the Maturation Phase is reached. In the Maturation Phase, most of the waste is stabilized and landfill gas generation is nearly complete.

Anaerobic conditions, of the Transition phase, can be induced and made more efficient by the addition and recirculation of liquid in the waste. Anaerobic conditions created within waste allow methane-producing microorganisms, called methanogens, to thrive. As the methanogens consume the waste, methane is produced as a by-product. The better the landfill conditions are for methanogens, the more active they are and therefore, the faster they are able to produce methane and the faster the waste is stabilized.

Supplemental liquid additions provide better biological conditions for methane generation, so the methane generation phase occurs earlier and more controllably, and the waste stabilizes in a shorter time. Complete waste stabilization and landfill gas generation in the Yolo County Project should be reached within 10 years. This is an immense reduction in time as compared to conventional landfills, where waste stabilization can vary between 30-80 years, or even longer [1].

Pilot Scale Project Monitoring. Between September 2001 and December 2002 leachate from the enhanced cell was monitored for field chemistry and sampled for laboratory analysis at least once a quarter. Leachate has not been generated from the control cell in sufficient volumes to allow for field monitoring or sampling.

Full Scale Project Monitoring. Prior to the start of liquid addition in March 2002, leachate was monitored for field chemistry and sampled for laboratory analysis from the northeast anaerobic cell. Between May 2002 and December 2002 leachate was monitored for field chemistry and sampled for laboratory analysis at least once a quarter.

2.4.1.2 Task 2 and Task 4. Monitoring and Testing of Landfill Gas

Landfill gas is composed of principal gases, which are found in large amounts. Principal gases include carbon dioxide, methane, nitrogen and sometimes some oxygen[1]. Trace gases (H2S, VOC's) are present in very small amounts. However, the largest constituents of landfill gas are the methane and carbon dioxide, which are typically present at levels between 40 and 60 percent. The percentage of methane is a very useful indicator, both to quantify the energy potential of the gas and also to provide further insight concerning bacterial activity in the landfill cells.

Pilot Scale Project Monitoring. Landfill gas was monitored two to three times a week for methane, carbon dioxide, oxygen, and concentrations of "balance gas" (from entrained air). During 2002, landfill gas was sampled for analytical testing once a quarter.

Full Scale Project Monitoring. Landfill gas was monitored two to three times a week for methane, carbon dioxide, oxygen, and balance concentrations. During 2002, landfill gas was sampled for analytical testing once a quarter.

2.4.1.3 Task 5. Project Management, Data Management, Analysis, and Interpretation

The data collected and analyzed included gas composition, gas flow, leachate chemistry, and leachate flow.

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[1] Tchobanoglous et al, "Integrated Solid Waste Management, Engineering Principles and management Issues", McGraw-Hill, 1993.

Further data management and analysis not covered by this contract, but included in the EPA XL agreement, included head on the liner (full-scale project), temperature, moisture, and surface emission monitoring.

The sensors in the pilot scale project are connected to a datalogger. The recorded data is downloaded and transferred to a database for further analysis. A Supervisory Control and Data Acquisition (SCADA) System monitors and controls the operation of the full-scale project cells. The sensors from the full-scale project are connected to a central processor that is radio linked to a computer in the Woodland office. From the SCADA system, data can be viewed and transferred to a database for further analysis.

2.4.1.4 Task 6. Operations and Maintenance

Pilot scale project issues have mainly included maintenance while operational issues have predominated in the full-scale project. Some of the main issues are summarized below.

Pilot Scale Project

1. Accelerated settlement in the enhanced cell has caused rainwater to accumulate during the winter season in the low areas on the surface liner. The two main low areas are located in the northwest area of the cell and in the southwest area of the cell. A portable pump was utilized to remove ponding water in these areas.

2. The control cell gas flow meter stopped functioning on several occasions due to mechanical problems. During these times, the gas flow from the control cell was calculated by taking the difference between the total gas flow meter (combines gas flows from the enhanced cell and control cell) and the enhanced cell gas flow meter.

3. In June 2002, the data logger located at the landfill stopped responding to user commands. It would not establish communication with the Woodland office, and would not receive data from the sensors located in the cells. The datalogger was returned to Campbell Scientific for servicing and was found to have several minor problems that were repaired. The data logger was reinstalled, however the datalogger was unable to establish communication with the Woodland office. Currently, the data collected by the datalogger is being downloaded manually by connecting a laptop computer directly to the datalogger.

4. The control cell surface liner was found to have a rip due to excess tension around the penetration boot of the landfill gas well head. The liner patched by affixing a piece of surface liner over the area with a two-part epoxy designed to bond plastics.

Full Scale Project

1. In June 2002, several leaks were found in the leachate injection system at the saddle fittings connecting the individual injection lines to the main header line. The fittings were repaired and no leaks have since been detected.

2. In August 2002, leachate injection laterals in the northeast anaerobic cell were found to have calcium carbonate scale buildup, to the extent that the injection lines were almost completely shut down. Yolo County investigated various options to remove the scaling and opted to inject a solution of citric acid in the lines to dissolve the scaling. On September 11, 2002,

approximately 3000 gallons of citric acid (pH approximately 4) was added to the injection laterals on the northeast anaerobic cell. The citric acid was added to the injection laterals and allowed to set for approximately 14 hours. Groundwater was then flushed through the injection lines to remove the citric acid and scaling residue. After the leachate injection lines were cleaned, groundwater was added to dilute the leachate, which resolved the problem.

3. The filter used to remove large particulates from the leachate prior to injection was frequently clogging and found to have been installed incorrectly (backward, in fact) by a contractor. The filter was reinstalled properly to correct the problem.

4. During liquid addition, several of the gas collection lines on Layer 1 and Layer 2 became clogged with excess liquid and were closed. When liquid addition to these areas was reduced, the lines became unclogged and the wells were reopened.

3 CONSTRUCTION AND OPERATION OF LARGE SCALE CELLS

The construction of the 10,000 ton demonstration cells has been described earlier [2] so detail will be omitted here. Two large scale anaerobic cells, described earlier in section 2, were constructed. The following is a general description of features of the two large-scale cells, designated the northeast cell and the west side cell.

3.1 Construction

Construction of the large-scale anaerobic cells can be generally broken down into four major tasks: waste placement, liquid management system, gas management system, and surface liner installation. Each of these four tasks is discussed below.

3.1.1 Waste Placement

For both the northeast and west cells, waste was placed in lifts with an average thickness of 15 feet (Detail 3-1). In general, all waste received at the landfill was deposited in the northeast cell with the exception of the last lift of waste where self-haul waste was diverted to another area. The use of daily cover soil during waste filling was minimized to aid in the overall permeability of the waste. Instead, greenwaste or tarps were used as alternative daily cover (ADC). In the event soil was placed (for example, access roads or tipping pad), the soil was removed prior to placing the next lift of waste. All side slopes were constructed at approximately 2.5 to 1 (horizontal to vertical) and received at least one foot of soil cover. Instrumentation was placed between lifts, and base layer instrumentation was installed on the Module 6D base liner. .

3.1.2 Liquid Management system

Horizontal liquid injection lines were installed in each lift of waste (Image 3-1). Injection lines within the waste were placed with lateral separations of about 40 feet. Injection lines installed

[2] Yazdani, R., Moore, R. Dahl. K. and D. Augenstein 1998 Yolo County Controlled Landfill Bioreactor Project. Yolo County Public Works and I E M, Inc. Yolo County Public Works and I E M, Inc. report to the Urban Consortium Energy Foundation (UUCETF) and the Western Regional Biomass Energy Program, USDOE

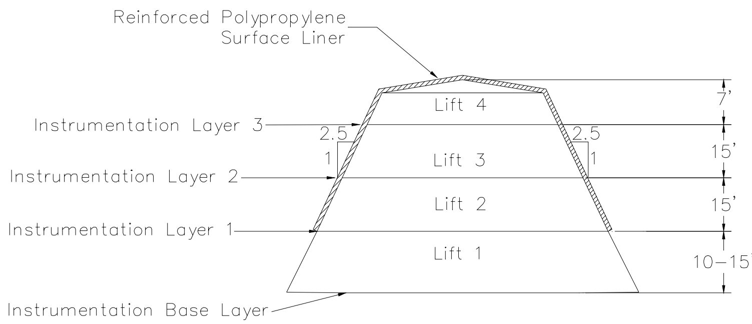

Figure 3-1. Anaerobic Cell Cross Section

on top of lift 4 were installed every 25 feet, with an additional injection line following the perimeter of the top deck. Each injection line consists of a 1.25-inch-diameter high-density polyethylene (HDPE) pipe placed horizontally (north to south), which extends completely through the waste. Each injection line was perforated by drilling a $^{3}/_{32}$-inch hole every 20 feet. A total of 8,130 feet of injection piping was installed with a total of 342 injection holes.

Each of the injection laterals is typically connected to a 4-inch-diameter HDPE injection header. Leachate injection for each lateral is monitored and controlled by individual solenoid valves connected to the SCADA system. A flow meter monitors the total volume and injection flow rate for each entire anaerobic cell.

Image 3-1: Horizontal LFG and leachate injection lines installed and being coverd by shredded tires.

3.1.3 Gas Management System

Horizontal landfill gas (LFG) collection lines are installed between each lift of waste (Image 3-1) and directly under the reinforced polypropylene (RPP) geomembrane cover. LFG collection lines consist of various combinations of alternating 4 and 6-inch–diameter, schedule 80 polyvinyl chloride (PVC) pipe (Image 3-2) as well as several variations using corrugated HDPE pipe. Surrounding each line was a highly permeable bedding of shredded tires used as the permeable medium. The gas collection lines between layers are spaced 40 feet apart horizontally and the lines directly under the RPP membrane are spaced at 25 feet. Each LFG collection line is connected to a 6-inch-diameter LFG collection header that will convey the gas to the on-site LFG-to-energy facility. Each LFG collection line incorporates a pre-manufactured wellhead capable of controlling flow and monitoring flow rate, temperature and pressure.

Image 3-2: Horizontal LFG collection line

To facilitate gas collection Yolo county placed trenches filled with shredded tires on the top lift of the cell.

3.1.4 Surface Liner

The County retained the services of Vector Engineering (Vector) to design the surface membrane covers for each of the bioreactor cells (Image 3-3).

Image 3-3: Northeast anaerobic surface liner

Based on Vector and County staff research, it was determined that a 36-mil reinforced polypropylene geomembrane (RPP) would be the preferred choice for an exposed geomembrane cover[3]. Reinforced polypropylene offered advantages over the other candidate materials including long service life (a 20-year warranty was obtained), superior strength due to the nylon reinforcement, and low thermal expansion and contraction.

To expedite construction and reduce the overall cost of the project, the County directly purchased and provided to the contractor the necessary membrane material for installation on the northeast cell. The plans and specifications for the installation of the RPP surface liner were issued for bid on June 15, 2001 but it was found that bids were not submitted because the liner companies could not locate a subcontractor to perform the earthwork. However after multiple iterations of bid specifications and biddings, Colorado Linings International was selected and the installation of surface liner and associated piping was completed in November 2001.

3.2 Monitoring

Temperature, moisture, leachate quantity and quality, and LFG pressure and composition are monitored through an array of sensors placed within the waste and in the leachate collection and recovery system (LCRS). Each sensor location received a temperature sensor (thermistor), a linear low-density polyethylene (LLDPE) tube, and a moisture sensor (a PVC moisture sensor and in some cases a gypsum block). For protection, each wire and tube was encased in either a 1.25-inch HDPE pipe or run inside the LFG collection piping. Sensors on instrumentation layers were placed on either a bedding of greenwaste (shredded yard waste), wood chips (chipped wood waste), or pea gravel to protect against damage from the underlying waste. Sensors installed on the primary liner (prior to any waste placement) were placed on geocomposite and covered with pea gravel prior to the placement of the chipped tire operations layer

3.2.1 Temperature

Temperature is monitored with thermistors, temperature range of 0°C to 100°C , manufactured by Quality Thermistor, Inc.

3.2.2 Moisture

Moisture levels are measured with polyvinyl chloride (PVC) moisture sensors and gypsum blocks. Both the PVC moisture sensors and gypsum blocks are read utilizing the same meter. The PVC sensors are perforated 2-inch-diameter PVC pipes with two stainless steel screws spaced 8 inches apart and attached to wires to form a circuit that includes the gravel filled pipe. The PVC sensors were designed by Yolo County and used successfully during the pilot scale project[4]. The PVC moisture sensor can provide a general, qualitative assessment of the waste's moisture content. A reading of 0 to 40 equates to no free liquid, 40 to 80 equates to some free liquid, and 80 to 100 means completely saturated conditions.

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[3] Vector Engineering, "Design Report for the Surface Liners of the Module D Phase 1 Bioreactors at the Yolo County Central Landfill", October 2001.

[4] Yazdani, R., Moore, R. Dahl. K. and D. Augenstein 1998 Yolo County Controlled Landfill Bioreactor Project. Yolo County Public Works and I E M, Inc. Yolo County Public Works and I E M, Inc. report to the Urban Consortium Energy Foundation (UUCETF) and the Western Regional Biomass Energy Program, USDOE.

The gypsum blocks manufactured by Electronics Unlimited are most typically used for soil moisture determinations in agriculture. Gypsum blocks establish equilibrium with the media in which they are placed and are, therefore, reliable at tracking increases in the soil's moisture content. However, the gypsum block can take considerable time to dry and therefore may not reflect the drying of the surrounding environment

3.2.3 Leachate Quantity and Quality

Leachate that is generated from each cell drains to a sump. A dedicated pump then either removes the leachate and pumps it to one of the on-site leachate storage ponds or recirculates it back to the cell. A flow meter measures rate and total volume pumped from the sump. Leachate is monitored for pH, electrical conductivity, dissolved oxygen, oxidation-reduction potential, and temperature, dissolved solids, biochemical oxygen demand, chemical oxygen demand, organic carbon, nutrients (NH_3, TKN, TP), common ions, heavy metals and organic priority pollutants.

3.2.4 Pressure

Pressure within the northeast anaerobic cell is monitored with ¼-inch inner diameter and $^3/_8$-inch outer diameter LLDPE sampling tubes. Each tube can be attached to a pressure gage and supplemental air source. By first purging the tube with the air source (to remove any liquid), and then reading the pressure, an accurate gas and/or water pressure (whatever is present at the tubing end in the waste) can be measured at each sensor location.

3.2.5 Landfill Gas Composition

Gas composition is measured utilizing a GEM-500 combustible gas meter, manufactured by Landtec.

3.2.6 Waste Sampling

Yolo County conducted the first waste sampling event for the northeast anaerobic cell on June 5, 2002 to quantify the methane generation potential of the waste prior to liquid addition. Waste was drilled with a 2-foot diameter auger to an approximate depth of 50 feet with samples taken at 5-foot intervals. Waste will be sampled from the northeast anaerobic cell annually for the next two years to monitor the progress of waste decomposition and compare actual methane generation to laboratory methane generation.

3.2.7 Surface Scan

Under current federal guidelines (40 CFR 60.752), landfills exceeding a specific size must monitor for methane surface emissions and any reading in excess of 500 PPM (40 CFR 60.755 (c)) requires corrective action to be taken. The Yolo County Central Landfill is not currently required to test for methane surface emissions. However, as part of the FPA, the County has proposed to conduct quarterly surface scans to demonstrate the emissions (or lack of) from a controlled bioreactor landfill. Methane concentrations are monitored with a model TVA-1000 Flame Ionization Detector (FID). Methane surface concentrations are monitored along the perimeter of the collection area and along a pattern that transverses the landfill at 15 meter intervals. A summary of the surface scans performed on the northeast anaerobic cell is presented below in Table 3-1.

Table 3-1. Surface Scan Results
Northeast Anaerobic Cell with Synthetic Surface Cover System

Surface Scan No.	Date	Max. Emissions Detected	Location of Max. Emissions
1	April 3, 2002	No fugitive emissions detected	Not Applicable
2	June 6, 2002	9 ppm	Southwest corner of the cell
3	September 19, 2002	8 ppm	Northwest corner of the cell

As presented in the table above, methane surface emissions from the northeast 3.5-acre cell are essentially negligible at under 1/50 of the "action concentration" of 500ppm. This effective control of surface emissions is due to 1) The installation of a membrane cover over the entire cell, and 2) The use of an active landfill gas extraction system. This is a highly significant finding, and strong evidence for the attainment of one of the project objectives, the near-total abatement of emissions of methane and VOC's.

3.3 NORTHEAST CELL OPERATION

Operation of the northeast anaerobic cell as a bioreactor began on March 27, 2002 when supplemental liquid was first added to the cell. The west side cell did not receive liquid during the contract period.

3.3.1 Leachate Recirculation

Leachate addition to the northeast cell began on March 27, 2002 . Each of the horizontal liquid injection lines was initially tested by pumping liquid into the line to confirm operation and correlate flow versus pressure for each injection lateral. Full-scale liquid addition commenced on June 13, 2002. Once the waste reaches field capacity, only enough liquid to maintain field capacity will be added.

During August 2002, leachate injection was temporarily halted due to scale buildup in the injection laterals which was significantly reducing the flow in the injection lines. In September a citric acid solution (pH approximately 4) was added to the injection laterals on the northeast anaerobic cell to dissolve the scale. This solved the problem as discussed earlier. Liquid injection resumed in the northeast cell on September 24, 2002. Approximately 1,009,643 gallons of supplemental liquid has been added and 466,940 gallons of leachate recirculated through the end of December 2002 with 67 percent added to Layer 1 and 31 percent added to Layer 2 (Appendix A, Figure 3-1).

3.3.2 Landfill Gas Collection

Landfill gas collection began December 13, 2001 once the necessary piping was installed at the end of November 2001. Gas collection prior to leachate addition was necessary to prevent "billowing" or excess gas pressure under the surface liner.

3.3.3 Results And Discussion

Nomenclature sensor names are represented numerically by the instrumentation layer in which the sensor is located, followed by the assigned sensor number. Layer 1 is represented by a 1, Layer 2 is represented by a 2, and so forth. The complete name of the sensor is denoted by the layer number – the sensor number. For example, the second sensor on Layer 1 is named 1-02.

3.3.3.1 Temperature

Temperature readings provide information on the wetting front of the waste. Temperature results are presented in Appendix A, Figures 3-2 to 3-5. Recent temperature fluctuations in Layer 1 and Layer 2 correspond to the addition of cool water (approximately 70°F) to the waste. Representative sensors that demonstrate the cooling trend during liquid injection and subsequent warming trend following liquid injection are provided in Appendix A, Figure 3-6. A summary of the results is presented below in Table 3-2.

Table 3-2. Temperature Summary for the Northeast Anaerobic Cell

	7/1/02 to 9/30/02			10/1/02 to12/31/02		
Layer	Minimum Temp. (°C)	Maximum Temp. (°C)	Average Temp. (°C)	Minimum Temp. (°C)	Maximum Temp. (°C)	Average Temp. (°C)
1	22.0	52.2	38.8	23.4	48.2	38.4
2	46.7	63.3	56.4	32.6	62.9	51.2
3	39.3	66.8	52.6	33.3	63.3	50.4

3.3.3.2 Moisture

The SCADA system started automated moisture data collection in March 2002. Moisture was previously measured manually with a Model MM 4 moisture meter manufactured by Electronics Unlimited. During the pilot scale project, Yolo County conducted laboratory tests with the PVC sensors to determine the relationship between the multimeter readings and the presence of free liquid in the PVC sensor. It was determined that a meter reading of less than 40 corresponded to an absence of free liquid. A reading between 40 and 80 corresponds to the presence of free liquid in the PVC pipe but less than saturated conditions. Readings of greater than 80 indicate saturated conditions; i.e. the PVC sensor is full of liquid.

Moisture sensors readings provide valuable information for assessing and controlling the liquid distribution within the waste. This information allowed better liquid management because liquid addition could be stopped in wetter areas while liquid addition continued in drier areas. Moisture results are presented in Appendix A, Figures 3-7 to 3-12. Since the start of full-scale liquid addition, the average moisture levels in Layer 1 and Layer 2 have generally increased to moisture levels in the some free liquid zone and completely saturated zone. In Layer 3, full-scale liquid addition has not commenced and moisture levels remain in the no free liquid zone. A summary of the results is presented below in Table 3-3.

Table 3-3. PVC Moisture Summary for the Northeast Anaerobic Cell

	7/1/2 to 9/30/02			10/1/02 to12/31/02		
Layer	**Minimum Moisture**	**Maximum Moisture**	**Average Moisture**	**Minimum Moisture**	**Maximum Moisture**	**Average Moisture**
1	3.8	94.8	47.8	1.9	94.8	66.9
2	3.4	94.8	30.0	2.8	94.8	61.9
3	3.3	89.4	25.6	1.9	91.3	25.3

3.3.3.3 Landfill Gas

Gas composition is measured from the horizontal gas collection wellheads located on top of the northeast anaerobic cell with the GEM-500. Gas flow is measured by differential pressures at the wellheads with a Dwyer Instruments, Inc., "Magnehelic" pressure gage. A thermal mass flow meter installed in the main header pipeline near the instrumentation shed records flow rate and total for all of the northeast cell. The meter is equipped with two separate calibration curves (for different gas constituent concentrations) and automatically corrects for temperature and pressure and records in standard cubic feet.

Gas collection lines are represented numerically by the layer in which the line is located, followed by a "G" and the number that denotes the line on a specific layer. For example, the first gas collection line on layer 3 is denoted 3-G1.

Landfill gas results are presented in Appendix A, Figures 3-13 to 3-17. Methane concentrations from the wellheads fluctuate based on the applied vacuum, barometric pressure, and the status of waste decomposition. In June 2002, the increase in oxygen and balance concentrations and the decline in methane and carbon dioxide concentrations can be attributed to the increase in vacuum applied to the gas collection system. In order to reduce landfill gas emissions while drilling for waste samples, the vacuum applied to the gas extraction system was increased resulting in some air intrusion into the northeast anaerobic cell. A summary of the results is presented below in Table 3-4.

Table 3-4. Landfill Gas Summary for the Northeast Anaerobic Cell for the period of December 16, 2001 to December 31, 2002.

Parameter	**Results**		
Cumulative Methane from December 16, 2001 to December 31, 2002	13.8×10^6 standard cubic feet (scf) (which is equivalent to approximately 2200 barrels of oil) 0.13 scf per lb. dry waste		
LFG Flow Rate	Minimum	Maximum	Average
	50.7 scf	150.7 scf	105.5 scf
Methane Concentration	Minimum	Maximum	Average
	47.5 %	55.6 %	52 %

By the yardstick of normalized yield at a specific interval since initiation of liquid addition, methane generation per pound of dry waste from the northeast anaerobic cell lags behind the pilot scale project by approximately 0.20 standard cubic feet (scf) as presented in Appendix A, Figure 3-17. The difference is most likely because liquid has primarily wetted the first and second lifts of waste (i.e. only part of the waste) in the northeast anaerobic cell whereas liquid was added in a manner that wetted all of the enhanced cell waste in the pilot scale project. Results from the June 2002 waste sampling generally indicates higher biochemical methane potential (BMP) in the northeast cell (BMP ranging between 19 and 82 mg of methane per gram of dry waste) than in the enhanced cell from the pilot scale project (BMP ranging between 28 and 32 mg of methane per gram of dry waste), as presented in Appendix A, Figures 3-18 and 7-16. Additionally, results indicate higher cellulose and hemicellulose to lignin ratios in the northeast cell than in the enhanced cell (Appendix A, Figure 3-19). These results confirm that the enhanced cell has already undergone a majority of the decomposition and gas production whereas the majority of waste from the northeast cell is still undergoing decomposition.

Full-scale liquid addition commenced in the northeast anaerobic cell in June 2002 and the rate of landfill gas generation subsequently increased. Additionally, the average methane concentration of landfill gas increased from 37.8 percent to 50.2 percent after August 2002, approximately two months after the start liquid addition (Appendix A, Figure 3-20).

Analytical results from December 2002 indicate lower methane levels at 40 percent compared to 48 percent detected by the GEM-500 in the field. Higher methane levels read in the field could be due to the presence of other gases, particularly hydrocarbons, that, according to the manufacturer, would be recorded as methane by the GEM. Results also show a general decline in volatile organic compounds (VOC). Figure 3-21 in Appendix A compares the difference between analytical results between March 8, 2002 with May 29, 2002 and December 5, 2002. When comparing landfill gas analysis results for May 2002 and December 2002, the concentration of vinyl chloride and cis-1,2-dichloroethane increased by 3,050 parts per billion (ppb) and 520 ppb respectively. These two constituents are the products of the anaerobic decomposition of both trichloroethene (TCE) and tetrachloroethene (PCE), both of which have shown a decreasing trend in concentration. We anticipate that all of the volatile constituents monitored in the landfill gas will eventually decrease over time to values similar to the recent concentrations recorded in the pilot scale project.

During liquid addition, several of the gas collection lines became filled with injected liquid and were temporarily closed. Even with several gas collection lines closed, no billowing of the surface liner was observed, suggesting the remaining open lines were able to effectively remove gas. Additionally, when landfill gas was monitored from the LCRS layer below the waste, only minimal methane was detected, suggesting the landfill gas collection system has effectively created an inward gradient over the entire outer surface, including the base, of the waste mass.

To further assess performance of the horizontal landfill gas collection system, methane flow rates for gas collection lines with continuous piping were compared with those with only partial piping. Figure 3-2 below presents data from two representative gas lines (other gas lines—data omitted here--yielded similar results). Results suggest strongly that effective gas capture is possible with only partial piping provided a highly permeable medium such as shredded tires is used appropriately in the extraction system design. Further monitoring will be necessary to confirm these results because of the non-homogeneous nature of waste.

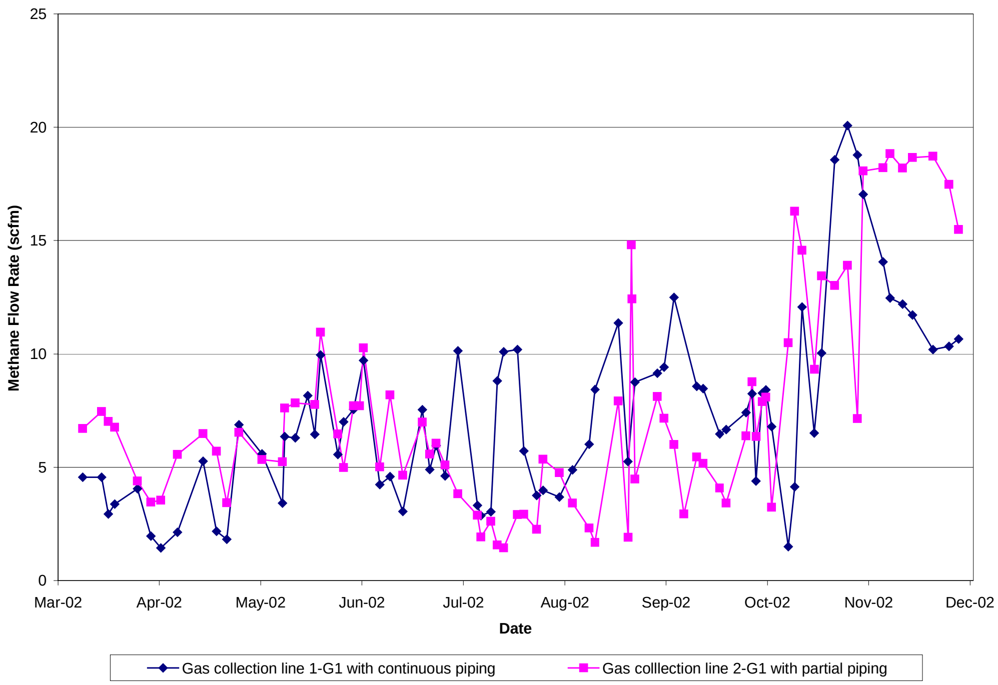

Figure 3-2. Methane flow rates for selected gas collection lines.

3.3.3.4 Leachate Quantity and Quality

After July 24, 2002, all leachate generated was recirculated back to the northeast anaerobic cell with the exception of 35,460 gallons of leachate removed during injection line cleaning between September 24, 2002 and October 4, 2002. Approximately 1,009,643 gallons of supplemental liquid has been added and 466,940 gallons of leachate recirculated to the northeast anaerobic cell since March 27, 2002 (Appendix A, Figure 3-1).

A background leachate sample was collected from the northeast 3.5-acre cell in February 2002 prior to liquid addition. Leachate was sampled on a monthly basis from May 2002 to October 2002 for analytical testing. Although liquid addition began in March 2002, samples were not collected for April because leachate pumping records indicated that only minimal leachate had been generated by the cell, and thus any samples collected and analyzed would have been representative of baseline conditions. Field chemistry and selected analytical results are presented below in Table 3-5.

In October 2002, the biochemical oxygen demand (BOD) was nearly twice the chemical oxygen demand (COD). Because leachate chemistry typically indicates higher COD than BOD, the October 2002 results are suspect and will be confirmed during the next monitoring event.

Table 3-5. Field Chemistry and Selected Laboratory Chemistry for Leachate Sampled from the Northeast Anaerobic Cell

PARAMETER	**Date:**	**2/14/2002**	**5/14/2002**	**6/20/2002**	**7/23/2002**	**8/13/2002**	**9/26/2002**	**10/17/2002**
Field Parameters:	**Units**							
PH		7.13	7.40	7.60	7.44	7.48	7.47	7.35
Electrical Conductivity	µS	6583	6095	4054	11510	15860	12440	10230
Oxidation Reduction Potential	mV	-119	80	94	-7	43	-35	-25
Temperature	C	19.9	25.9	26.5	30.5	30.5	28.4	26.0
Dissolved Oxygen	mg/L	0.65	1.4	2.04	0.33	1.31	3.66	2.96
Total Dissolved Solids	ppm	5244	4059	3062	9740	14050	10770	8640
General Chemistry:								
Bicarbonate Alkalinity	mg/L	1740	1760	1110	3740	5150	3960	4010
Total Alkalinity as CO_3	Mg/L	1740	1760	1110	3740	5150	3960	4010
BOD	mg O/L	20	19	10	200	490	1400	3000
Chemical Oxygen Demand	mg O/L	633	791	196	1620	2820	2830	1810
Chloride	Mg/L	1070	1030	617	1950	2830	1870	1380
Ammonia as N	Mg/L	30	26.3	13.5	131	264	255	289
Nitrate-Nitrite as N	Mg/L	<0.03	<1.5	<0.015	0.061	0.22	1.4	<0.009
Total Kjeldahl Nitrogen	Mg/L	53.1	40	21.8	201	354	326	358
Total (Non-Volatile) Organic Carbon	Mg/L	2.2	132	68.8	544	713	943	588
Total Sulfide	Mg/L	1.3	1.3	0.74	1.2	2.5	1.1	1.4
Dissolved Iron	Mg/L	1.1	0.39	0.19	2.9	1.8	3.9	4
Dissolved Magnesium	Mg/L	323	262	NA	535	655	480	437
Dissolved Potassium	Mg/L	152	133	NA	215	336	319	348

The biological activity in the landfill controls the leachate quality. Many studies have suggested that the stabilization of waste in a landfill takes place in several phases, as documented by Farquhar and Rovers, below. In a large-scale landfill such as the Yolo County full-scale Bioreactor landfill project, where waste is placed over a long period of time, the waste stabilization phases overlap and the leachate and gas characteristics will also reflect this phenomenon. The rate and characteristic of leachate produced and the landfill gas generated from a landfill varies in each phase of landfill stabilization. In addition, the type of waste placed in a landfill will greatly affect the volume of biogas produced.

In general, the leachate will start with high pollutant load as indicated by BOC and COD. As decomposition proceeds the pollutant load will fall. The northeast cell, which is still having liquid added and is partially dry, has not reached a point where bioremediation of pollutants is evident. Instead it is expected that as more water is injected in the upper lifts of waste in the bioreactor the leachate pH will continue to drop. Shortly after, the methane fermentation process will begin to consume the acids and as the leachate recirculation continues the concentration of metals and nutrients seen in the leachate should decrease over time with increase in landfill gas generation.

3.3.3.5 Leachate Injection System

Following full-scale liquid injection on Layer 1 June 2002, the average PVC moisture level on Layer 1 quickly increased from sensor-specific qualitative readings (significance described earlier) near 15 to 43. Moisture levels on Layer 2 likewise increased from near 24 to 35 in July 2002 following full-scale liquid injection. Temperatures on Layer 1 and Layer 2 subsequently declined as the initial wetting front reached waste and the temperature sensors in those layers. These results indicate good liquid distribution from the horizontal injection lines.

Flow rates vary for several of the leachate injection lines. This may be due to kinks incurred in the leachate injection piping during waste compaction. While flow rates vary, results from flushing the leachate injection lines to remove HDPE particles suggest the lines are still continuous. Leachate injection lines were flushed to remove HDPE particles that may have entered the line from pipe work on the injection system. While flushing, the liquid exited the opposite end of the injection lines. This outcome occurred for all injection lines, indicating leachate injection lines are continuous and have no severe fractures that will affect operations.

3.4 WEST-SIDE ANAEROBIC CELL

The west-side anaerobic cell is located on the western 6 acres of Phase 1, Module D. Filling in the west-side anaerobic cell was complete in August 2002 with a total of 166,294 tons of waste placed.

3.4.1 Construction

Construction of the west-side anaerobic cell comprised steps of waste placement, liquid management system, gas management system, and surface liner installation. An overview of these steps is presented below.

3.4.1.1 Waste Placement

Waste placement began on March 8, 2001 and was completed on August 31, 2002. Waste was filled in the same fashion as with the northeast cell. However waste was placed in four lifts of approximately 15-foot thickness. Side slopes were 2.5 feet horizontal to1 foot vertical on interior slopes and 3 feet horizontal to 1 foot vertical on exterior slopes.

3.4.1.2 Liquid Management System

Horizontal liquid injection lines were installed between lifts 2 and 3, and 3 and 4 laterally spaced about 40 feet apart. In addition, three injection lines were installed on top of lift 4, spaced every 25 feet. Each injection line was a 1.25-inch-diameter high-density polyethylene (HDPE) pipe placed horizontally (east to west), and extending completely through the waste. Each injection line was perforated by drilling a $^{1}/_{8}$ or $^{3}/_{32}$-inch hole every 10 or 20 feet (depending on which line). Connection to laterals was as with the northeast cell (described previously).

3.4.1.3 Gas Management System

Horizontal landfill gas (LFG) collection lines were installed between lifts 2 and 3, and 3 and 4, and on top of lift 4. The gas collection lines between layers are spaced approximately 80 feet apart and consist of alternating 4 and 6-inch–diameter schedule 80 polyvinyl chloride (PVC) pipe. At each line, shredded tires were used as the permeable media. For gas collection from the top lift of the cell Yolo County constructed trenches filled with tires.

3.4.1.4 Surface Liner

Vector was retained to provide design, plans and specifications for a surface lining system (refer to section 3.1.4). In contrast to the northeast anaerobic cell, which utilized a reinforced polypropylene membrane (RPP), a 40-mil linear low-density (LLDPE) geomembrane material was found at a greatly reduced cost, and selected. The installation of the surface liner was completed in October 2002.

3.4.2 Monitoring

Temperature, moisture, leachate quantity and quality, and LFG pressure and composition are monitored as with the northeast cell. Monitoring was through an array of sensors placed within the waste and in the leachate collection and recovery system (LCRS). Each sensor location received a temperature sensor (thermistor), a PVC moisture sensor, and in some locations, a linear low-density polyethylene (LLDPE) tube.

Waste temperature is monitored with thermistors identical to those of the northeast cell.

Moisture levels are measured with polyvinyl chloride (PVC) moisture sensors and gypsum blocks as with the northeast cell .

Leachate generated from the west-side anaerobic cell either drains to the west-side Module D leachate collection sump and is pumped either pumped to one of the on-site leachate storage ponds or recirculated back to the cell. A flow meter measures rate and total volume pumped from the sump. Leachate levels within waste for the west-side anaerobic cell is monitored with ¼-inch inner diameter and $^3/_8$-inch outer diameter LLDPE sampling tubes. These tubes can also be used for gas sampling.

Landfill Gas Composition is measured as with the northeast cell, utilizing a GEM-500 combustible gas meter manufactured by Landtec

3.4.2.1 Waste Sampling

Yolo County conducted the first waste sampling event for the west-side anaerobic cell on June 5, 2002 to quantify the methane generation potential of the waste prior to liquid addition. Waste was sampled as with the northeast cell whose sampling took place at the same time.

3.4.2.2 Surface Scan

West side cell methane concentrations were monitored with a model TVA-1000 Flame Ionization Detector (FID. A summary of the surface scans performed on the west-side anaerobic cell is presented below in Table 3-6.

Table 3-6. Summary of Surface Scans Performed on the West-Side Anaerobic Cell with no Synthetic Surface Cover System

Surface Scan No.	Date	Max. Emissions Detected	Location of Max. Emissions
1	April 3, 2002	50 ppm	Southwest corner of the cell
2	June 6, 2002	37 ppm	On top the cell, along the access road leading to the active waste placement area
3	September 19, 2002	124 ppm	Southwest corner of the cell. This area was rescanned and surface concentrations decreased to approximately 10 ppm.

It was expected that results from the surface scan for methane emissions from the west-side anaerobic cell would be greater than from the northeast anaerobic cell since the west-side cell was still undergoing active waste placement and a membrane cover had not yet been installed. We expect lower surface emissions to be detected during the next surface scan after the installation of the surface cover system.

3.4.3 Operation Plan: West Side Cell

Operation of the west-side anaerobic cell will begin once waste placement, sensor installation, landfill gas (LFG) collection system, leachate recirculation systems, and SCADA control systems are complete. Leachate recirculation and landfill gas collection are planned to follow the same general procedure as with the northeast cell

3.4.4 Results And Discussion to Date

Sensor names are represented numerically by the instrumentation layer in which the sensor is located and by the assigned sensor number for that layer. Layer 1 is represented by a 1, Layer 2 is represented by a 2, and so forth. The complete name of the sensor is denoted by the layer number – the sensor number. For example, the second sensor on Layer 1 is named 1-2.

3.4.4.1 Temperature

Temperature results are presented in Appendix A, Figures 4-1 to 4-4. A summary of the results is presented below in Table 3-7.

3.4.4.2 Moisture

Moisture results are presented in Appendix A, Figures 4-5 to 4-8. The average moisture levels in the west-side cell are higher than moisture levels observed in the northeast cell. This is most likely due to a large portion of the waste placed during the winter months. A summary of the results is presented below in Table 3-8.

Table 3-7. Temperature Summary for the West-Side Anaerobic Cell

	7/1/2 to 9/30/02			10/1/02 to12/31/02		
Layer	**Minimum Temp. (°C)**	**Maximum Temp. (°C)**	**Average Temp. (°C)**	**Minimum Temp. (°C)**	**Maximum Temp. (°C)**	**Average Temp. (°C)**
1	31.7	44.6	40.1	34.3	43.8	40.5
2	40.9	44.3	42.8	43.7	45.6	44.4
3	24.3	56.7	45.4	43.9	58.8	48.1

Table 3-8. PVC Moisture Summary for the West-Side Anaerobic Cell

	7/1/2 to 9/30/02			10/1/02 to12/31/02		
Layer	**Minimum Moisture**	**Maximum Moisture**	**Average Moisture**	**Minimum Moisture**	**Maximum Moisture**	**Average Moisture**
1	24.2	66.7	38.2	27.0	67.4	40.1
2	0.0	63.0	60.3	0.8	66.6	66.2
3	28.2	42.3	38.2	39.4	47.8	42.6

3.4.4.3 Landfill Gas Results to Date

Landfill gas results have been assembled in Appendix A, Figures 4-9 to 4-11. Methane concentrations from the wellhead fluctuate based on the applied vacuum, barometric pressure, and the status of waste decomposition. After surface liner installation in October 2002, the collection rate of landfill gas could be drastically increased. Additionally, methane and carbon dioxide concentrations increased while and oxygen and balance concentrations decreased. A summary of the results is presented below in Table 3-9.

Table 3-9 Landfill Gas Summary for the West-Side Anaerobic Cell for the period of May 7, 2002 to December 31, 2002.

Parameter	**Results**		
Cumulative Methane from May 7, 2002 to December 31, 2002	2.5×10^6 standard cubic feet (scf) (which is equivalent to approximately 410 barrels of oil) 0.008 scf per dry lb. Waste		
LFG Flow Rate	Minimum	Maximum	Average
	3.0 scfm	41.2 scfm	23.2 scfm
Methane Concentration	Minimum	Maximum	Average
	14.0 %	47.7 %	33.4 %

Landfill gas was last sampled from the west-side base layer wellhead in May 2002 and sent to an independent laboratory for analytical testing.

3.4.4.4 Leachate Quantity And Quality

Prior to October 2001, leachate data reflects rainfall rather than actual leachate generation because the cells were only partially filled, and portions of the leachate collection and removal system were exposed to rainfall. Between October 2001 and December 2002, approximately 108,100 gallons of leachate was generated from the west-side cell (Appendix A). Leachate field chemistry and selected analytical results are presented below in Table 3-10.

Table 3-10 Field Chemistry and Selected Laboratory Chemistry for Leachate Sampled from the West-Side Anaerobic Cell

PARAMETER	**DATE:**	**2/14/2002**	**5/14/2002**	**6/20/2002**	**7/23/2002**	**8/13/2002**
Field Parameters:	**Units**					
PH		6.74	6.8	6.72	6.85	6.71
Electrical Conductivity	µS	3530	3851	3944	3899	3810
Oxidation Reduction Potential	mV	-62	-46	-19	-38	-36
Temperature	C	24.9	26.2	25.2	25.7	26.9
Dissolved Oxygen	mg/L	3.15	1.54	1.31	3.62	2.6
Total Dissolved Solids	ppm	2617	2871	2960	2965	2908
General Chemistry:						
Ammonia as N	mg/L	20.3	23.5	21.2	23.8	25
Bicarbonate	mg/L	1700	1780	1730	1710	1680
BOD	mg O/L	28	12	12	7.9	12
Chemical Oxygen Demand	mg O/L	350	300	274	270	262
Chloride	mg/L	187	333	358	341	366
Nitrate/Nitrite as N	mg/L	0.016(tr)	<1.5	<0.03	<0.015	<0.015
Sulfate	mg/L	1.7(tr)	<10	0.80(tr)	2.2	0.75(tr)
Total (Non-Volatile) Organic Carbon	mg/L	112	85.2	86.5	82.7	78.1
Total Alkalinity as CaCO3	mg/L	1700	1780	1730	1710	1680
Total Kjeldahl Nitrogen	mg/L	32.6	31.1	31.5	31.4	31
Total Sulfide	mg/L	0.033(tr)	<0.014	<0.014	0.023	<0.014
Dissolved Iron	mg/L	0.4	0.035(tr)*	1.9	0.59	0.11
Dissolved Magnesium	mg/L	198	343	NA	217	185
Dissolved Potassium	mg/L	55.2	58.6	NA	37.8	32.5

3.5 MODULE 6D BASE LINER

The three bioreactor cells share a common composite liner system, designated the Module 6D primary liner. This composite liner system was constructed in 1999 and was designed to exceed the requirements of Title 27 of CCR and Subtitle D of the Federal guidelines.

Readers interested in details of the base liner may consult the more detailed Yolo County report submitted to the National Energy Technology Laboratory under DE-AC26-99FT40613. For purposes here, it can be noted that leachate heads over the base liner have been well below allowable limits. There have been no indications of any breaches of liner integrity.

4 SUPERVISORY CONTROL AND DATA ACQUISITION SYSTEM (SCADA)

The Supervisory Control and Data Acquisition (SCADA) system is used to monitor the various sensors and control the operation of the full-scale bioreactor. The field electronics are linked by radio signal to a computer located in our Woodland office.

4.1 Hardware Installation

The data collection hardware has been installed in a shed located at the southern limit of Module 6D. All instrumentation installed in the northeast anaerobic, west-side anaerobic, aerobic, and on the Module 6D composite liner will be connected to an Allen-Bradley central processor which is radio linked to a computer located in our Woodland office.

Image 4-1: Completed hardware installation

4.2 Software Programming

The SCADA programming using Wonderware software is currently being developed by a consultant, A-TEEM Electrical Engineering. The first phase of the software development is complete and encompasses data collection from the instrumentation installed on the Module 6D liner, northeast anaerobic, and southeast aerobic modules. (The southeast aerobic module is not covered in this report) Once the remaining instrumentation in the west-side anaerobic cell has been run to the shed, it will be incorporated into the system. The following images provide an overview of the SCADA programming.

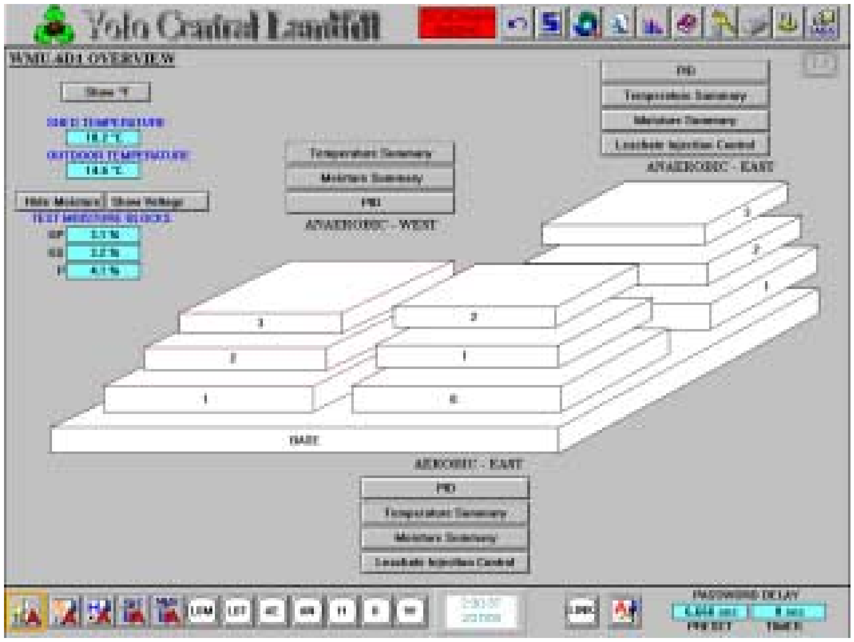

Image 4-2: SCADA overview screen. From here you can access each layer within the bioreactor cells.

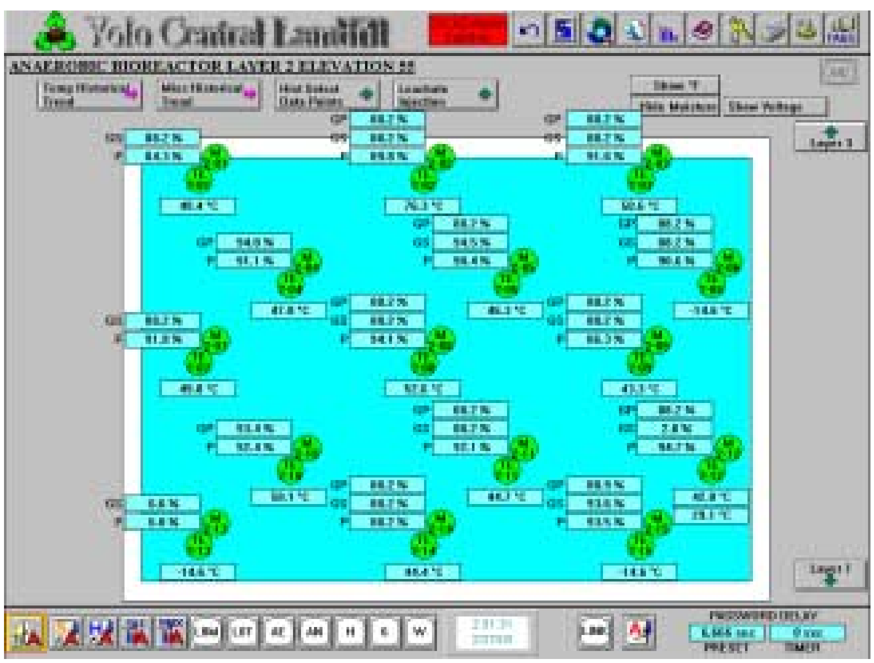

Image 4-3: NE anaerobic cell, layer 2 screen depicting temperature and moisture data.

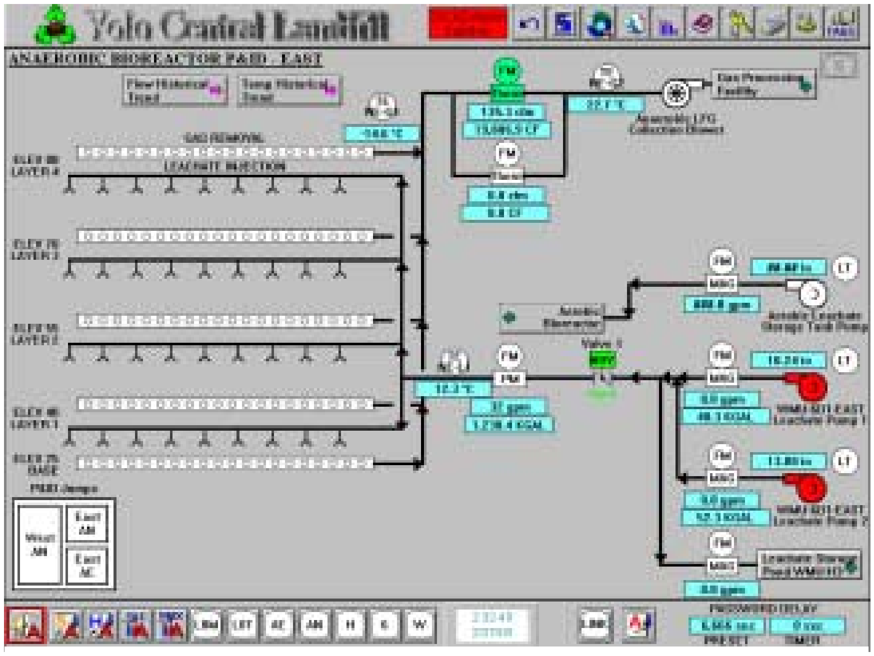

Image 4-4: Piping overview screen, displaying flows from the various meters. This screen can also be used to access leachate injection controls.

Image 4-5: NE anaerobic bioreactor layer 3 and 4 leachate injection control.

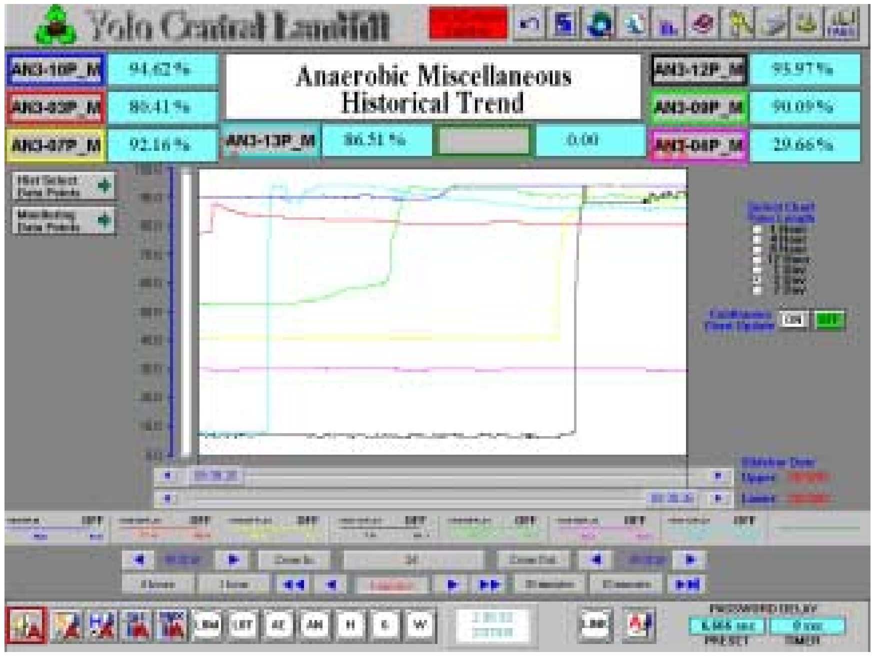

Image 4-6: Historical data can be graphed and displayed directly on the screen.

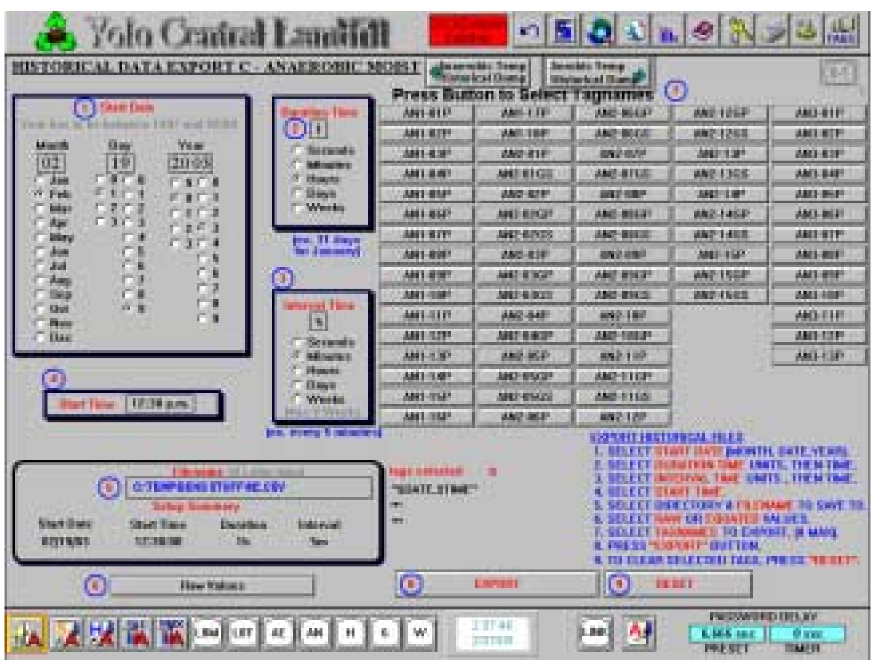

Image 4-7: Historical data export screen. Data is exported to a database for manipulation and graphing

5 CONTINUING OPERATION OF THE 10,000 TON PILOT SCALE PROJECT

The pilot scale project consists of two, 10,000 square foot, test cells that began operation in 1996. This project, incidentally, holds an all-time record for being the longest-running pilot project of its type in the world. One cell has been designated the "enhanced" cell in which supplemental liquid was added and leachate was recirculated. The "control" cell was constructed identically to the "enhanced" cell, however no liquid has been added. The earlier details of operation have been described[2] and so that detail is omitted here. A paper is also being prepared for the Solid Waste Association of North America Landfill Conference, and electronic copies will be available from (among others) Don Augenstein, IEM, 650-856-2850. Only a brief summary of results will be presented below

5.1 Operation

Two cells of approximately 9,000 tons capacity were constructed in 1994-95. Methane enhancement began in late 1996 with wellwater addition and recirculation of resultant leachate. Liquid inflows and outflows were monitored by flowmeters. Gas flows were monitored by accurate corrosion resistant positive displacement flowmeters. Temperature, moisture, waste composition and gas composition have been measured in a manner similar to the measurements described earlier for the northeast and west side cells.

5.2 Results

Refuse temperatures Multilevel temperatures recorded throughout the waste from April 1995-January 2003 are shown in Figures 5-1 and 5-2. 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 7-2, Appendix A shows cumulated moisture flows into, and leachate exiting the 9,000 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 added carefully.

[5] Yazdani, R., Moore, R. Dahl. K. and D. Augenstein 1998 Yolo County Controlled Landfill Bioreactor Project. Yolo County Public Works and I E M, Inc. Yolo County Public Works and I E M, Inc. report to the Urban Consortium Energy Foundation (UCETF) and the Western Regional Biomass Energy Program, USDOE

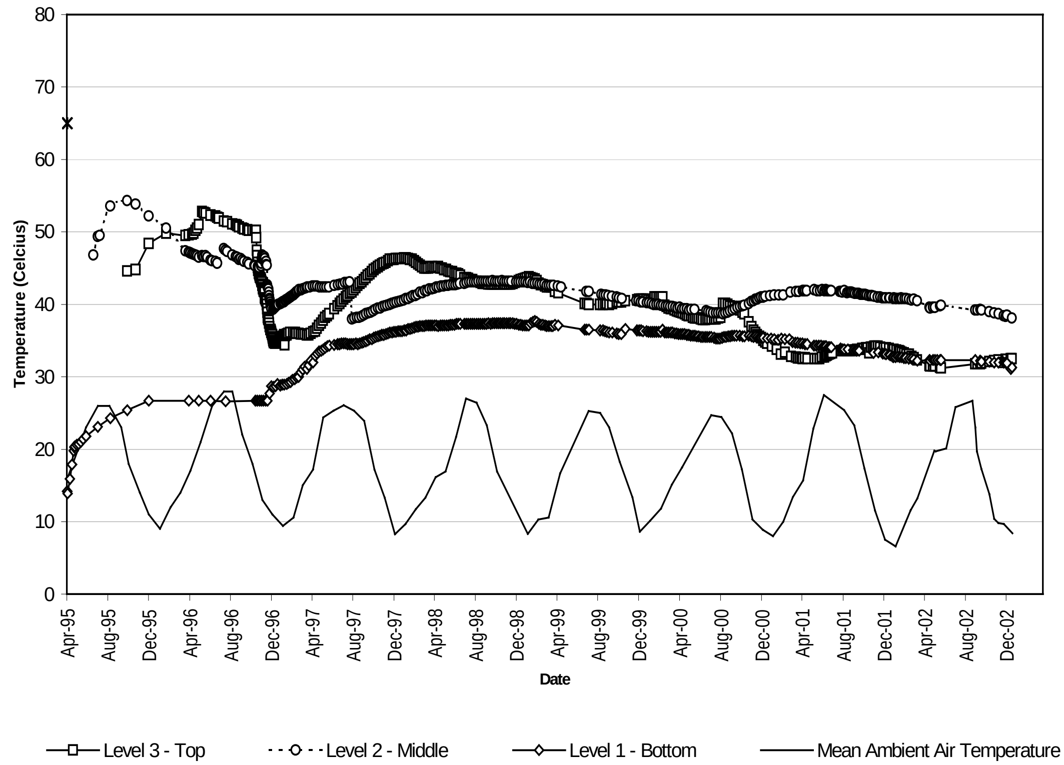

FIGURE 5-1 ENHANCED CELL TEMPERATURE vs. TIME Apr 1995-Jan. 2003

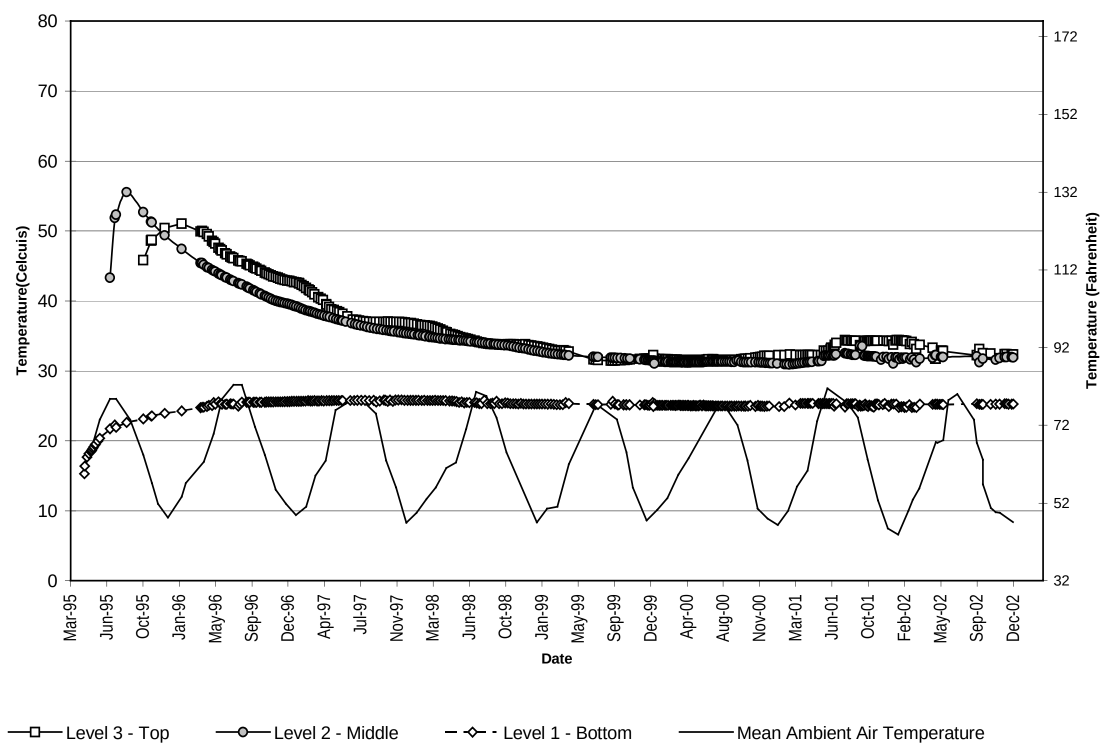

FIGURE 5-2. CONTROL CELL TEMPERATURE VS. TIME Apr. 1995-Jan 2003

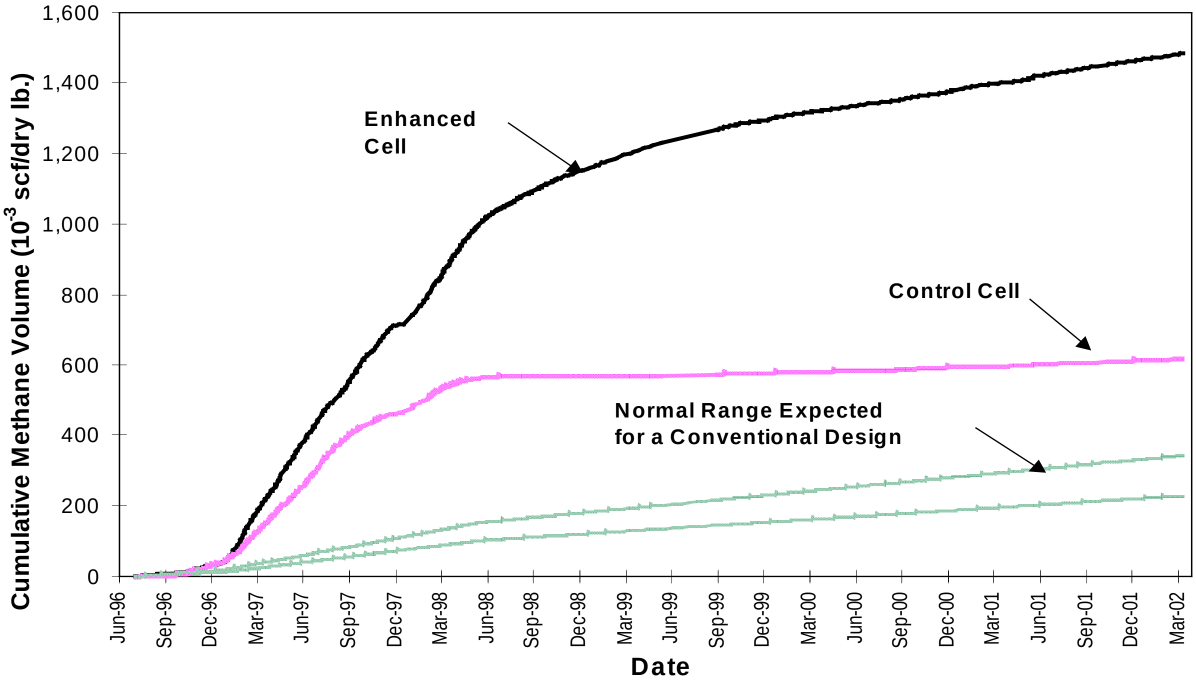

FIGURE 5-3 ENHANCED AND CONTROL CELL CUMULATED METHANE vs. TIME 1996-2003 AND COMNPARISON WITH "NORMAL"

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 per square feet 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. It is important to note that the rates of moisture addition at 0.2 to 0.6 gallons per square feet 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.

Methane generation enhancement is one of the most important findings of the project. Landfill gas data from June 1996 to April 2002 (see Figure 5.3) 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). 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 5.3 is quite interesting: The control cell also started with rapid methane generation. This rapid start is thought due to its initial elevated temperature 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. .

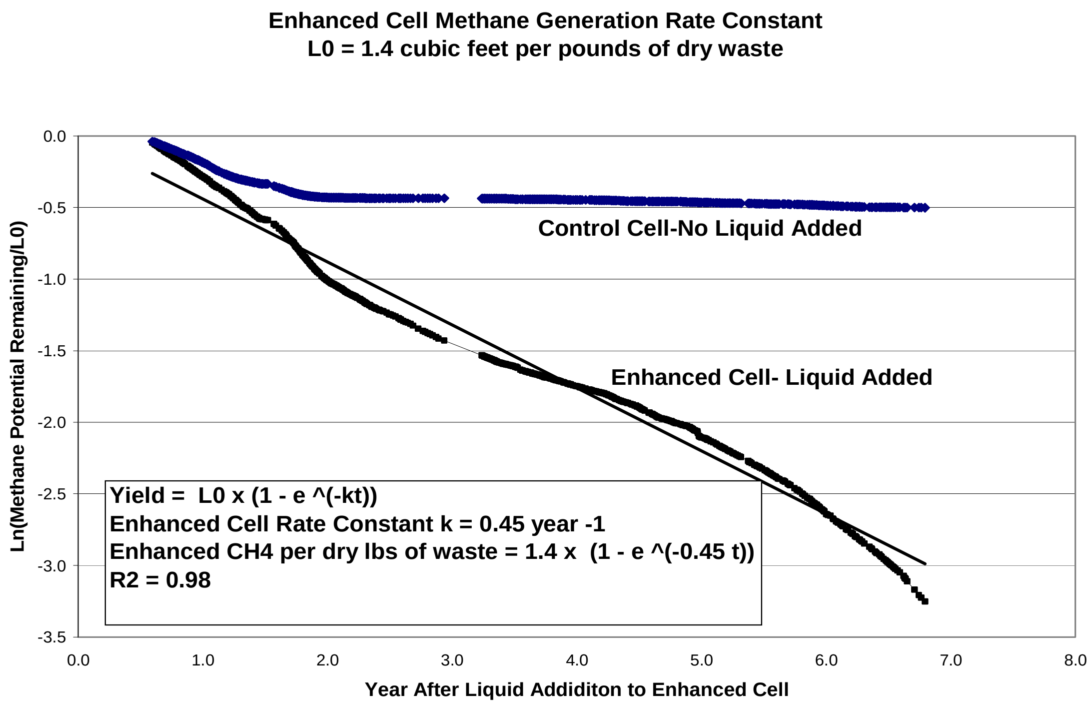

FIGURE 5-4 RATE CONSTANT CALCULATION FOR CONTROL AND ENHANCED PILOT-SCALE CELLS

Rate constant for methanogenesis (i.e. decomposition to methane, Figure 5-4). The rapid decomposition of waste in the enhanced cell, as seen from 6 years' results, indicates a k value over 0.4 $year^{-1}$, over fivefold the "normal" range of k = 0.04-0.08 $year^{-1}$. For these first 6 years, a "standard" plot using assumed Lo of 1.4 cubic feet of methane per dry pounds of waste suggests an apparent k value of 0.45 $year^{-1}$. At the assumed Lo 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. 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.

Leachate chemistry monitoring has continued through the contract interval. The leachate composition in terms of selected parameters from the pilot scale enhanced cell is shown in Table 5-1.

Table 5-1. Field Chemistry and Selected Laboratory Chemistry for Leachate Sampled from the Enhanced Cell between November 2001 and November 2002.

PARAMETER	**DATE:**	**11/8/01**	**2/26/02**	**3/27/02**	**5/14/02**	**8/26/02**	**11/21/02**
Field Chemistry:							
PH		7.24	7.39	7.36	7.46	7.35	7.38
Temperature	C	24.2	23.5	24.3	24.9	27.8	24.7
Oxidation Reduction Potential	mV	-122	-154	-139	-154	-224	-77
Electrical Conductivity	µS	11,970	12,380	13,020	13,830	14,500	13,430
Dissolved Oxygen	mg/L	NA	0.17	0.13	0.16	0.21	0.22
Total Dissolved Solids	ppm	10,240	10,620	11,120	11,840	12,800	11,760
General Chemistry:							
Bicarbonate	mg/L	3810	4040	4160	4430	4400	4320
Total Alkalinity as CaCO3	mg/L	3810	4040	4160	4430	4400	4320
BOD	mg O/L	84	57	120	3.6[1]	120	77
Chemical Oxygen Demand	mg O/L	2060	2190	2530	2750	2810	2530
Chloride	mg/L	1570	1740	1870	1990	2240	1610
Ammonia as N	mg/L	510	517	483	505	650	567
Nitrate/Nitrite as N	mg/L	0.095	<0.051	<0.015	<1.5	<0.15	0.023(tr)
Total Kjeldahl Nitrogen	mg/L	543	520	534	615	693	678
Sulfate	mg/L	174	106	78.5	132	170	54.1
Total (Non-Volatile) Organic Carbon	mg/L	732	194	593	837	1110	792
Dissolved Iron	µg/L	340	450	500	310	600	1300
Dissolved Magnesium	mg/L	333	307	302	357	370	352

[1]=None of the sample dilutions met the criteria of at least 2 mg/l dissolved oxygen depletion. The reported result was from the least diluted sample. Due to holding time constraints, reanalysis was not possible.

The leachate pollutant load has decreased to a low and stable level indicated by Chemical Oxygen Demand (COD) ranging between 2000 and 2800 mg/liter. Representative leachate parameters are graphed in figures 5-5 and 5-6.

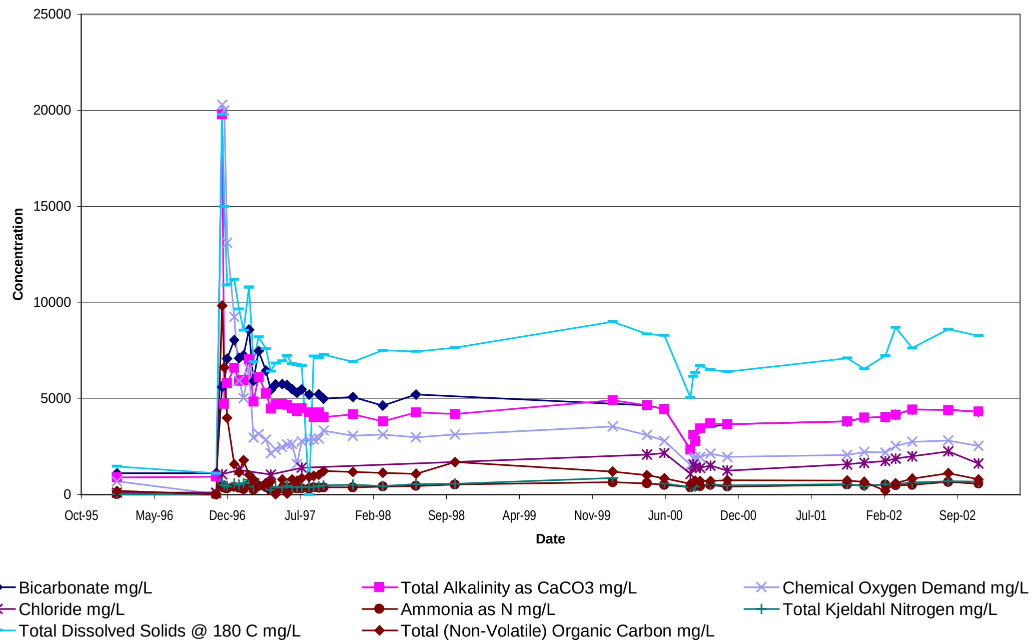

Figure 5-5. Selected Parameters for Leachate Sampled from the Enhanced Cell.

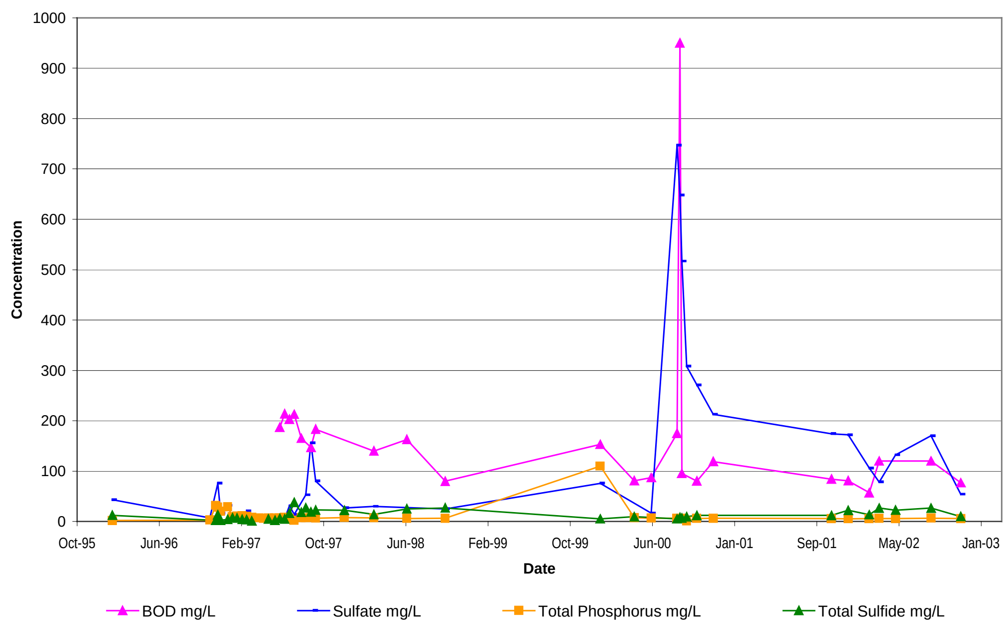

Figure 5-6 Additional Selected Parameters For Leachate Sampled From The Enhanced Cell

Settlement and volume reduction has been monitored since May 1996. With the start of liquid addition the enhanced cell settlement dramatically increased. As of January 2003, the enhanced cell settled more than four times as much as the control cell, averaging 17.71 percent (2,104 cubic yards) and 4.01 percent (498 cubic yards) respectively. A graph of the control and enhanced cell average settlement is provided below as Figure 5-7.

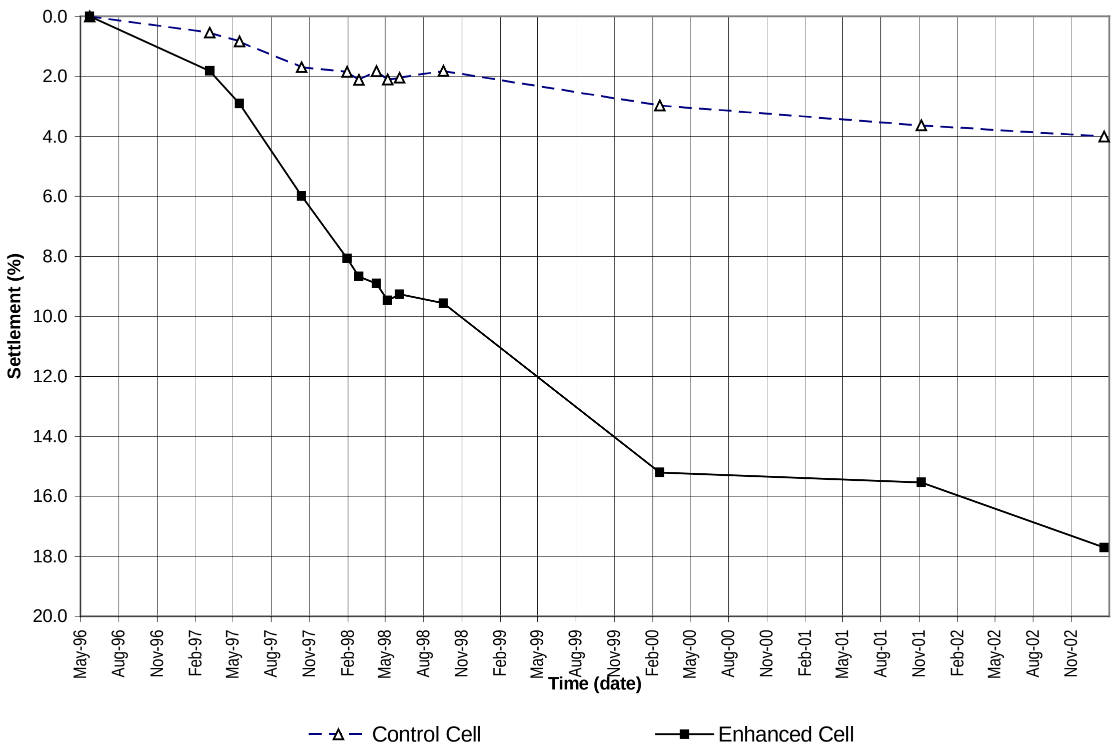

Figure 5-7. Average Settlement for the Pilot Scale Project

6 CONCLUSIONS

Results from the pilot scale project demonstrate the bioreactor "controlled" landfill ability to maximize the energy potential of municipal solid waste by accelerating waste stabilization and biogas generation and combining this better generation control with improved landfill gas collection efficiency. The full-scale project shows promising results that suggest it will give similar performance and methane enhancement to that of the pilot scale project. The performance of the cells were assessed by monitoring biological conditions in the cell (moisture, temperature, gas composition, leachate composition), gas generation, and gas collection system efficiency.

6.1 Full Scale Projects

With the construction complete, and full-scale operation underway, the response of the northeast anaerobic cell is generally as expected. Moisture sensors are indicating that injected liquid is being distributed relatively uniformly. Temperatures within the cell are normal and within the range necessary for anaerobic decomposition.

Gas production rate has steadily increased over time (and we expect it to continue to increase over the next year). Methane totaling 13.8 x 10^6 scf has been removed from 65,104 tons of waste in the northeast cell and 2.5 x 10^6 scf has been removed from 166,294 tons of waste in the west-side cell. Methane generation per pound of dry waste from the northeast anaerobic cell is lagging behind the pilot scale project at the same interval after liquid addition by approximately 0.20 standard cubic feet (scf). The difference is most likely because liquid addition has been partial, to the first and second lifts of waste in the northeast anaerobic cell whereas liquid was added to the top of the waste (thereby wetting the lower lifts) in the pilot scale project. Results from the June 2002 waste sampling event generally indicate higher biochemical methane potential (BMP) and higher cellulose and hemicellulose to lignin ratios in the northeast cell than in the enhanced cell. These results confirm that the enhanced cell has already undergone a majority of the decomposition and gas production whereas the majority of waste from the northeast cell is still undergoing decomposition. Thus, methane generation is expected to increase upon the commencement of liquid addition in upper lifts of the northeast anaerobic cell.

With less than a year of leachate injection and recirculation in the northeast cell, it is evident that recirculation is an effective strategy to reduce pollutants in landfill gas. Several VOC concentrations within the leachate and landfill gas have decreased since the start of liquid addition and recirculation. It is expected that as more liquid is injected in the waste the VOC levels in the landfill gas and leachate will continue to decline and concentration of metals and nutrients seen in the leachate to decrease.

During liquid addition, several of the gas collection lines became clogged with injected liquid and were temporarily closed. While several of the gas collection lines were closed, no billowing of the surface liner was observed, suggesting the remaining open lines were able to effectively remove gas. Methane flow rates between wells with continuous gas collection piping and partial piping indicate no significant difference in the performance of the wells based on construction materials. These results coupled with the amount of methane recovery suggest promising results as to the performance of the horizontal pipe and shredded tire media located in the waste and near the landfill surface for the gas recovery system.

Fugitive methane emissions from the northeast 3.5-acre cell are extremely low, from a practical standpoints near-negligible. Two major items that are responsible for this effective control of surface emissions are: 1) The installation of a synthetic cover over the entire cell, and 2) The use of an active landfill gas extraction system. Higher methane emissions have been detected from the west-side anaerobic cell. Because the west-side cell was still undergoing waste placement during the surface scans and a membrane cover had not been installed, greater methane emissions are expected, compared with the northeast cell. We expect to detect lower fugitive surface emissions in the future due to the installation of the west-side surface liner. These results further indicate that gas capture through shredded tire media located near the landfill surface is an effective strategy to minimize surface emissions.

Moisture sensors provided valuable information for controlling and assessing the liquid distribution within the waste while temperature sensors offered further information on the cooling trend in the waste. Both moisture and temperature data indicate that liquid was generally distributed uniformly at injection locations in the waste. These results coupled with liquid injection data indicate that horizontal pipes embedded in shredded tires are an effective strategy for liquid addition.

Monitoring results for the first year of operation from the northeast 3.5-acre bioreactor are promising. The results demonstrate that landfill operation as a bioreactor will increase gas generation, reduce constituents in landfill gas and leachate, and reduce fugitive surface emission. Additionally, results indicate that liquids can be added to the landfill with very acceptably low (under 10% of statutory limits) hydraulic head over the primary liner.

6.2 Pilot Scale Project

Since November 1999, landfill gas production from both the enhanced and control cells has remained relatively constant. Gas production from the control cell is limited by the moisture content of the waste as evident by the array of moisture sensors indicating dry waste. Low landfill gas production rates in the enhanced cell is most likely due to the steady depletion of biodegradable material remaining in the enhanced cell.

With the enhanced cell now operating for over six years, leachate recirculation has proved to be extremely effective in enhancing decomposition and methanogenesis by all available indicators. Analytical results suggest that the stabilization of leachate constituents occurred within the first two years of operation. Additionally, analytical results show that the concentration of leachate constituents and landfill gas constituents in the enhanced cell are considerably lower than those in the control cell.

Between May 1996 and January 2003, the enhanced cell settled more than four times as much as the control cell, averaging 17.71 percent settlement versus 4.01 percent settlement. Results indicate the majority of the settlement in the enhanced occurred within the first four years. The enhanced cell is still settling but at a slower rate than previous years. Between November 2001 and January 2003 the enhanced cell settled 2 percent per year compared to an average of 4 percent settlement per year between May 1996 and February 2000.

7 FUTURE OPTIONS AND PLANS—or, where to go from here?

7.1 Options for Yolo County

The success of the pilot and most recently the fullscale cells, present opportunity to Yolo County to increase renewable energy and electricity. The avenues for benefiting from the increased energy from controlled bioreactor landfill operation are being carefully considered by the County. Another benefit from the work is the potential for landfill life extension. The landfill life extension option that is under most serious consideration is to first, decompose waste anaerobically to the maximum extent possible. An optional further step is to decompose the waste aerobically to degrade organic fractions of the waste (like lignin) that require oxygen for their aerobic degradation. This results in waste material that is reduced in volume and stabilized to form compost. The waste, once stabilized and composted, can be excavated (mined) for the stabilized waste to be re-used as cover material or for other compost applications. It is worth noting that cost and effort to recover this stabilized waste for cover, whether stabilization is anaerobic or anaerobic/aerobic, should be less per unit of material than the types of cover soil that are commonly used. Based on expected volume reduction this strategy would extend landfill life by about 25%, an extremely attractive proposition.

Unless the landfill is completely "mined" of its waste, a landfill will ultimately comprise a series of cells containing stabilized waste. In such cases another option, once all waste within the landfill is stabilized, is beneficial re-use of the landfill "footprint". One use is for space for parks and recreation, and this is already being done to some extent now as conventional landfills slowly stabilize across the US. Another option in more urban areas would be as a construction site for commercial facilities. Again, this is actually being carried out in areas such as in urban California where urban land areas have high value.

7.2 Energy options in California and the US

The success of the project has engendered interest for a number of years from various parties. The California Energy Commission, (CEC) an original sponsor of the project, remains highly interested in application of the bioreactor "controlled" landfill to augment California's electricity supply. The CEC is interested in implementing the project at as many sites as possible in California. The supply of renewable electricity, from sites not yet exploited, could amount to 1% or more of California's electricity[6]. Though this may

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[6] See estimates in Augenstein, D. R. Yazdani, R. Moore and K. Dahl. 1998 Yolo County Controlled Landfill Project. Proceedings, California Integrated Waste Management Board (CIWMB) Symposium on Landfill Gas Assessment and Management. April. CIWMB, Sacramento CA

seem modest, it is enough to meet total electricity needs associated with all activities of 300,000 or more California citizens.

Most recently, also, an initial co-sponsor of the project, Sacramento County, has expressed interest in applying the technology to its large-scale landfill at Kiefer road. Numerous other waste management entities have also expressed interest, including entities from outside the US. Discussions are ongoing. Details of major developments along these lines will be reported to WRBEP

7.3 Remaining issues

The success of the project to date should not be construed to mean that issues do not remain. Several remaining issues requiring further investigation include modes of liquid addition, and also the issue of slope stability. It is considered (although not well documented) that the shear strength of wet waste, as in a bioreactor, is less than that of dry waste. Thus waste can be more susceptible to "wasteslides". Partial solutions to the shear strength problem are available in the slow addition of liquid, as done in this program, which keeps stability to a maximum, and through the mining strategy mentioned above. Although the tests in this report are a pronounced success, these remaining issues need, at least, more documentation.

8 ACKNOWLEDGEMENTS

The costs of the Yolo County Full-Scale Landfill Bioreactor Project are shared under repayable research contracts from the Western Regional Biomass Energy Program (WRBEP), the California Energy Commission (CEC) under subcontract with Sacramento Municipal Utilities District (SMUD), the California Integrated Waste Management Board (CIWMB), and the National Energy Technology Laboratory (NETL) a division of the Department of Energy (DOE).

The assistance of John Pacey and the Solid Waste Association of North America and Don Augenstein of the Institute for Environmental Management (IEM) in developing and co-sponsoring Yolo Counties application and subsequent selection for the EPA XL Program. Both Don and John also provided valuable technical guidance and advice during the design and planning phase of the project.

Each agency and organizations that signed the EPA XL agreement, has helped greatly. This includes the U.S Environmental Protection Agency and in particular the Mark Samolis and his staff from Region 9, Yolo County, the California Regional Water Quality Control Board, the State Water Quality Control Board, the Yolo-Solano Air Quality Management District, the California Air Resources Board, the Solid Waste Association of North America, and the Institute for Environmental Management. Without the regulatory flexibility made possible by the EPA XL Program, this project would not have been possible.

The work of the consultants and contractors was invaluable. Scott Purdy and Todd Ramey of Vector Engineering and Rick Thiel of Thiel Engineering for the expedited design of the aerobic base liner and anaerobic bioreactor surface liner. Richard L. Vogler, Sharon M. Kimizuka, and Matt Boering of ATEEM Electrical for the SCADA data acquisition and control system. Benjamin & Tim Geerts and the rest of the construction crew of B & D Geerts General Contractors for their assistance and patience in installing the various components of the monitoring and piping systems. Colorado Lining for the northeast cell surface liner and Sierra Geosynthetics for the west-side cell surface liner.

The ongoing support of the Yolo County Board of Supervisors has been essential to the success of the project.

The success of the Project to date is due, in large part, to the dedication, hard work, and creativity of all Yolo County staff members, from the scalehouse attendants who tracked the amount of waste to the Director who supported the concept of research into superior landfilling technologies.

9 REFERENCES

1. Tchobanoglous et al, "Integrated Solid Waste Management, Engineering Principles and management Issues", McGraw-Hill, 1993.

2. Vector Engineering, "Design Report for the Surface Liners of the Module D Phase 1 Bioreactors at the Yolo County Central Landfill", October 2001.

3. Yazdani, R., Moore, R. Dahl. K. and D. Augenstein 1998 Yolo County Controlled Landfill Bioreactor Project. Yolo County Public Works and I E M, Inc. Yolo County Public Works and I E M, Inc. report to the Urban Consortium Energy Foundation (UUCETF) and the Western Regional Biomass Energy Program, USDOE.

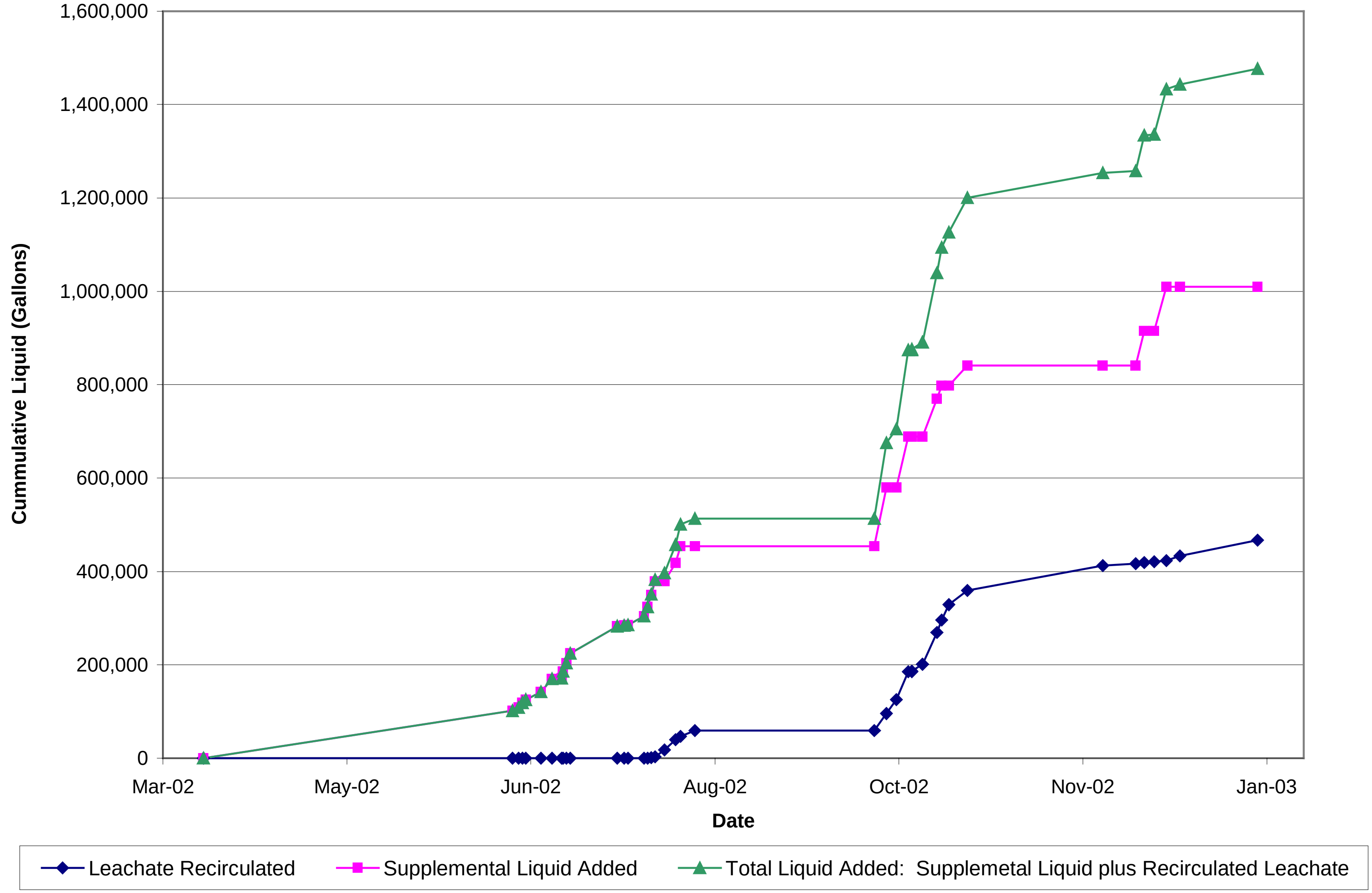
4. Golder Associates, "Final Report, Construction Quality Assurance, Yolo County Central Landfill, WMU 6, Module D, Phase 1 Expansion", December 1999.

5. California Regional Water Quality Control Board, Central Valley Region, "Waste Discharge Requirements for the Yolo County Central Landfill, No. 5-00-134", June 16, 2000.

6. Yolo County, IEM, SWANA, EPA, Final Project Agreement for the Yolo County Accelerated Anaerobic and Aerobic Composting (Bioreactor) Project, September 14, 2000.

APPENDIX A – GRAPHS AND DATA TABLES

Figure 3-1. Northeast Anaerobic Cell Liquid Recirculation and Addition Volumes (Full Scale Project)



Between September 24, 2002 and October 4, 2002 35,460 gallons of liquid was removed from the sump and used for injection line cleaning.

Figure 3-2. Northeast Anaerobic Cell Layer 1 Temperature Readings (Full Scale Project)

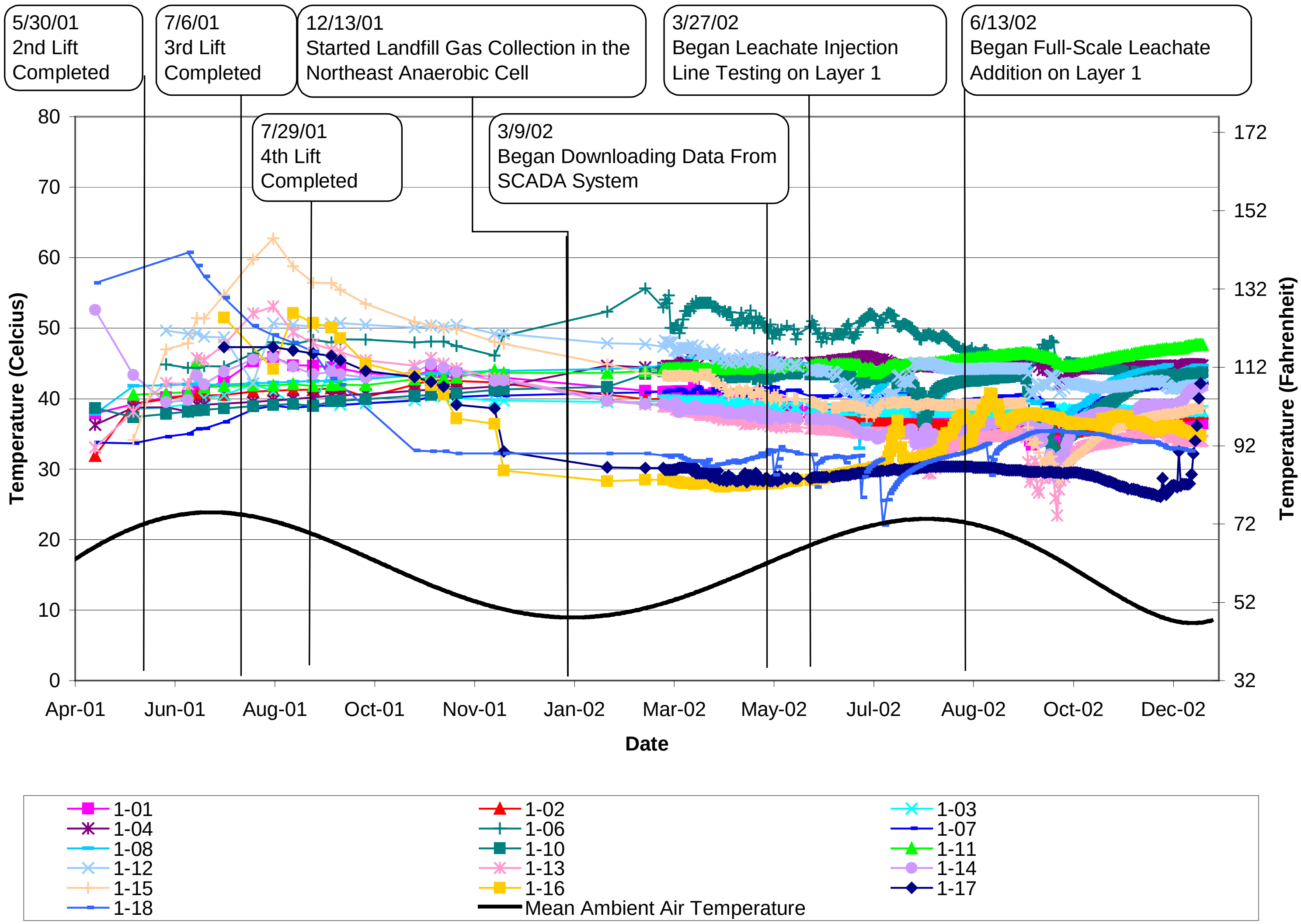


Figure 3-3. Northeast Anaerobic Cell Layer 2 Temperature Readings (Full Scale Project)

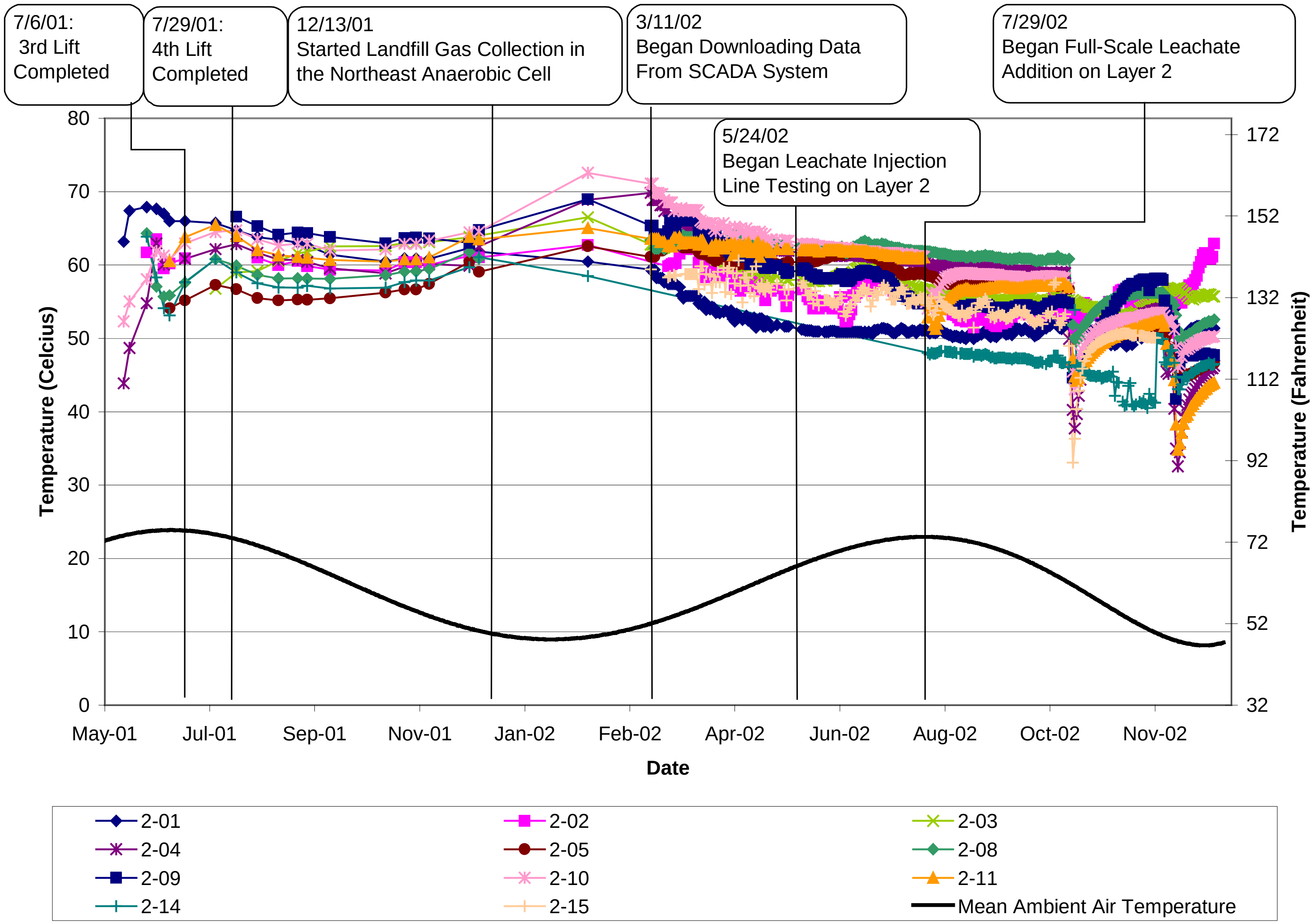


Figure 3-4. Northeast Anaerobic Cell Layer 3 Temperature Readings (Full Scale Project)

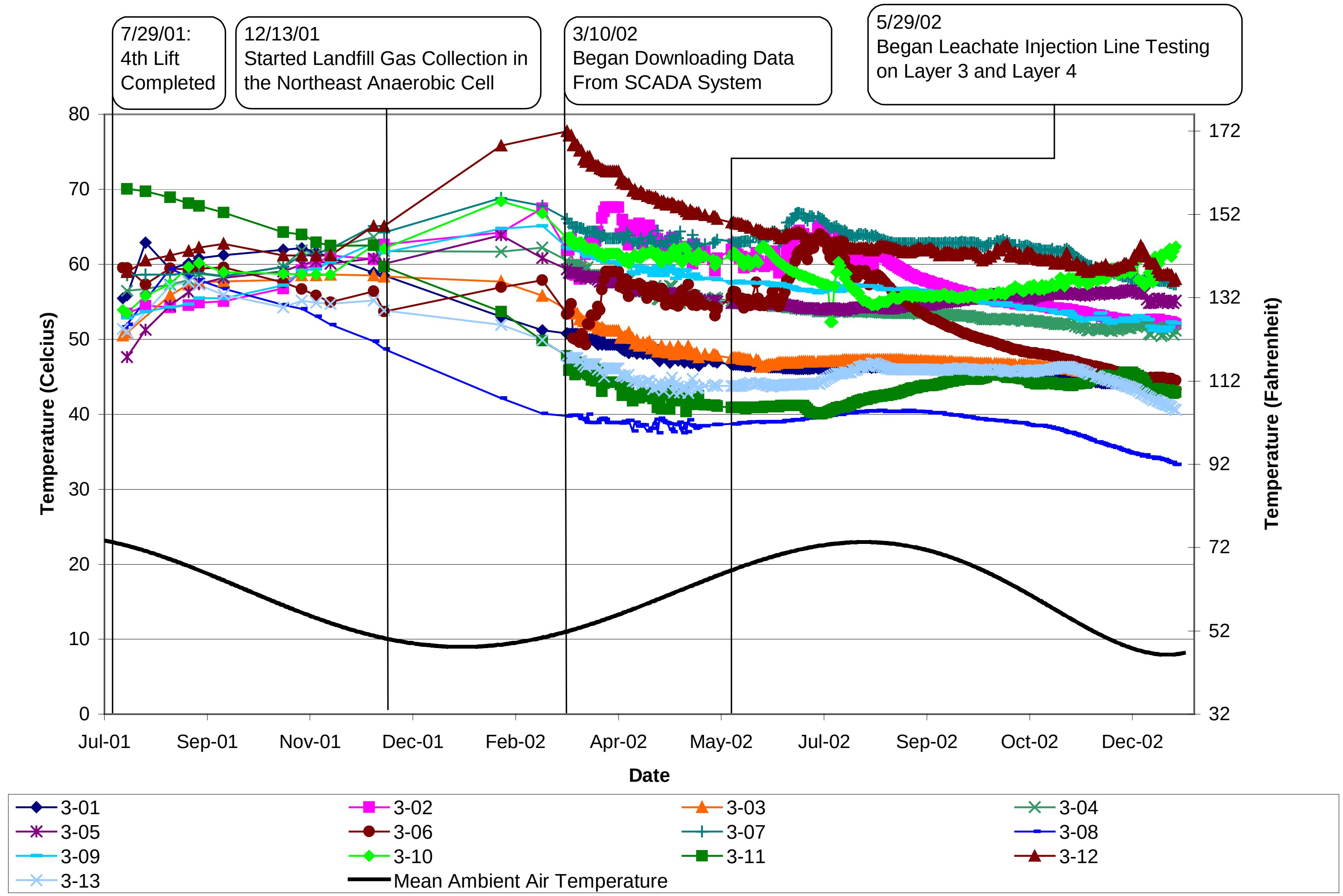


Figure 3-5. Northeast Anaerobic Cell Average Temperature Readings (Full Scale Project)

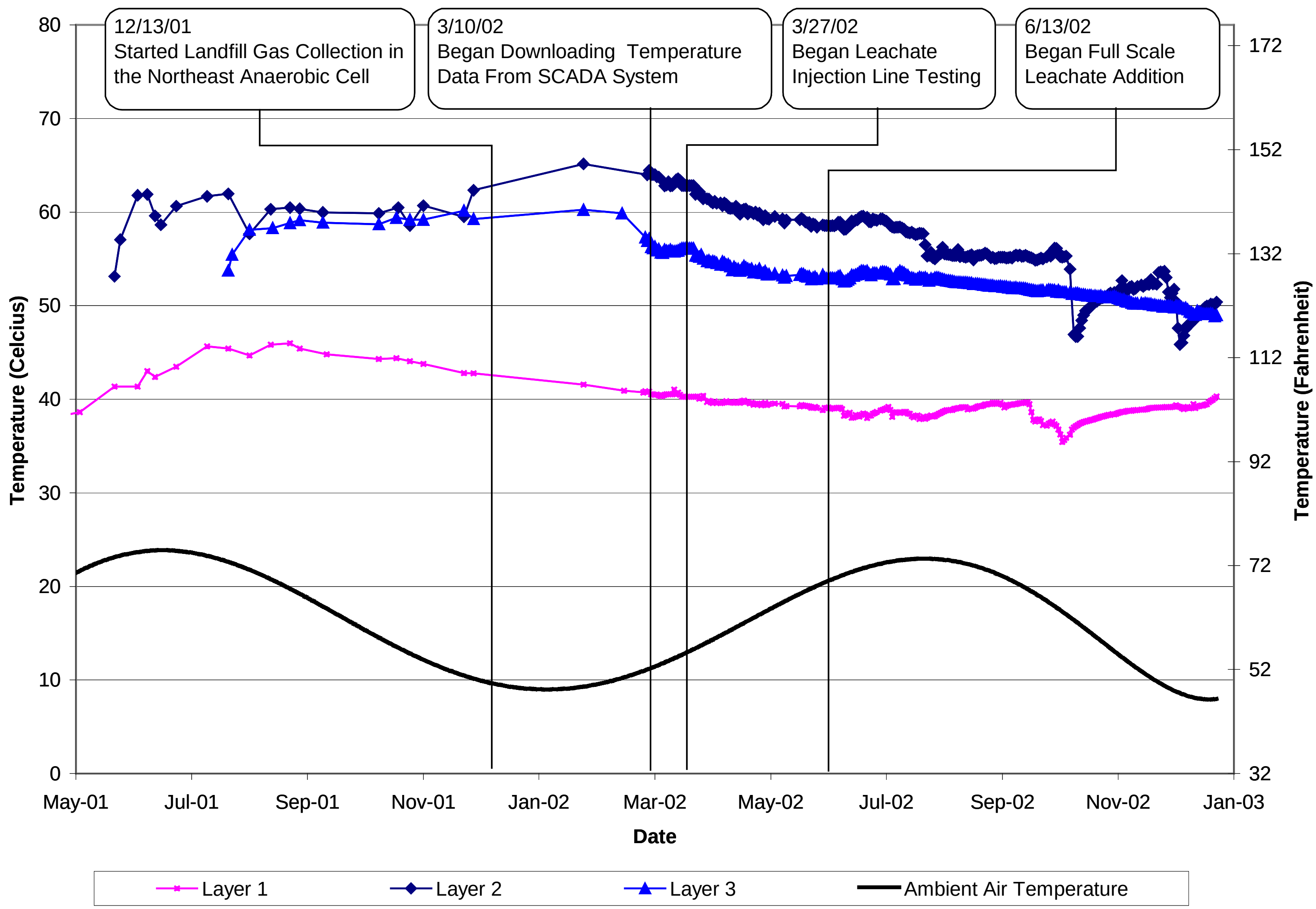


Figure 3-6. Northeast Anaerobic Cell Selected Temperature Readings (Full Scale Project)

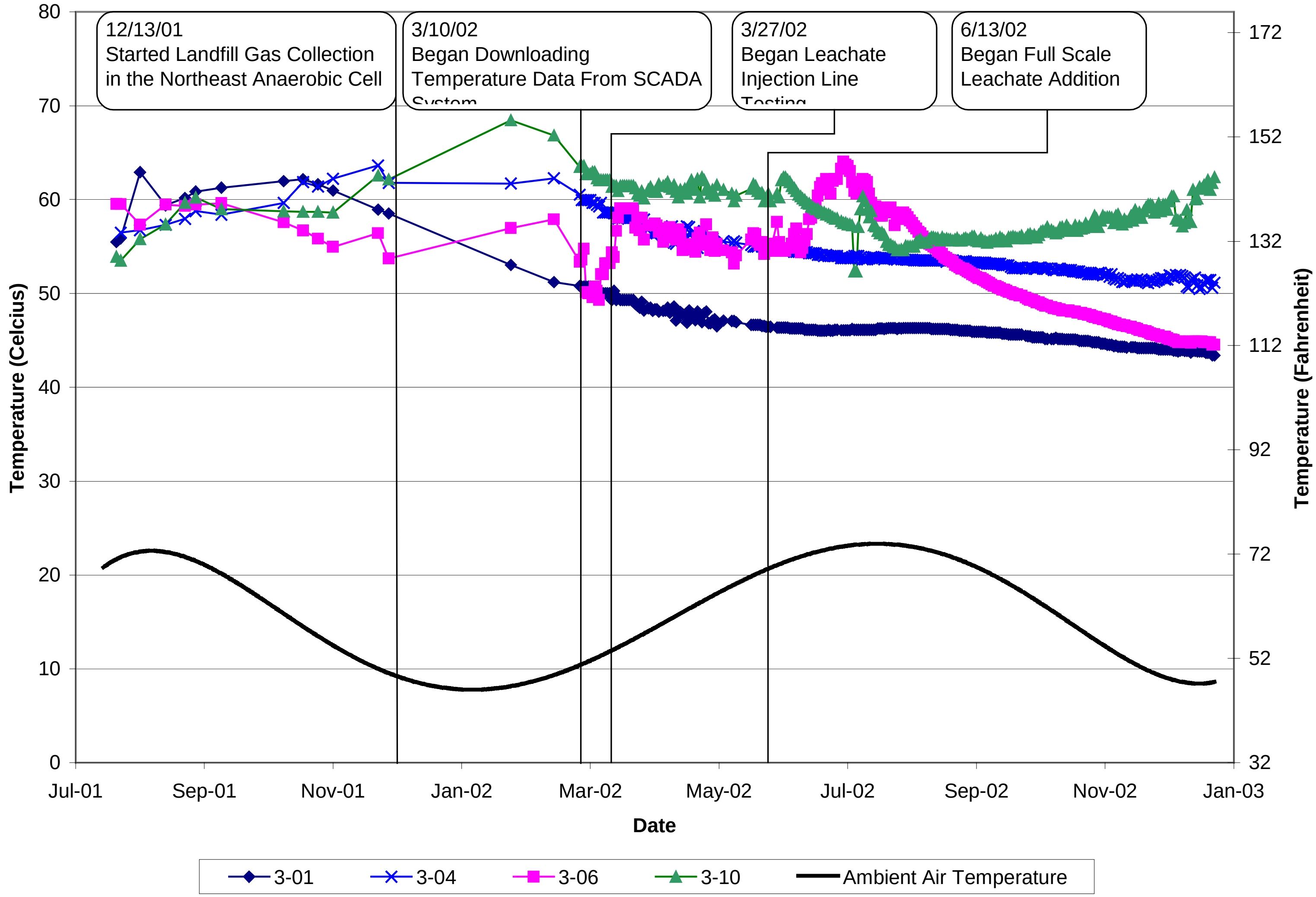


Figure 3-7. Northeast Anaerobic Cell Layer 1 PVC Moisture Readings (Full Scale Project)

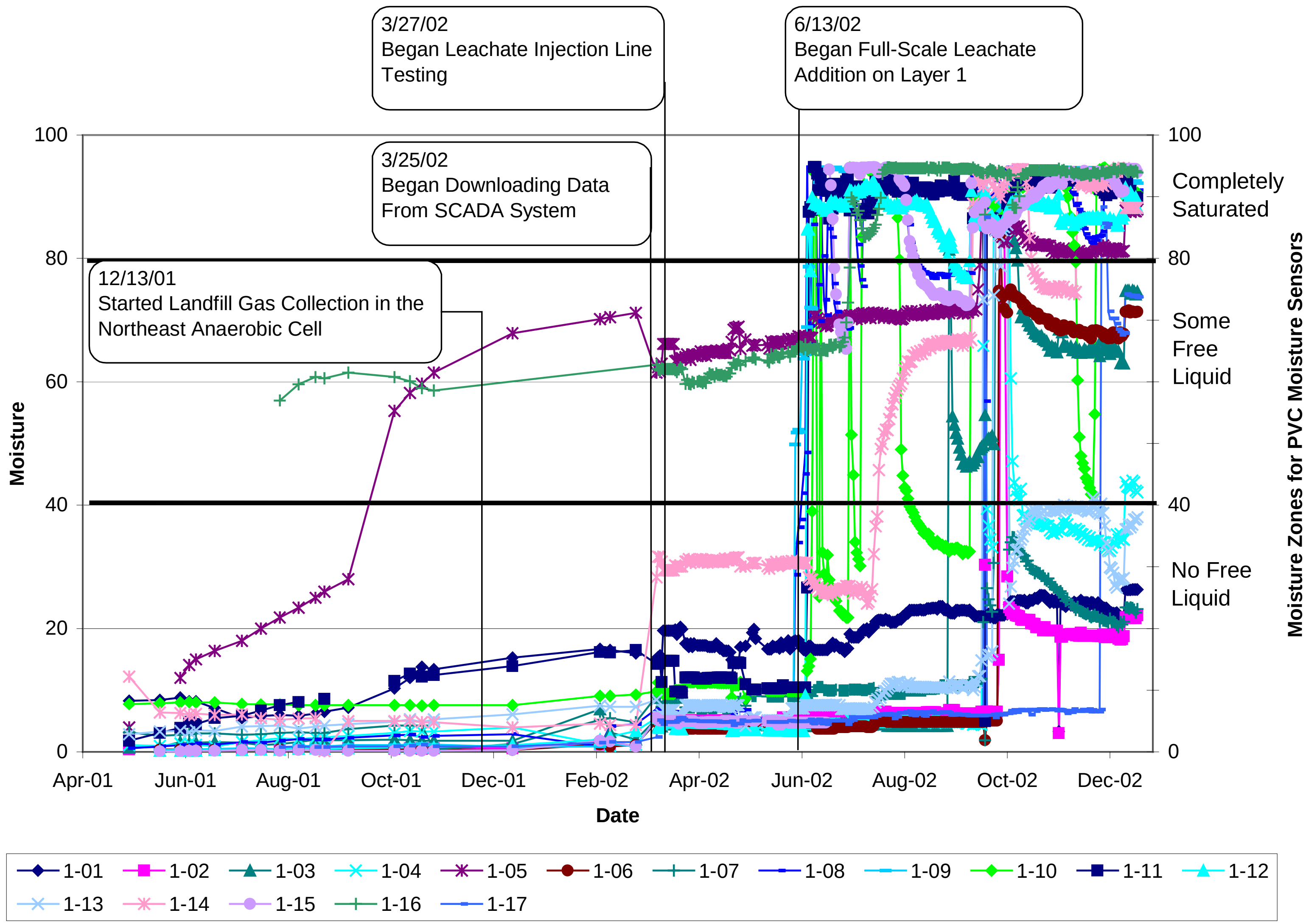


Figure 3-8. Northeast Anaerobic Cell Layer 2 PVC Moisture Readings (Full Scale Project)

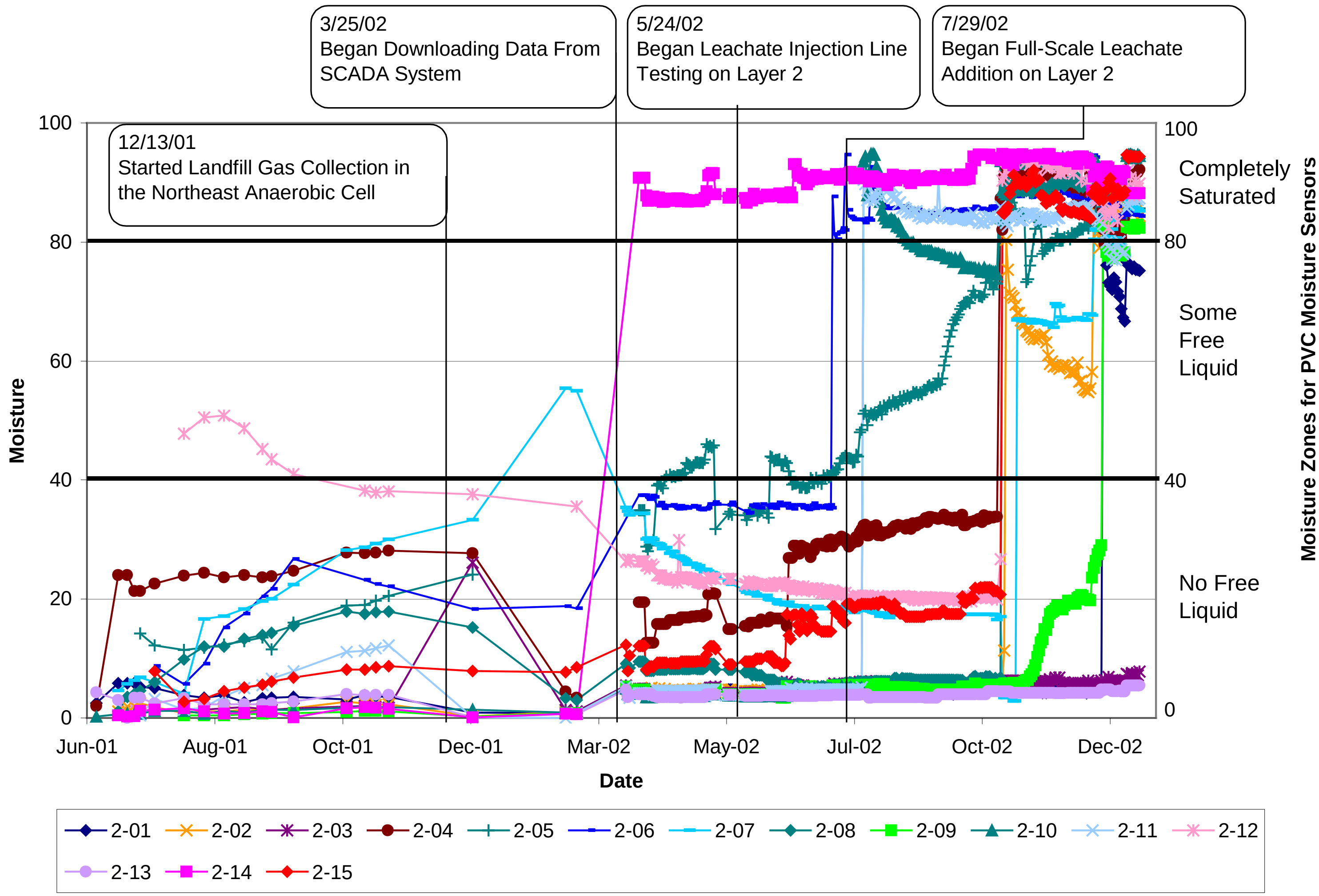


Figure 3-9. Northeast Anaerobic Cell Layer 2 Gypsum in Plaster Moisture Readings (Full Scale Project)

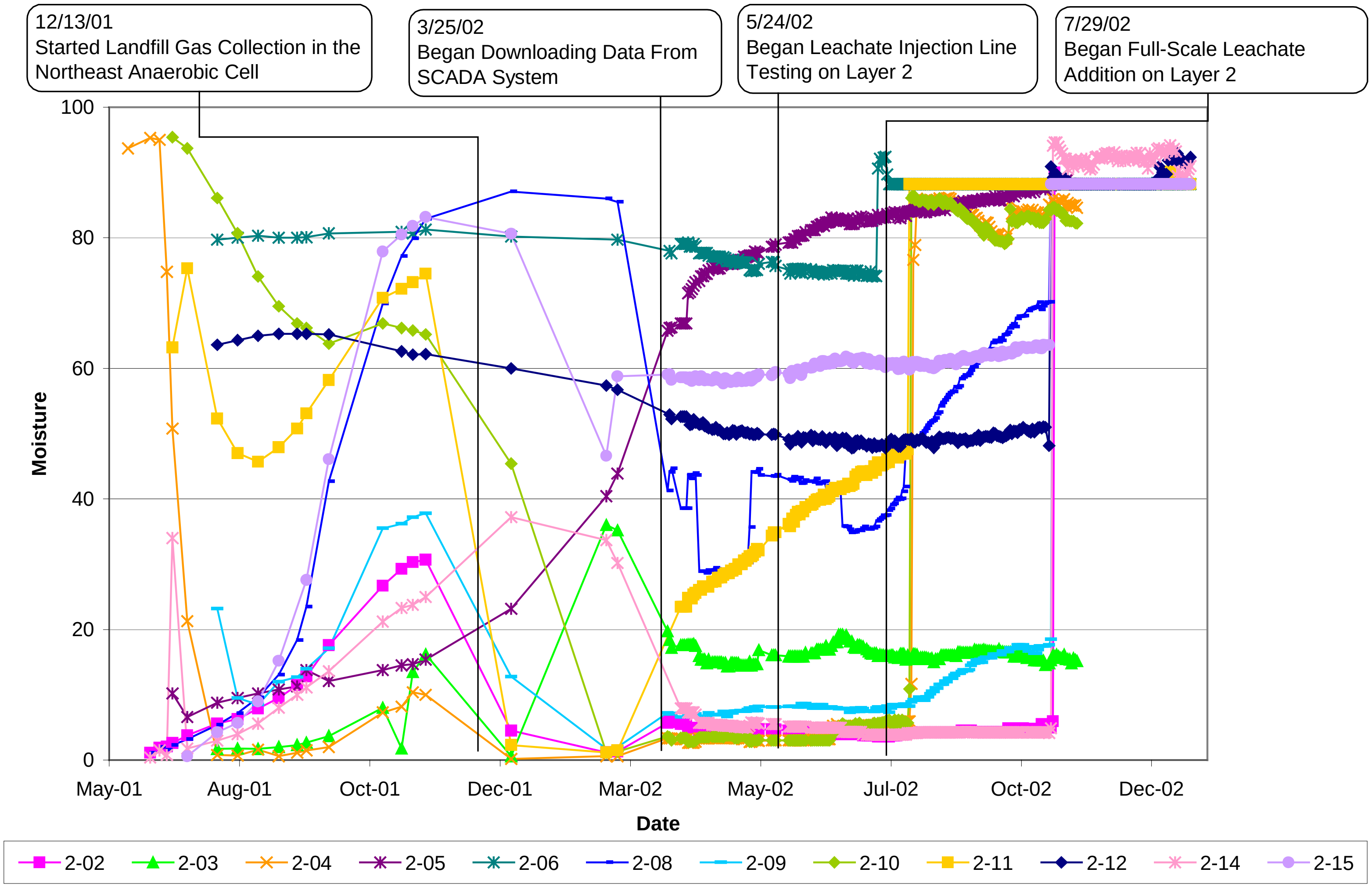


Figure 3-10. Northeast Anaerobic Cell Layer 2 Gypsum in Soil Moisture Readings (Full Scale Project)

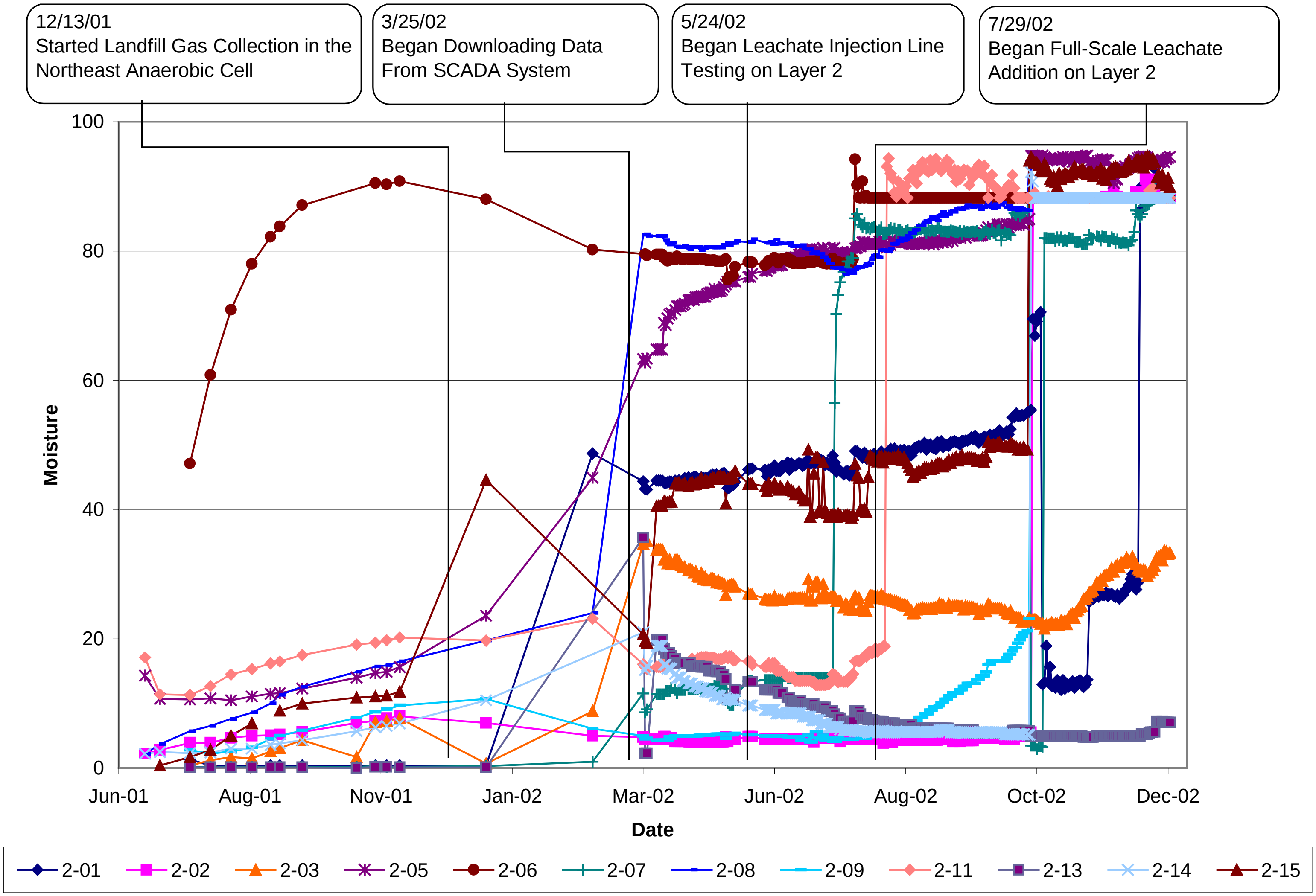


Figure 3-11. Northeast Anaerobic Cell Layer 3 PVC Moisture Readings (Full Scale Project)

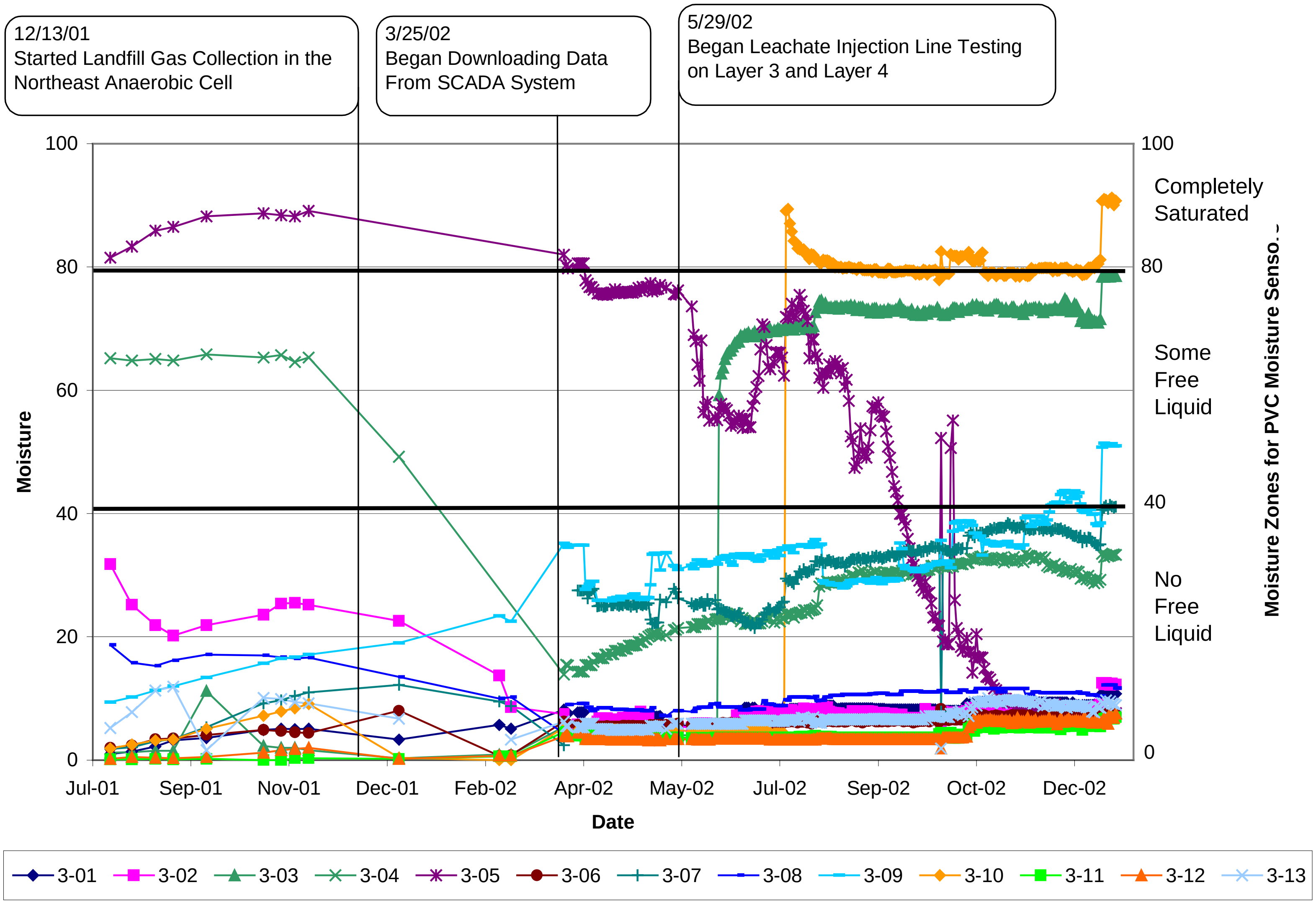


Figure 3-12. Northeast Anaerobic Cell Average Moisture Readings (Full Scale Project)

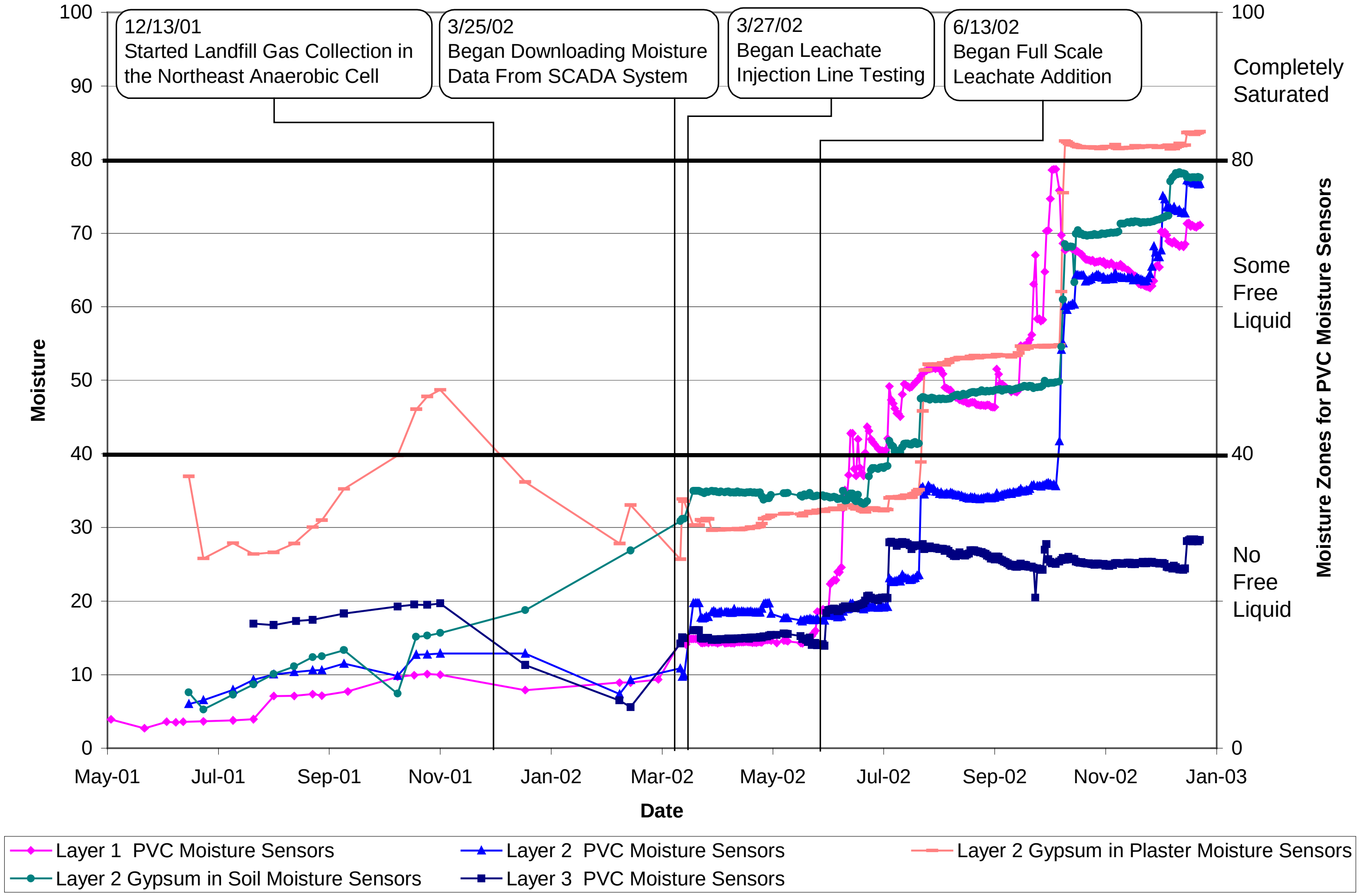


Figure 3-13. Northeast Anaerobic Cell Methane Concentrations from LFG Extraction Well Heads (Full Scale Project)

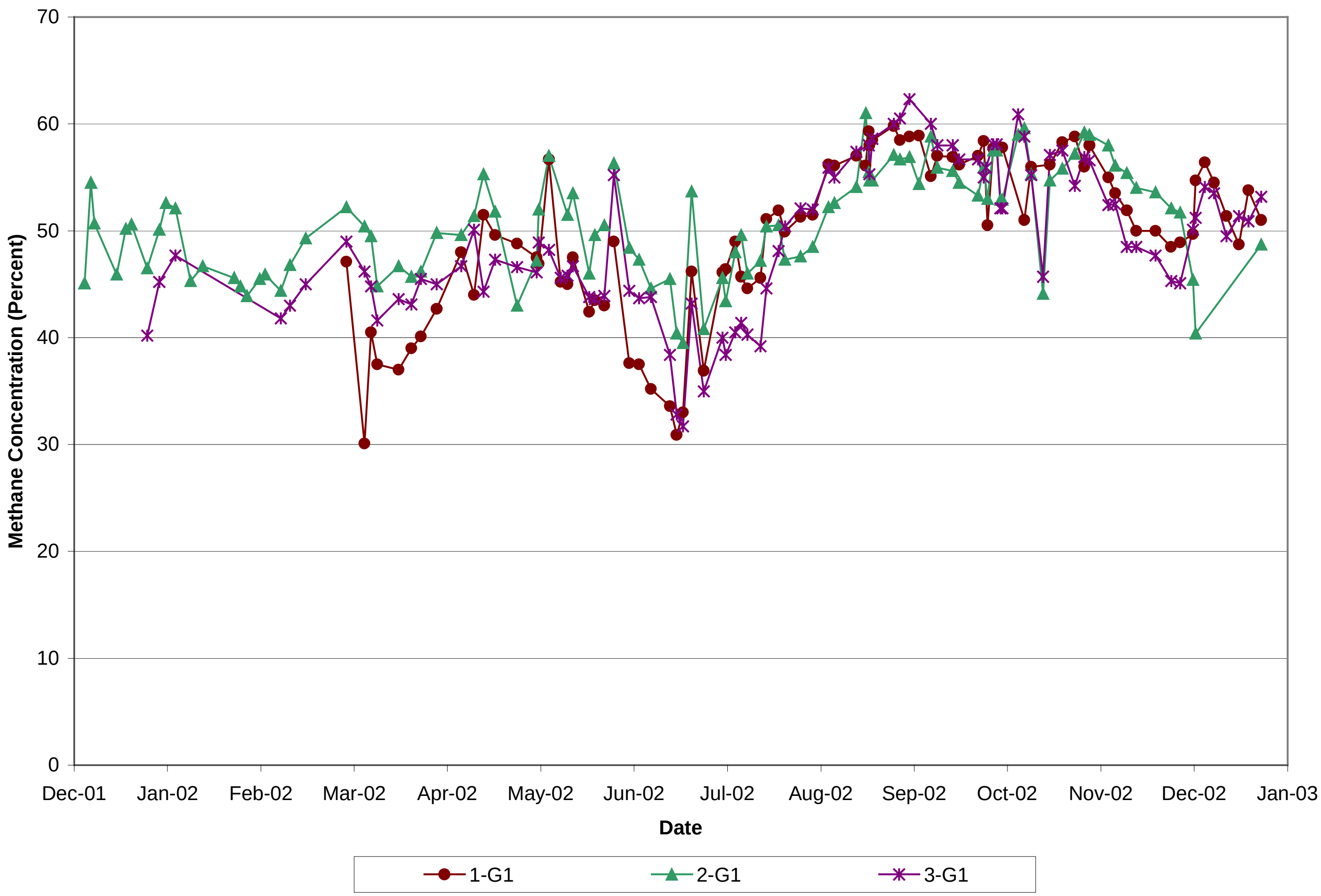


Figure 3-14. Northeast Anaerobic Cell Landfill Gas Concentrations from Header Line (Full Scale Project)

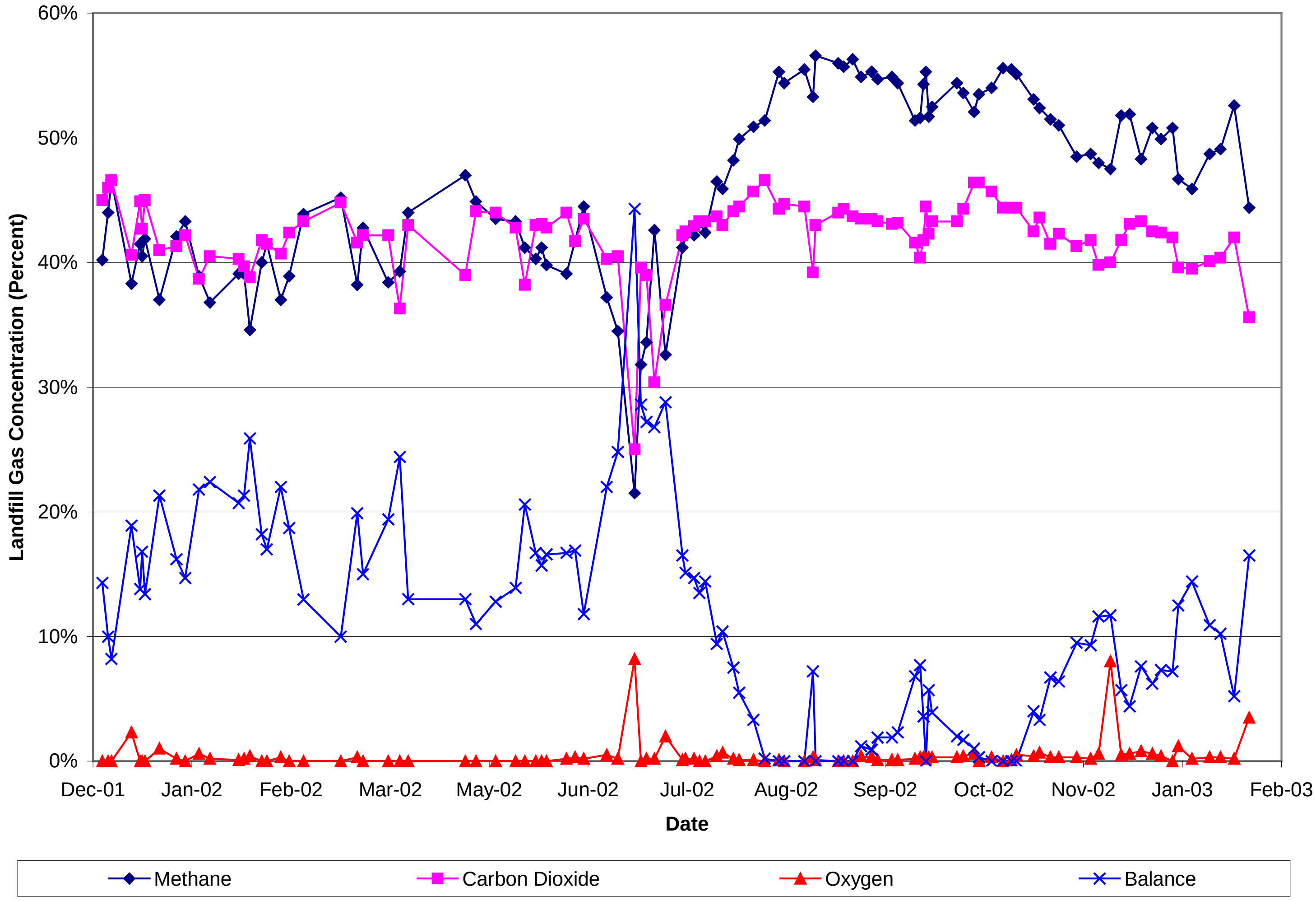


Figure 3-15. Northeast Anaerobic Cell Landfill Gas Flow Rate (Full Scale Project)

Figure 3-16. Northeast Anaerobic Cell Cumulative Methane (Full Scale Project)

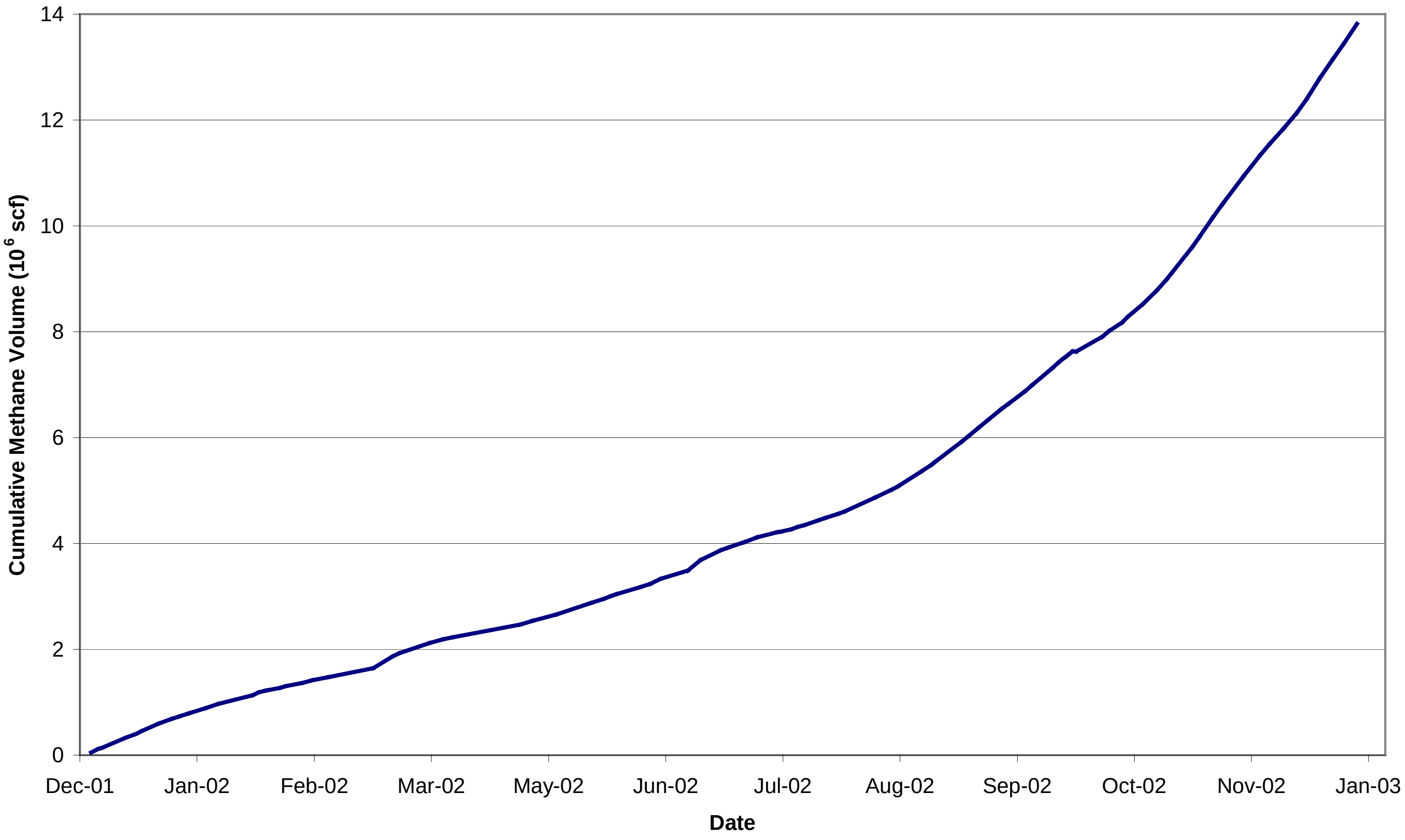


Figure 3-17. Cumulative Methane Per Pound of Dry Waste from the Northeast Cell (Full Scale Project) Compared to Previous Results from the Enhanced Cell (Pilot Scale Project)

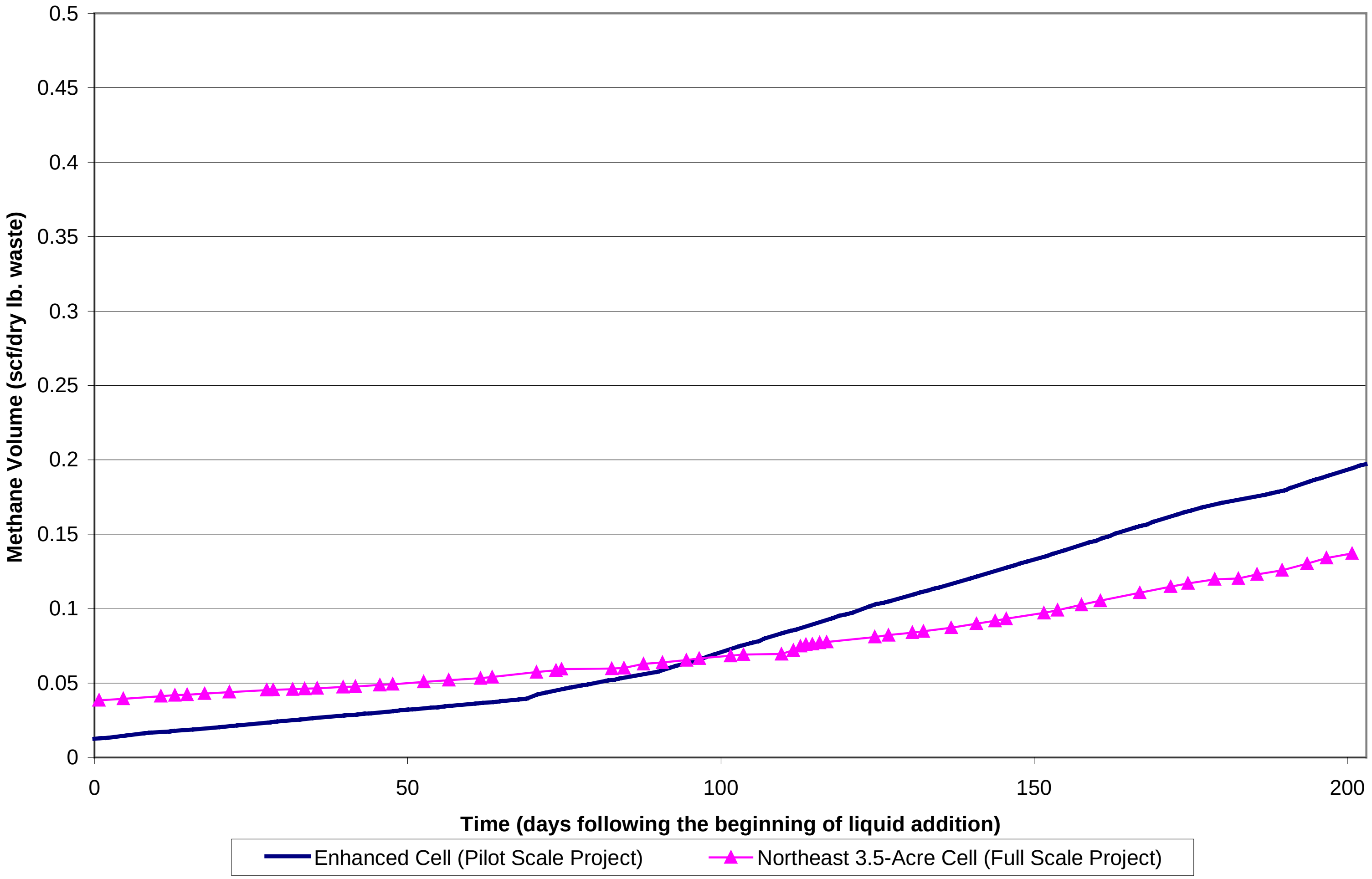


Figure 3-18. Results for Waste Sampled from the Northeast Anaerobic Cell in June 2002 (Full Scale Project)

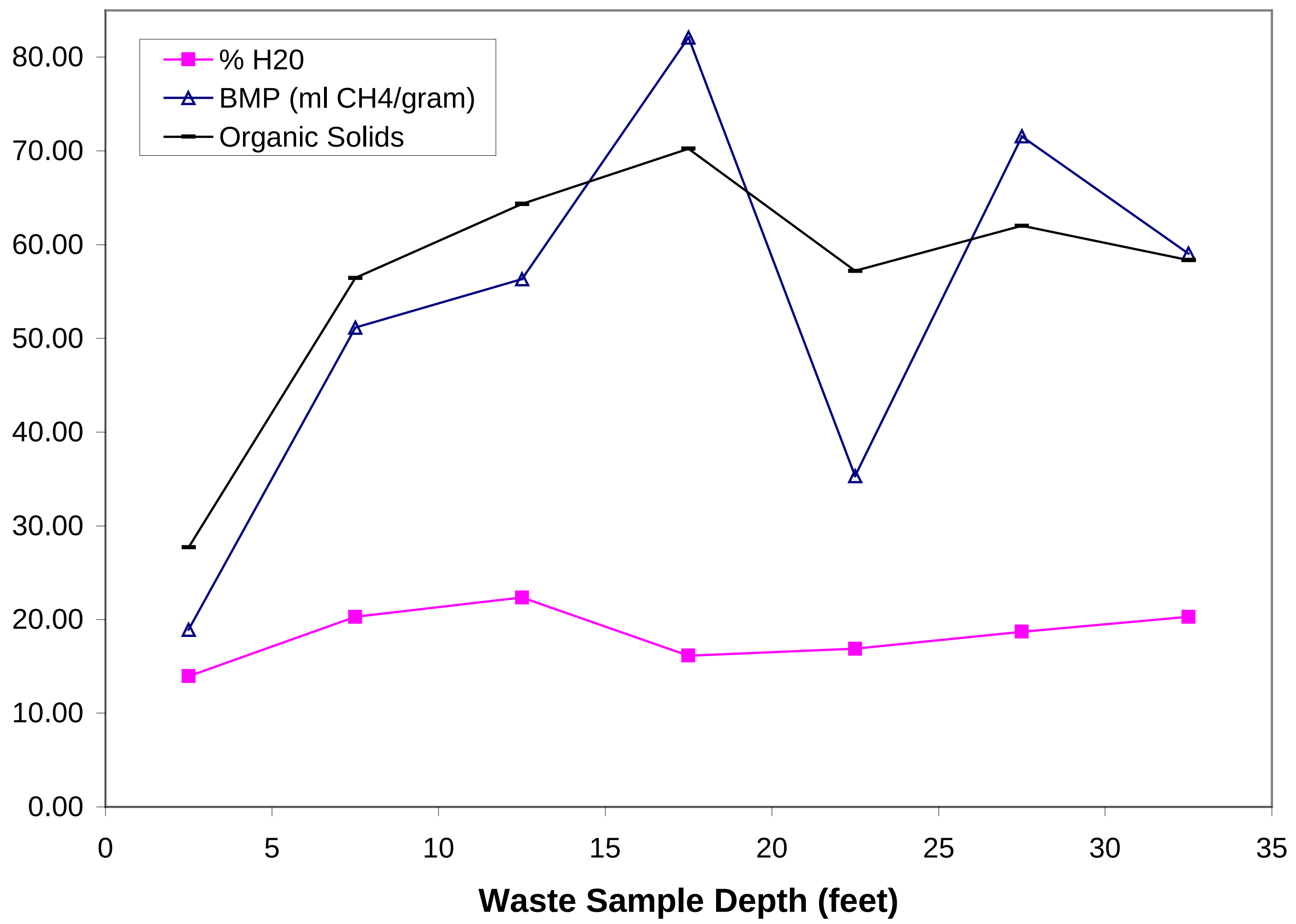


Figure 3-19. Cellulose and Hemicellulose to Lignin Ratios (C+H/L) from Waste Sampled in the June 2002

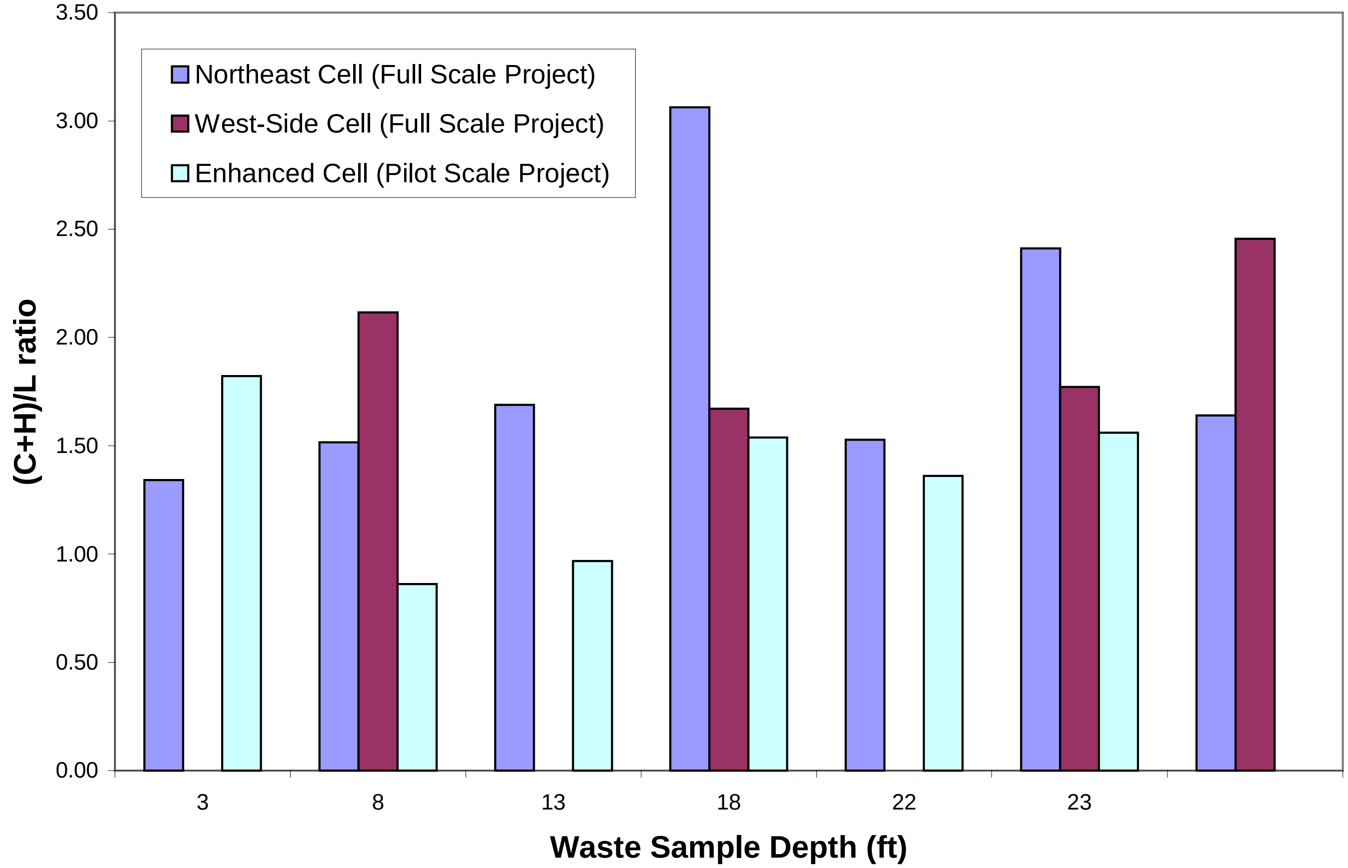


Figure 3-20. Average Methane Concentration of Each Individual Gas Wells Before and After Leachate Addition (Full Scale Project)

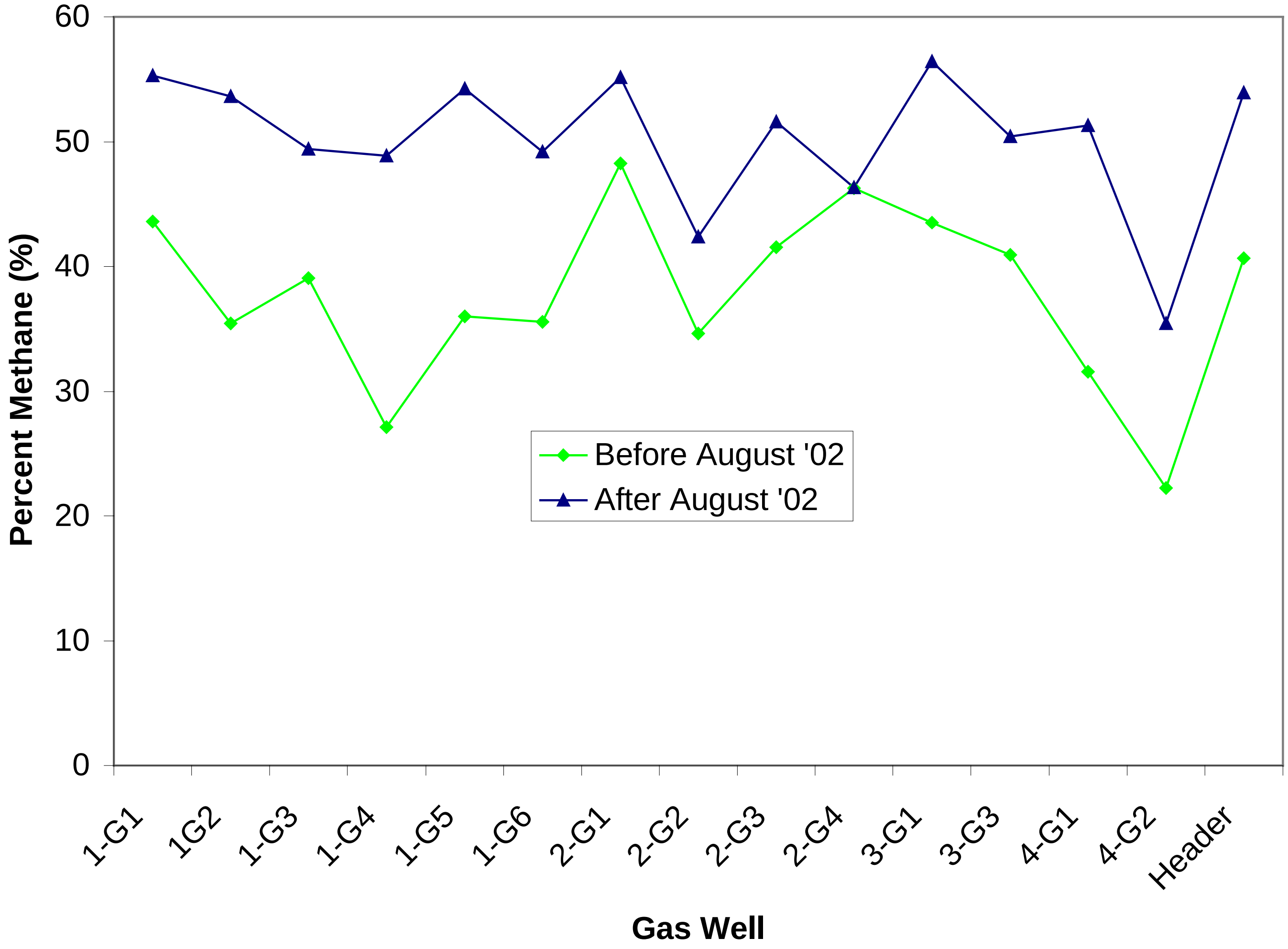


Figure 3-21. Reduction in Landfill Gas Constituent Concentrations (Full Scale Project)

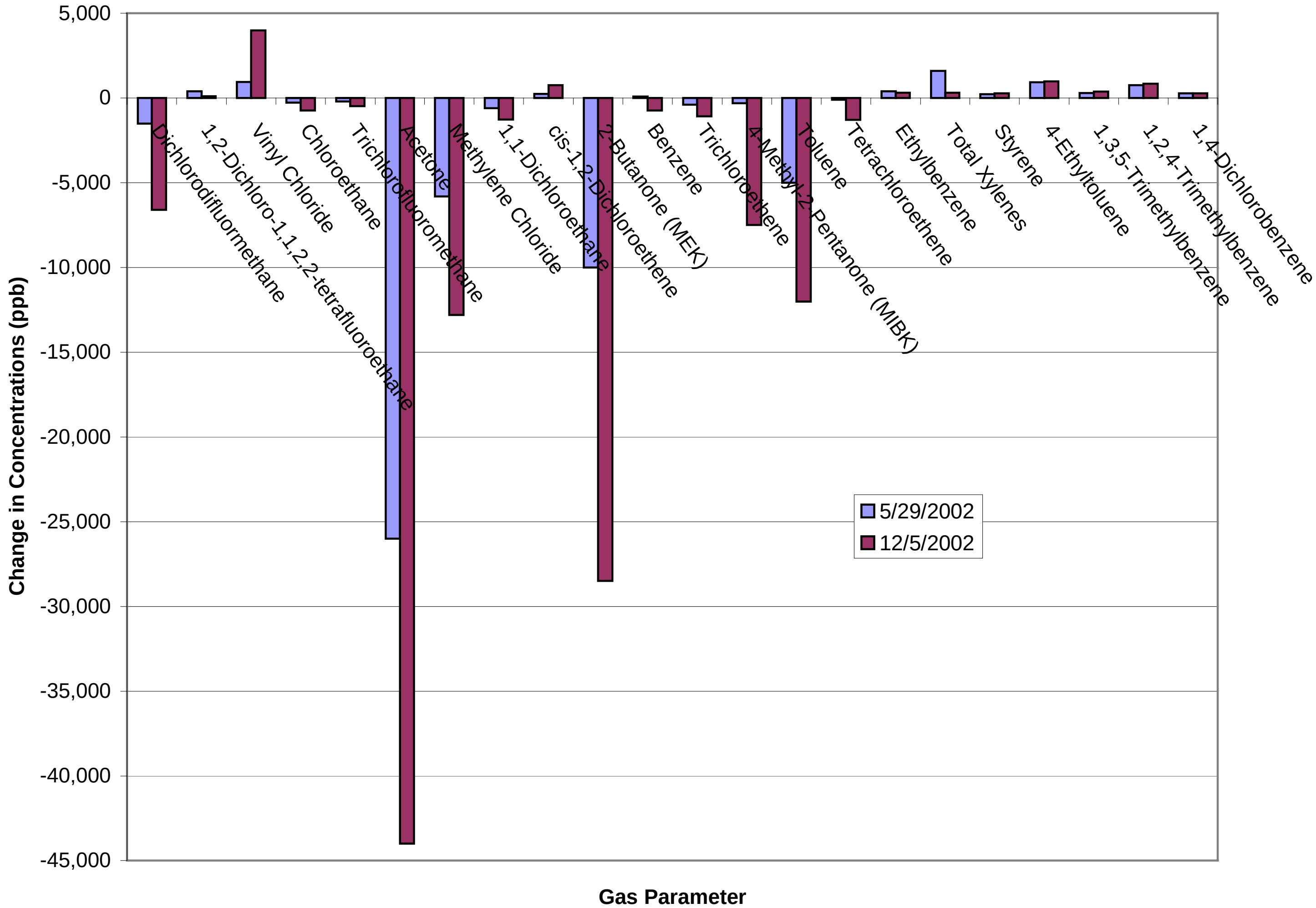


Figure 4-1. West-Side Anaerobic Cell Layer 1 Temperature Readings (Full Scale Project)

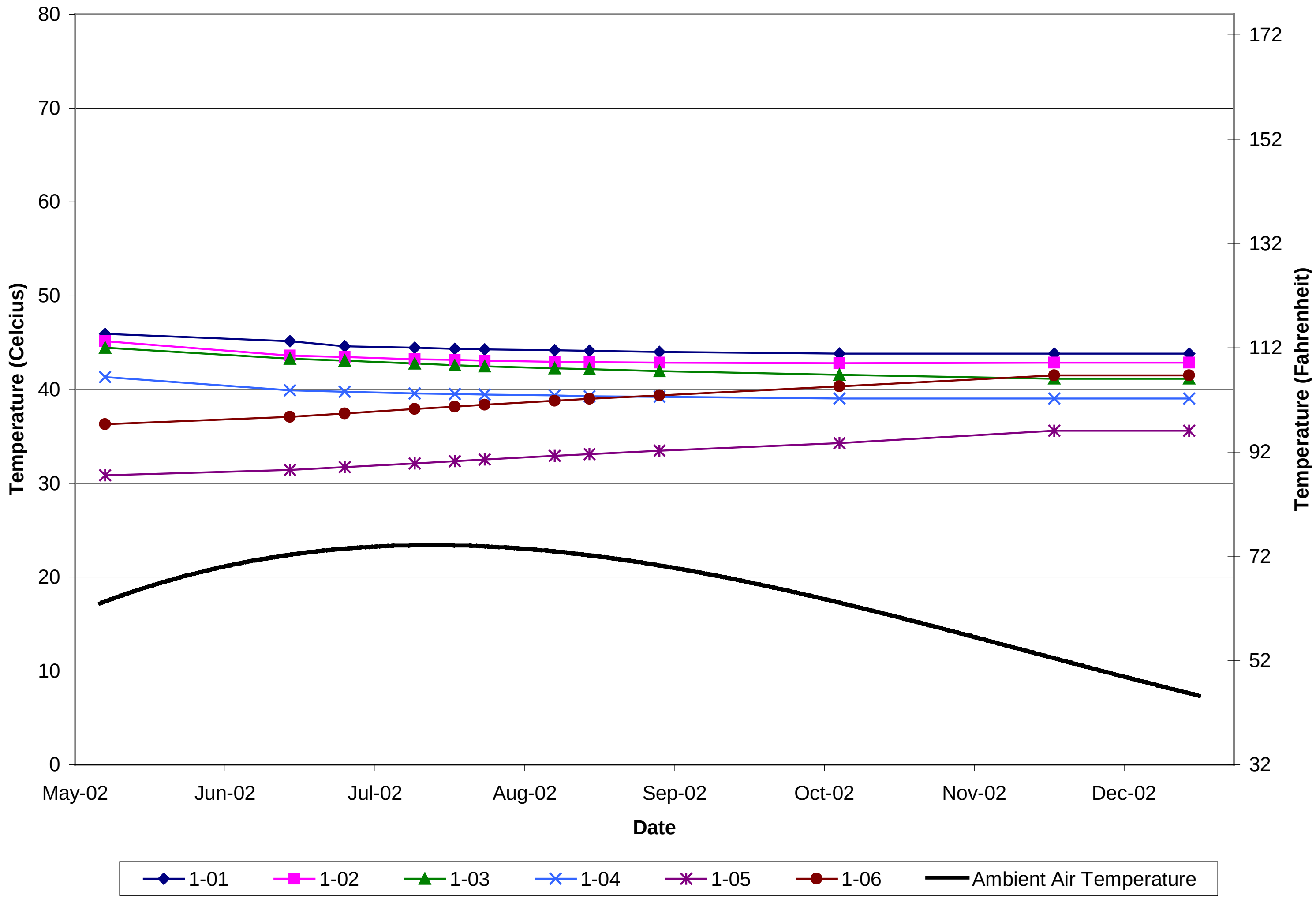


Figure 4-2. West-Side Anaerobic Cell Layer 2 Temperature Readings (Full Scale Project)

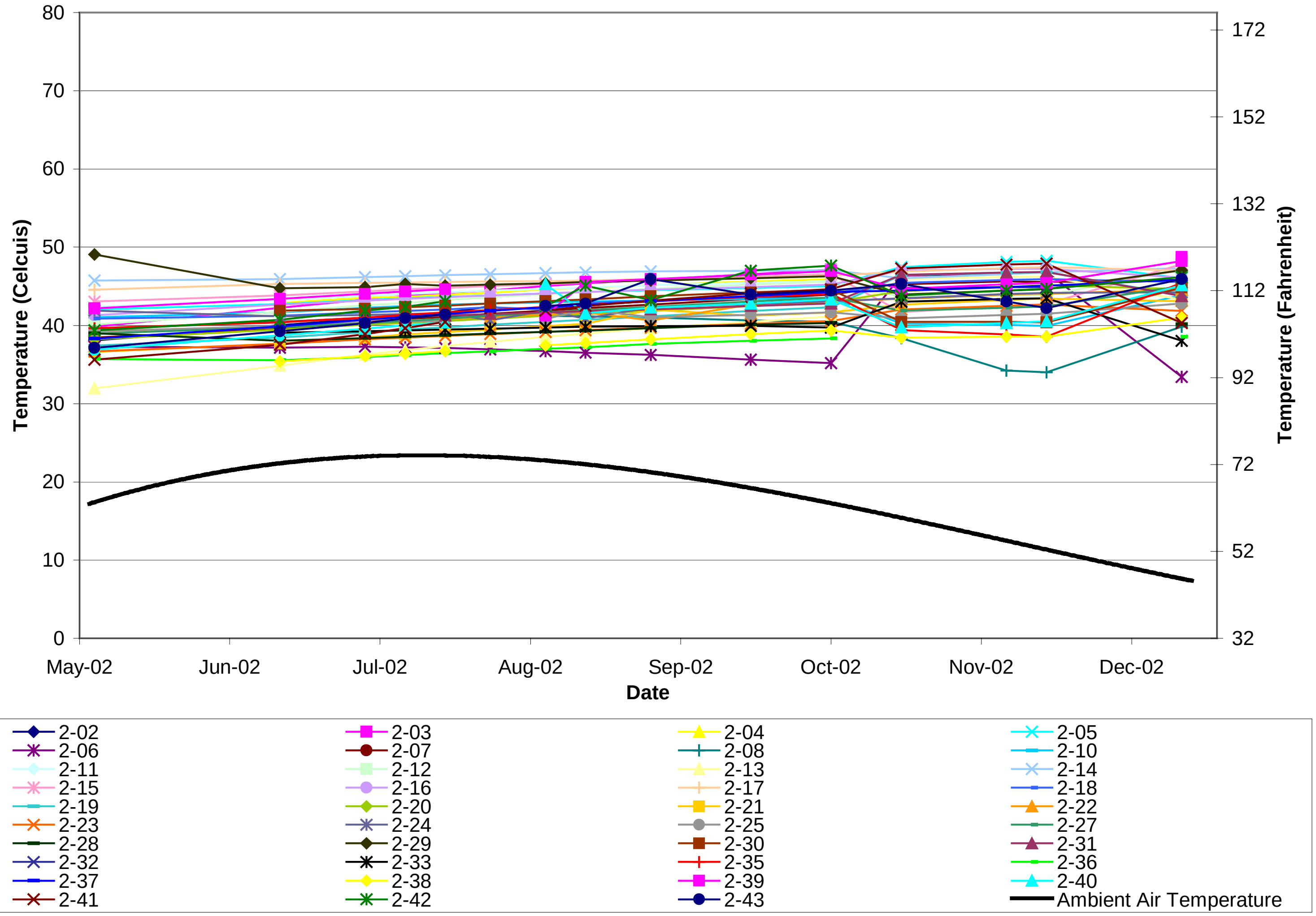


Figure 4-3. West-Side Anaerobic Cell Layer 3 Temperature Readings (Full Scale Project)

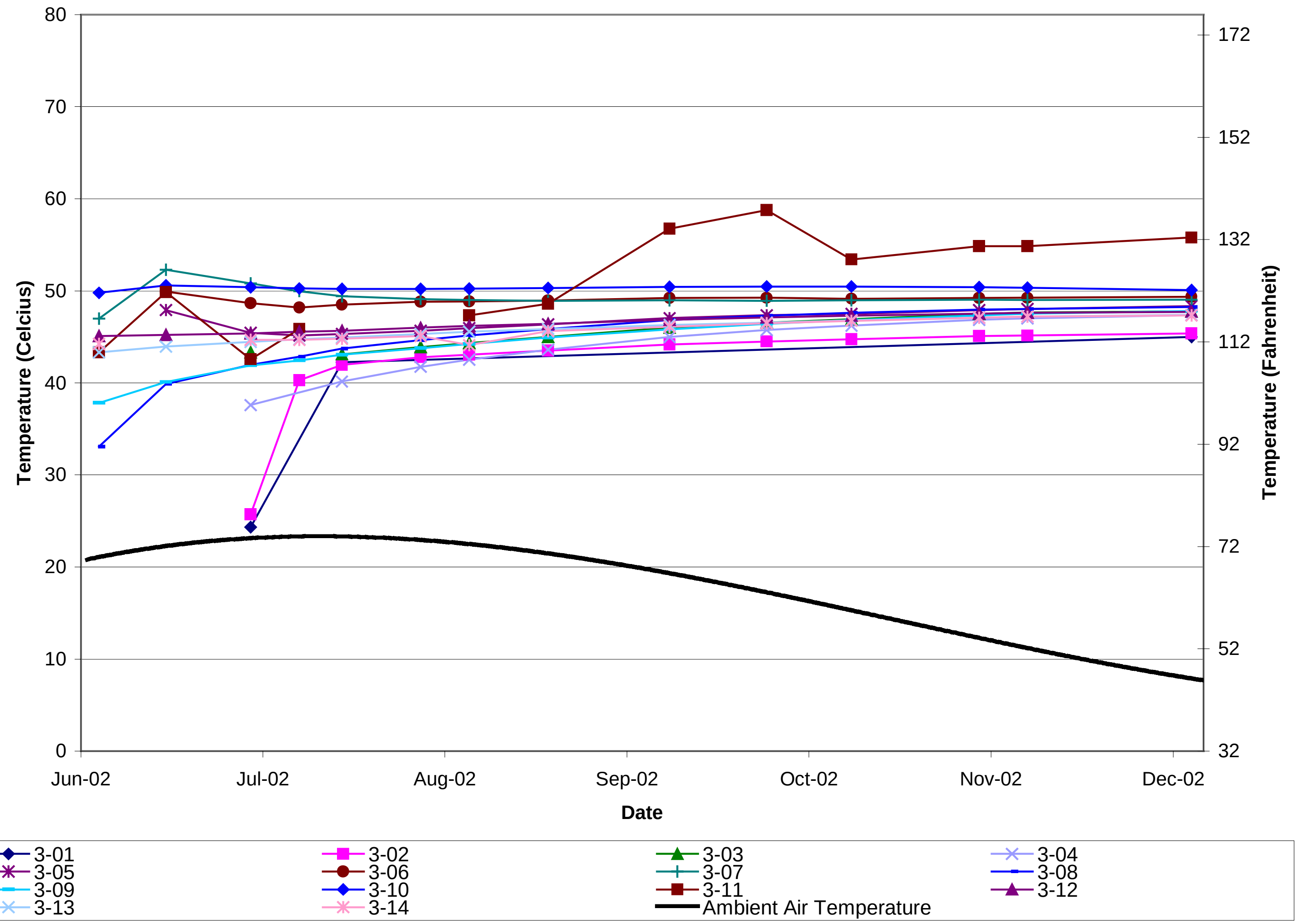


Figure 4-4. West-Side Anaerobic Cell Average Temperature Readings (Full Scale Project)

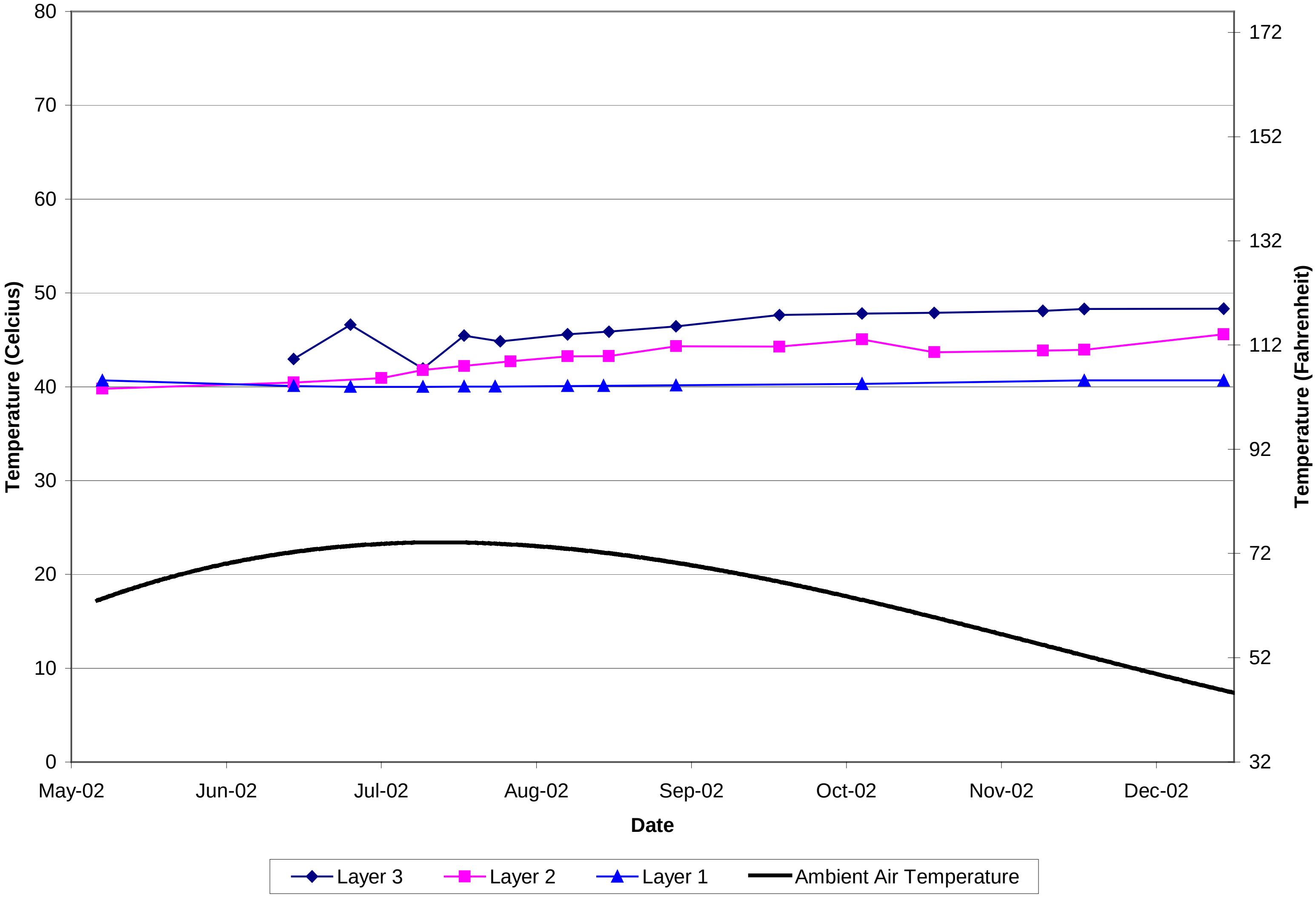


Figure 4-5. West-Side Anaerobic Cell Layer 1 PVC Moisture Readings (Full Scale Project)

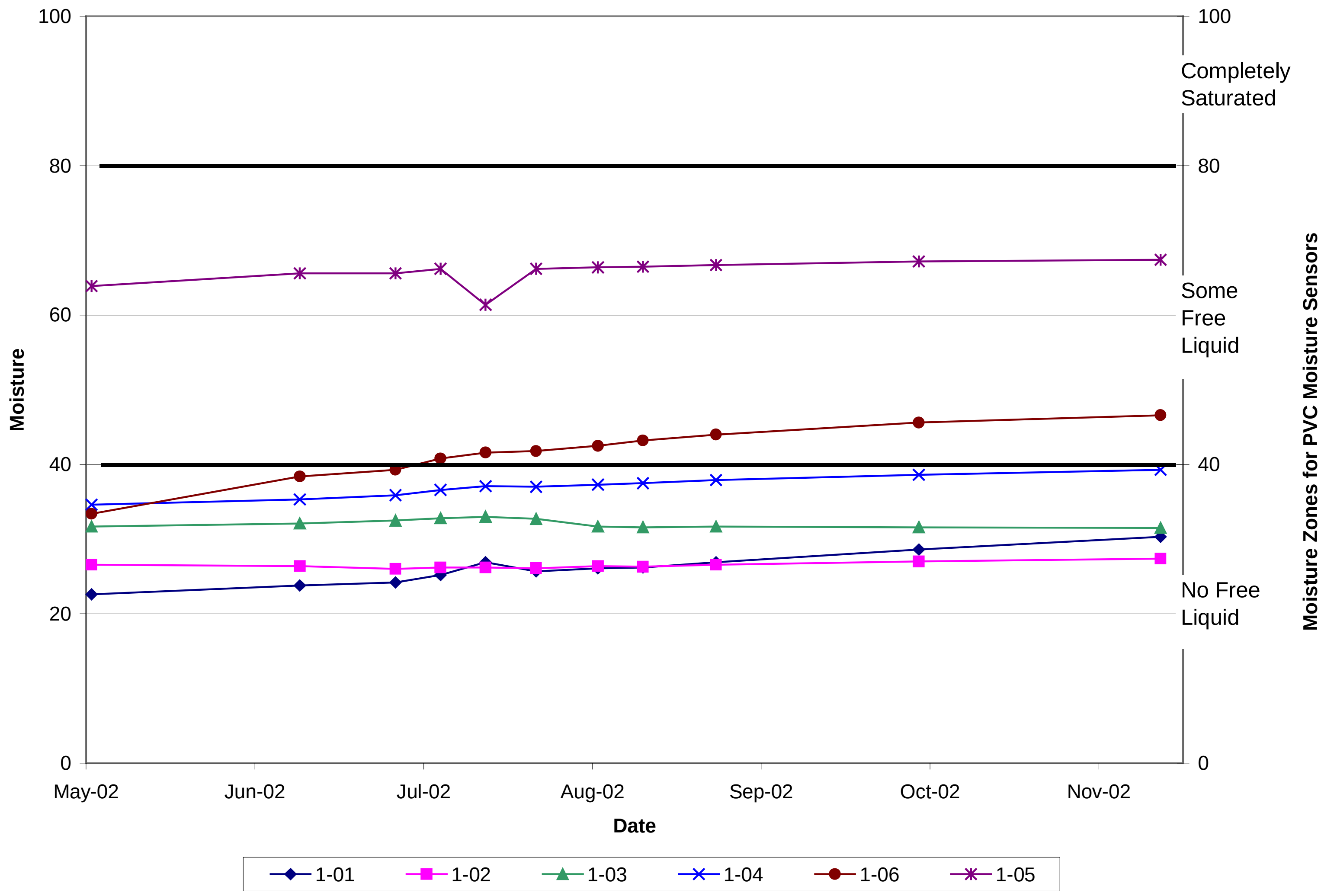


Figure 4-6. West-Side Anaerobic Cell Layer 2 PVC Readings (Full Scale Project)

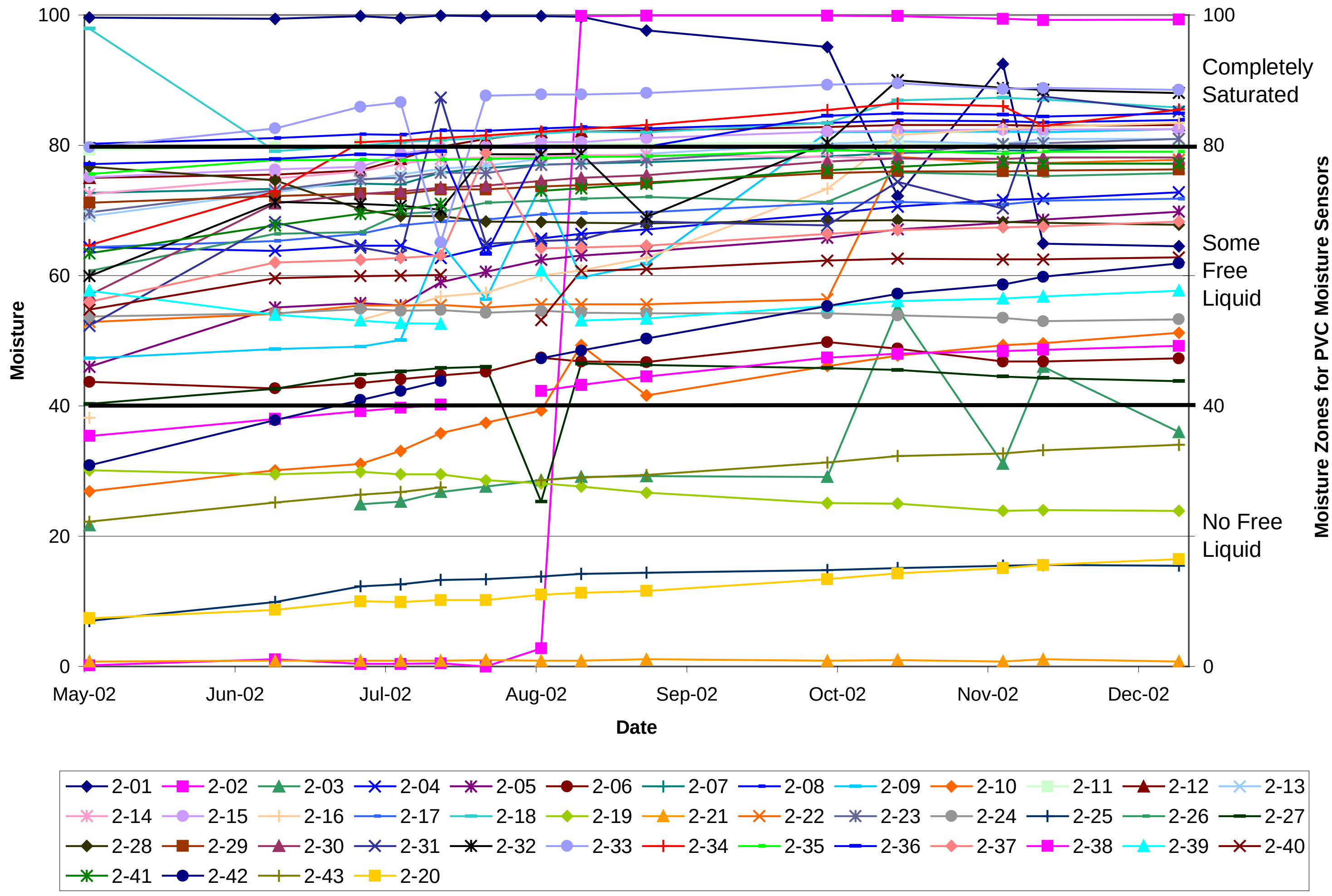


Figure 4-7. West-Side Anaerobic Cell Layer 3 PVC Moisture Readings (Full Scale Project)

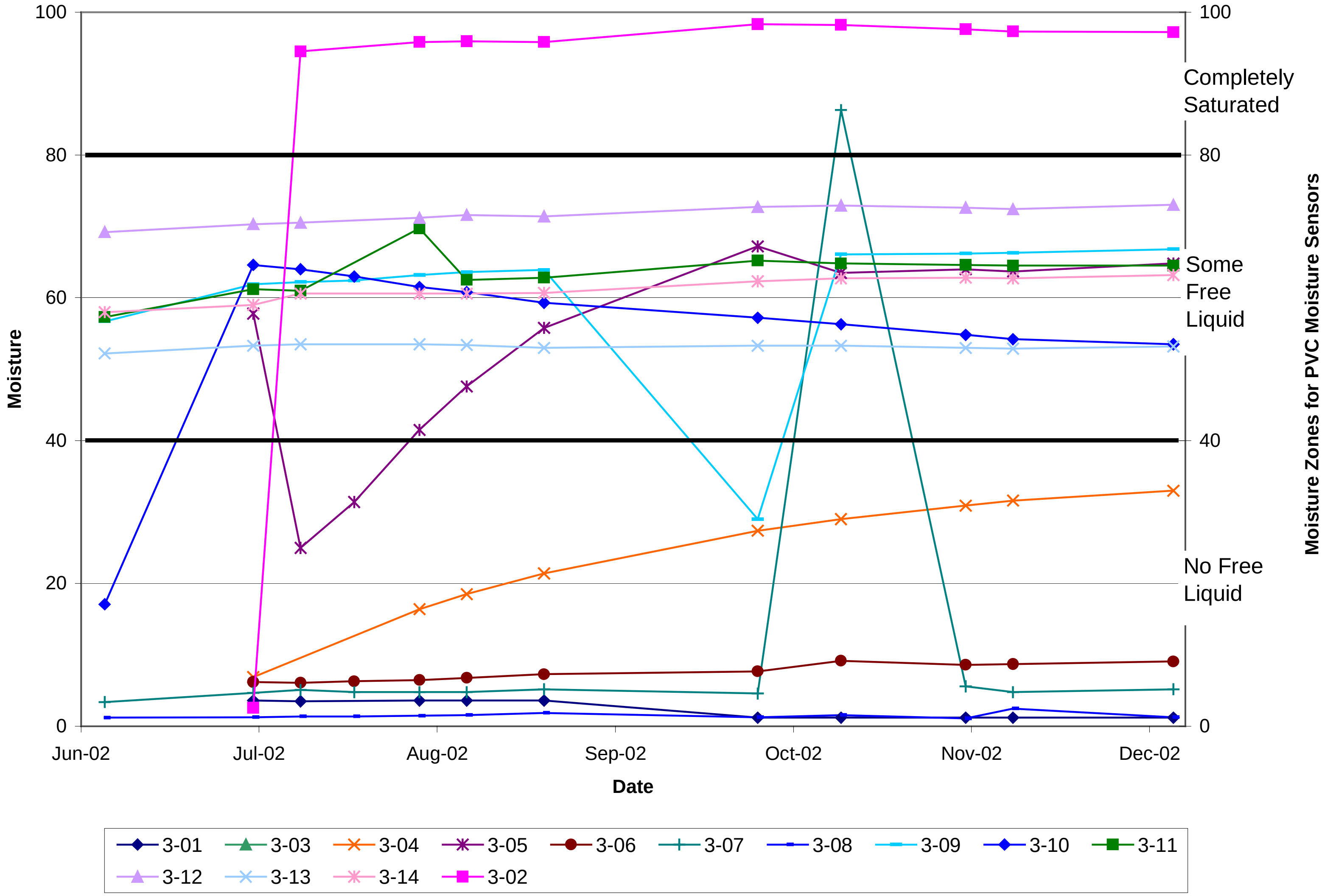


Figure 4-8. West-Side Anaerobic Cell Average PVC Moisture Readings (Full Scale Project)

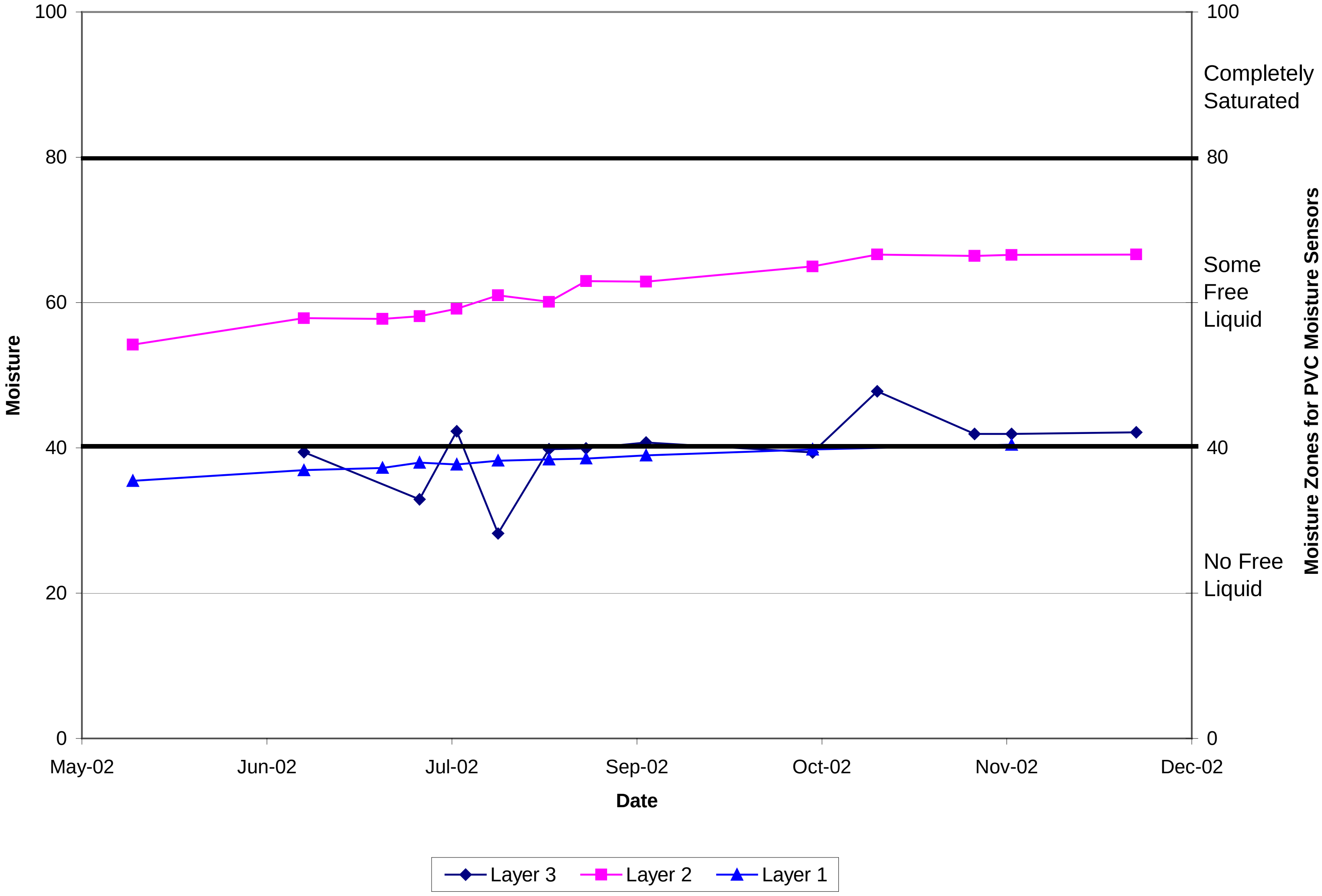


Figure 4-9. West-Side Anaerobic Cell Landfill Gas Concentrations from Header Line (Full Scale Project)

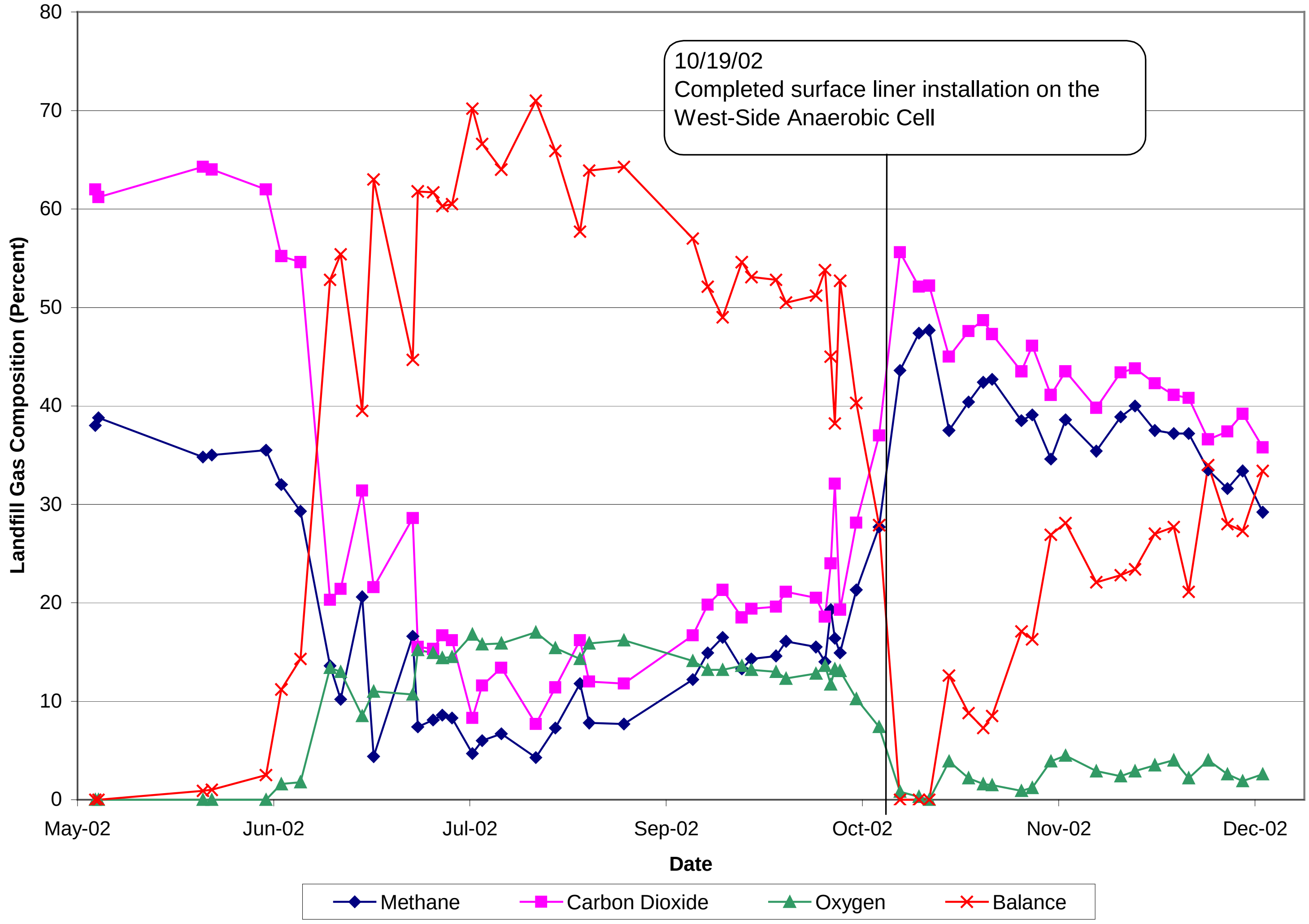


Figure 4-10. West-Side Anaerobic Cell Landfill Gas Flow Rate (Full Scale Project)

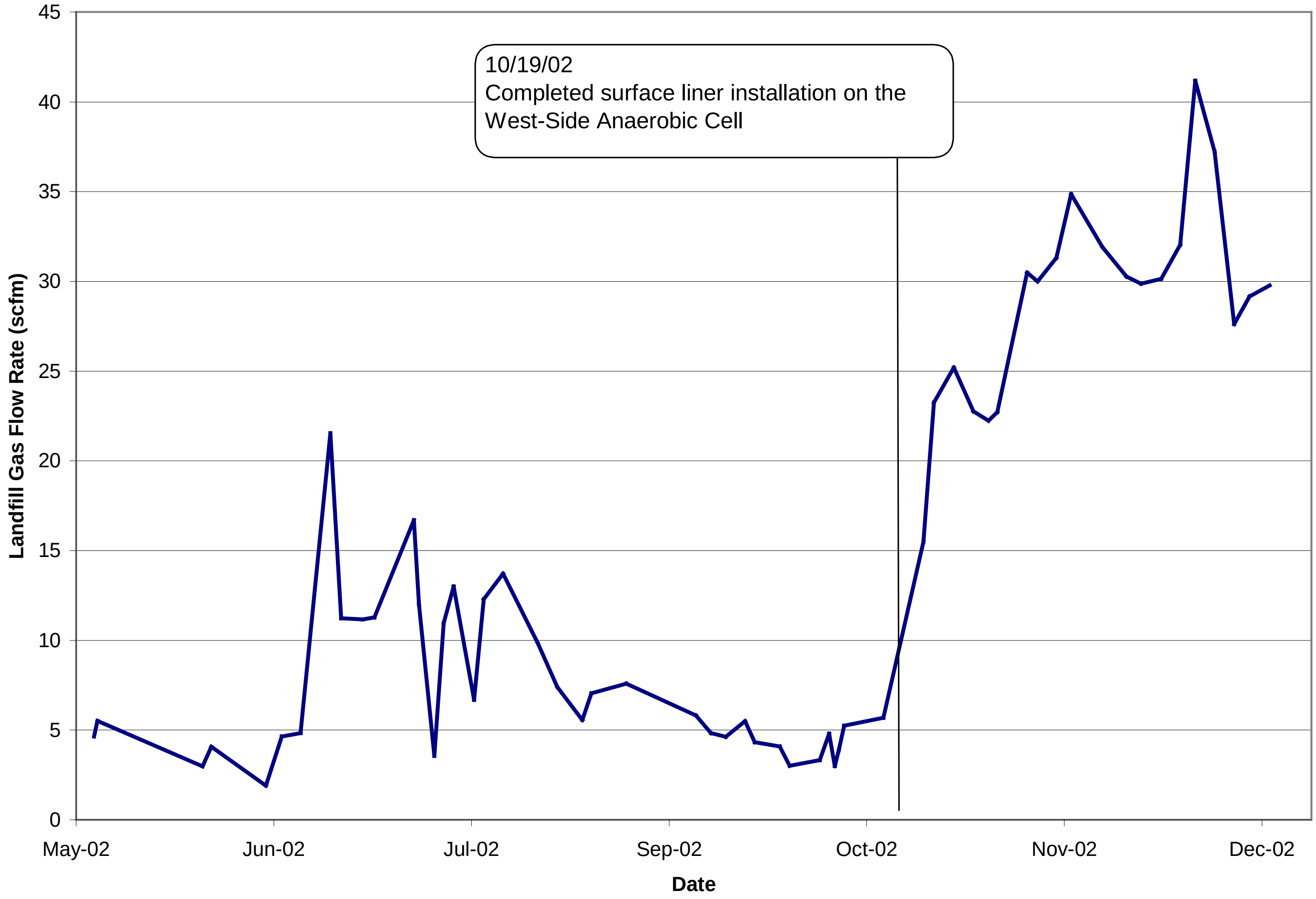


Figure 4-11. West-Side Anaerobic Cell Cumulative Methane (Full Scale Project)

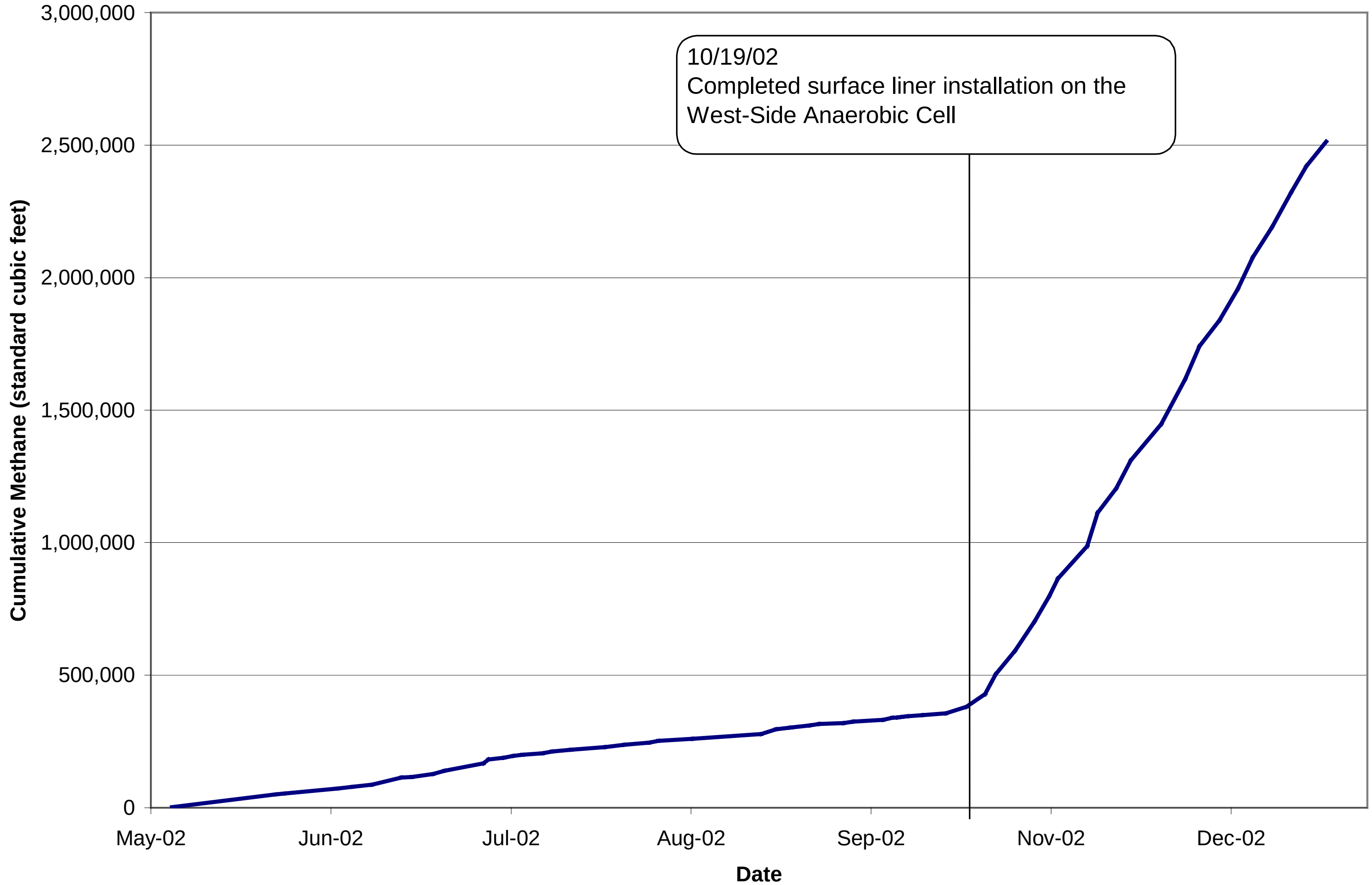


Figure 4-12. Cumulative Leachate Removed from the West-Side Leachate Collection and Removal System (LCRS) (Full Scale Project)

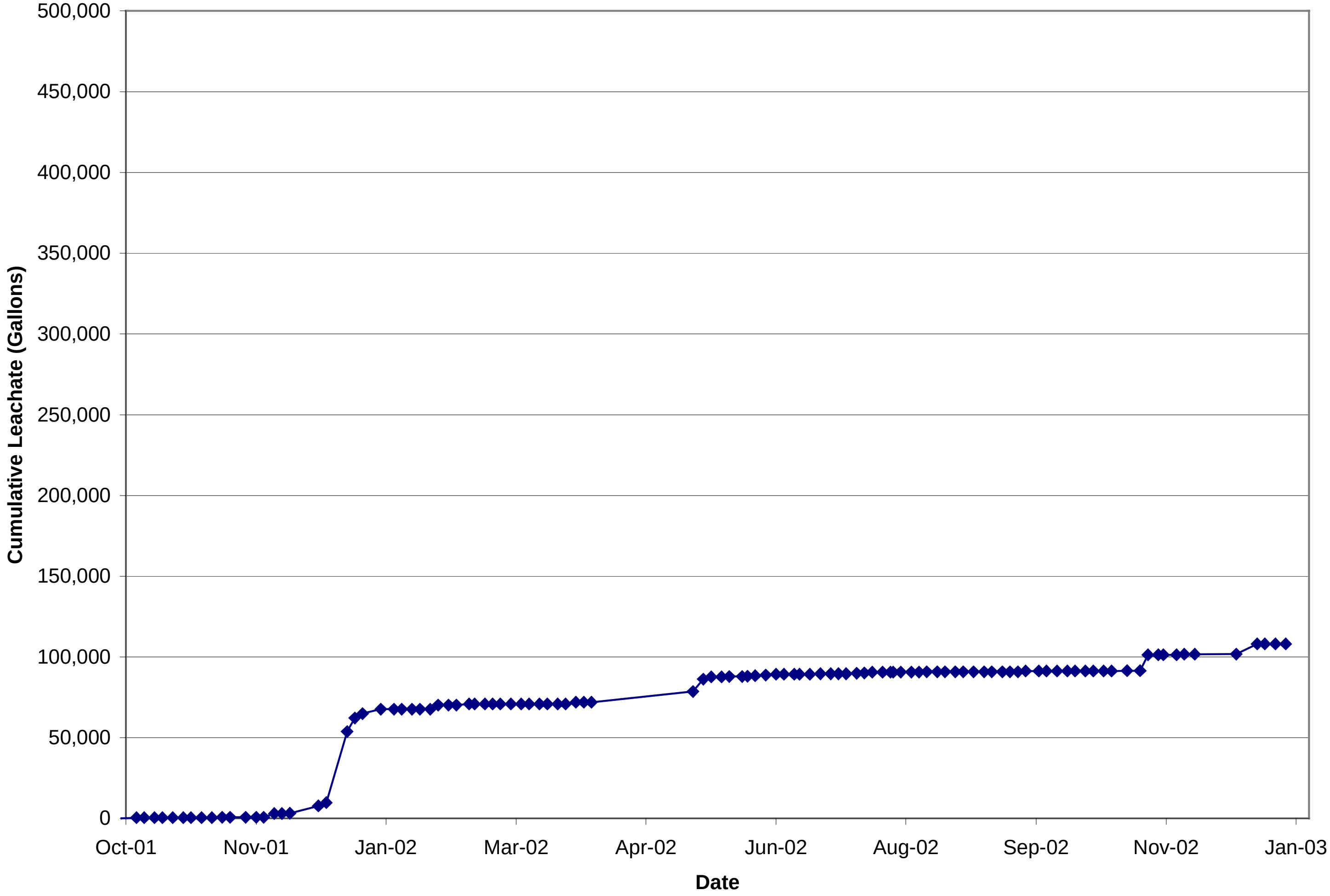


Figure 5-1. Module D Base Liner Temperature Readings (Northwest Quadrant) (Full Scale Project)

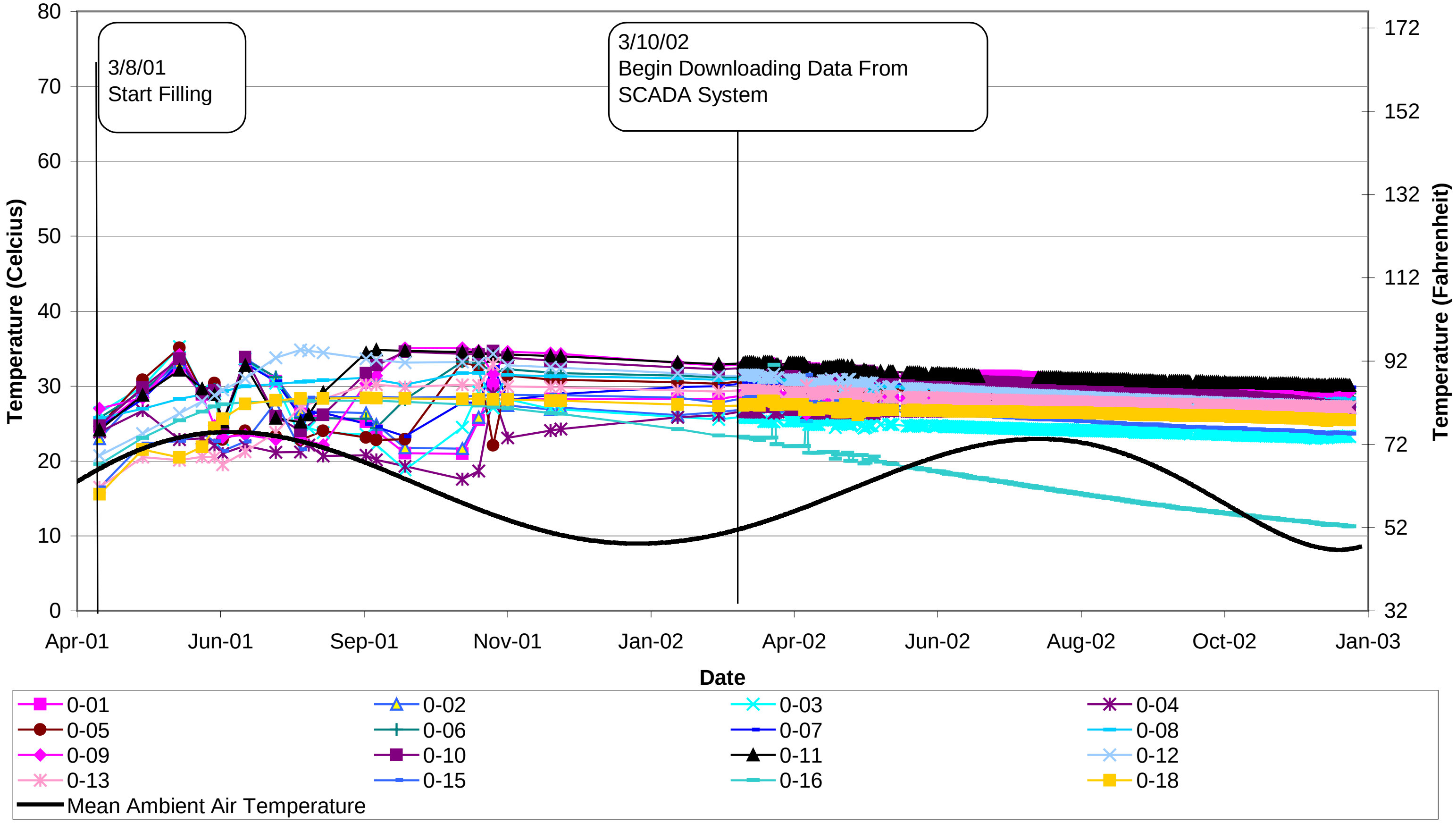


Figure 5-2. Module D Base Liner Temperature Readings (Southwest Quadrant) (Full Scale Project)

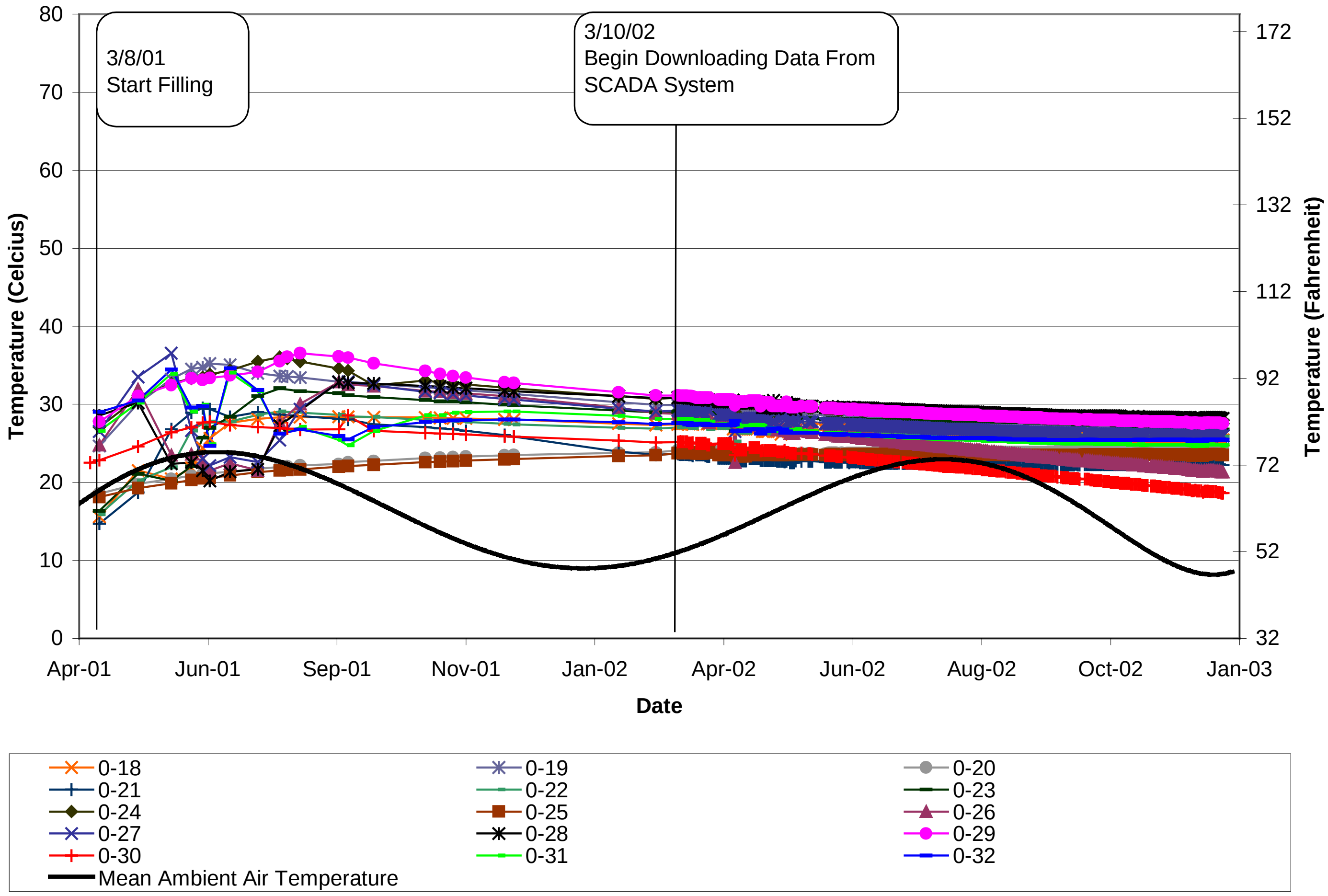


Figure 5-3. Module D Base Liner Temperature Readings (Northeast Quadrant) (Full Scale Project)

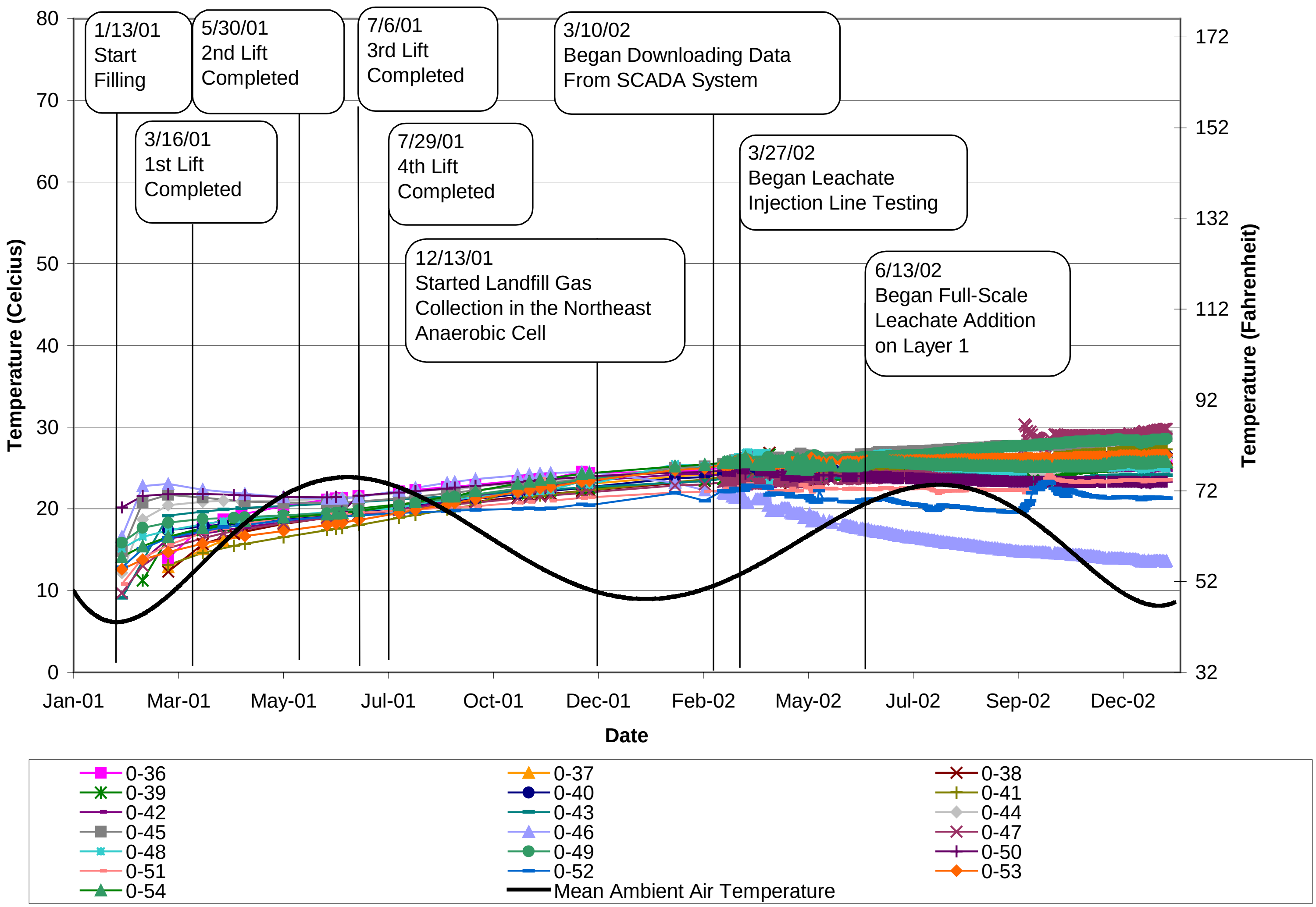


Figure 5-4. Module D Base Liner Temperature Readings (Southeast Quadrant) (Full Scale Project)

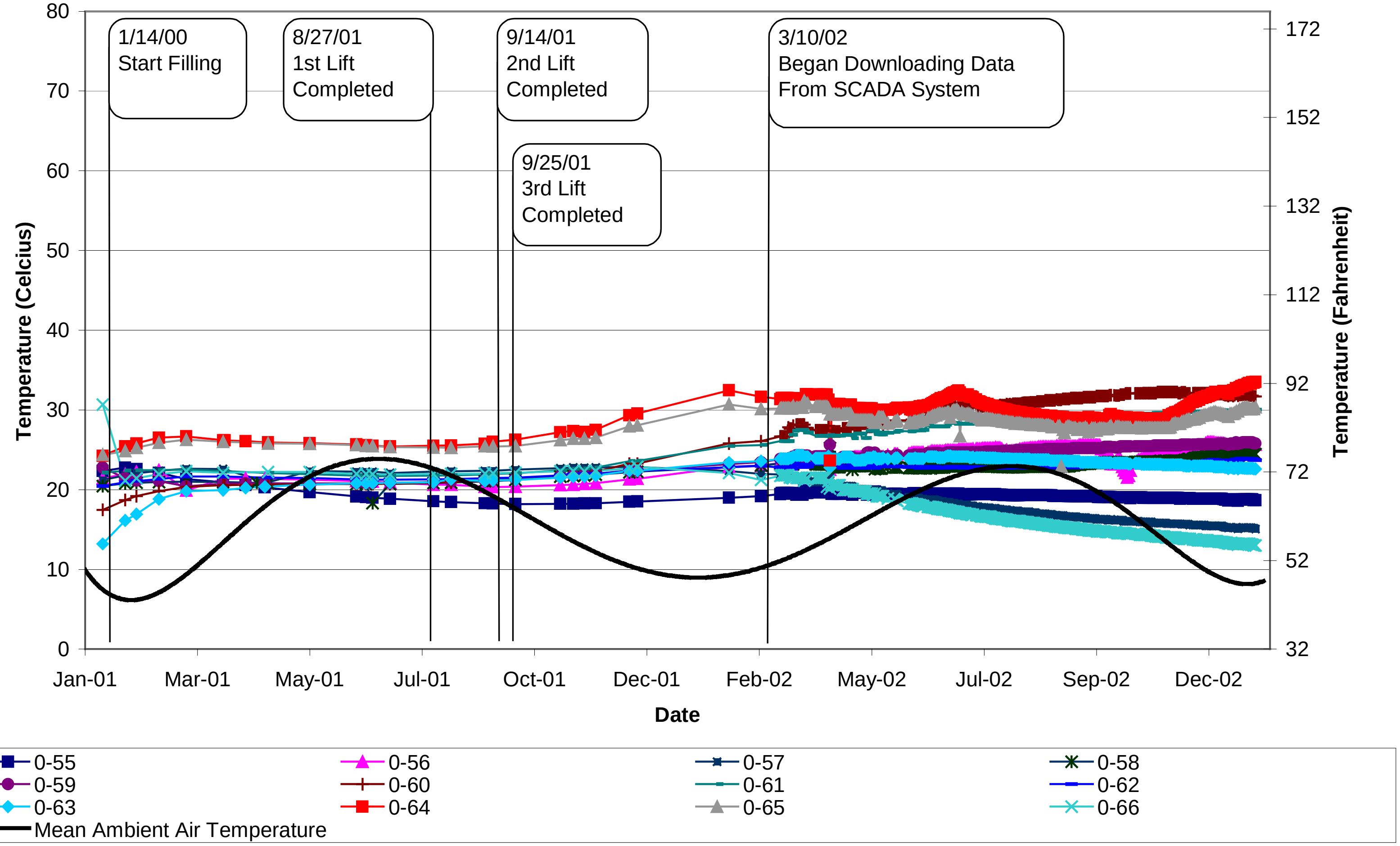


Figure 5-5. Module D Base Liner Average Temperature Readings (Full Scale Project)

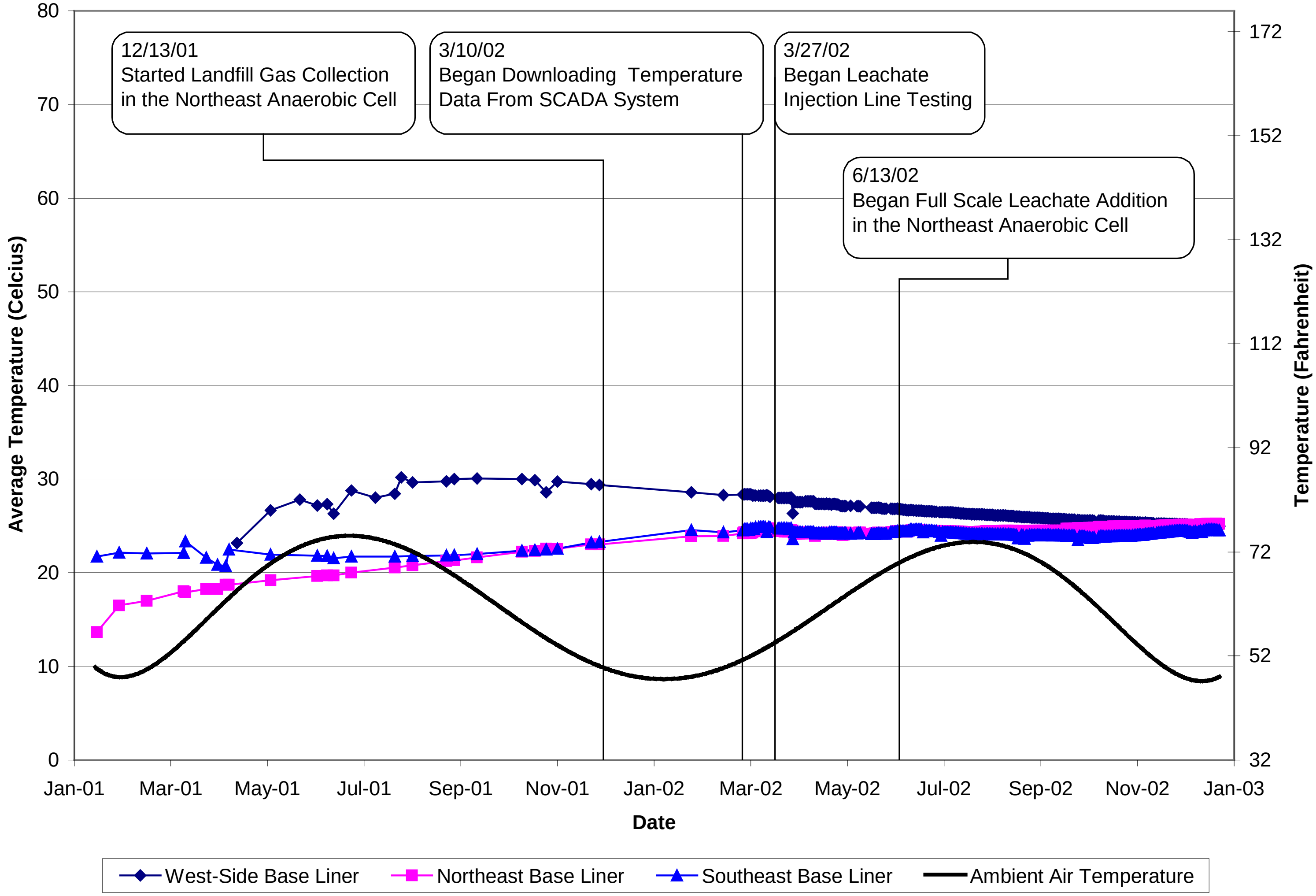


Figure 5-6. Module D Base Liner PVC Moisture Readings (Northwest and Southwest Quadrants) (Full Scale Project)

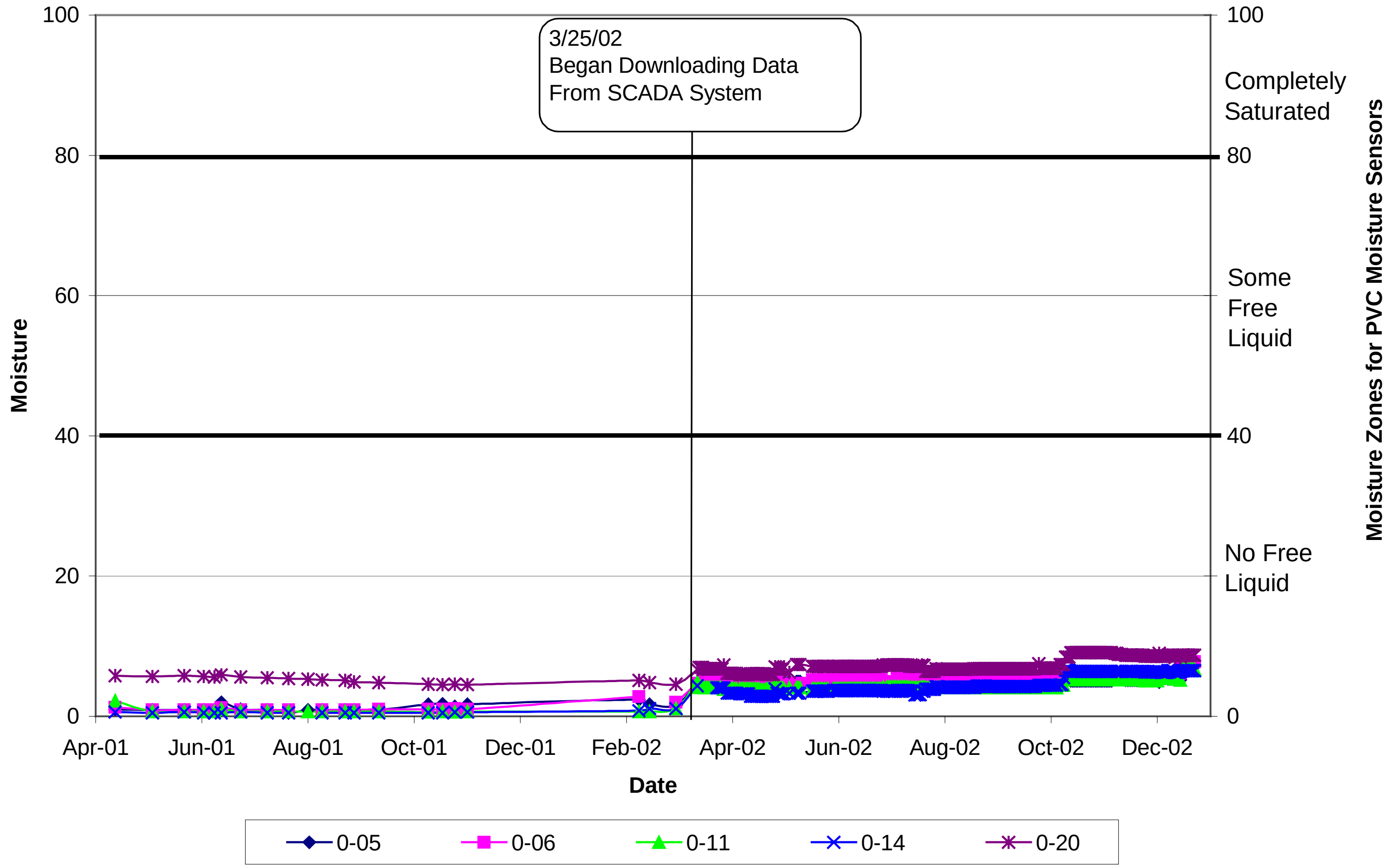


Figure 5-7. Module D Base Liner PVC Moisture Readings (Northeast Quadrant) (Full Scale Project)

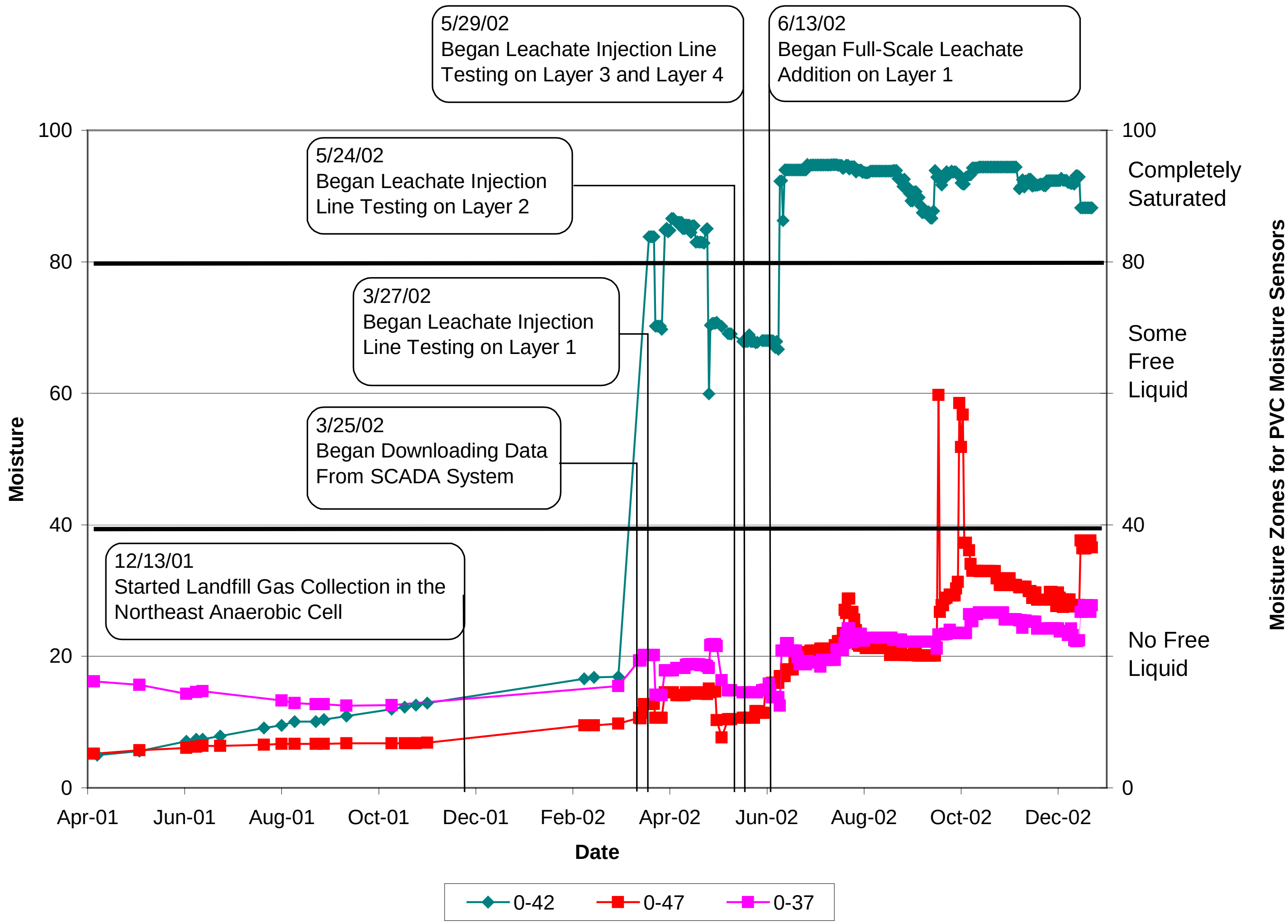


Figure 5-8. Module D Base Liner PVC Moisture Readings (Southeast Quadrant) (Full Scale Project)

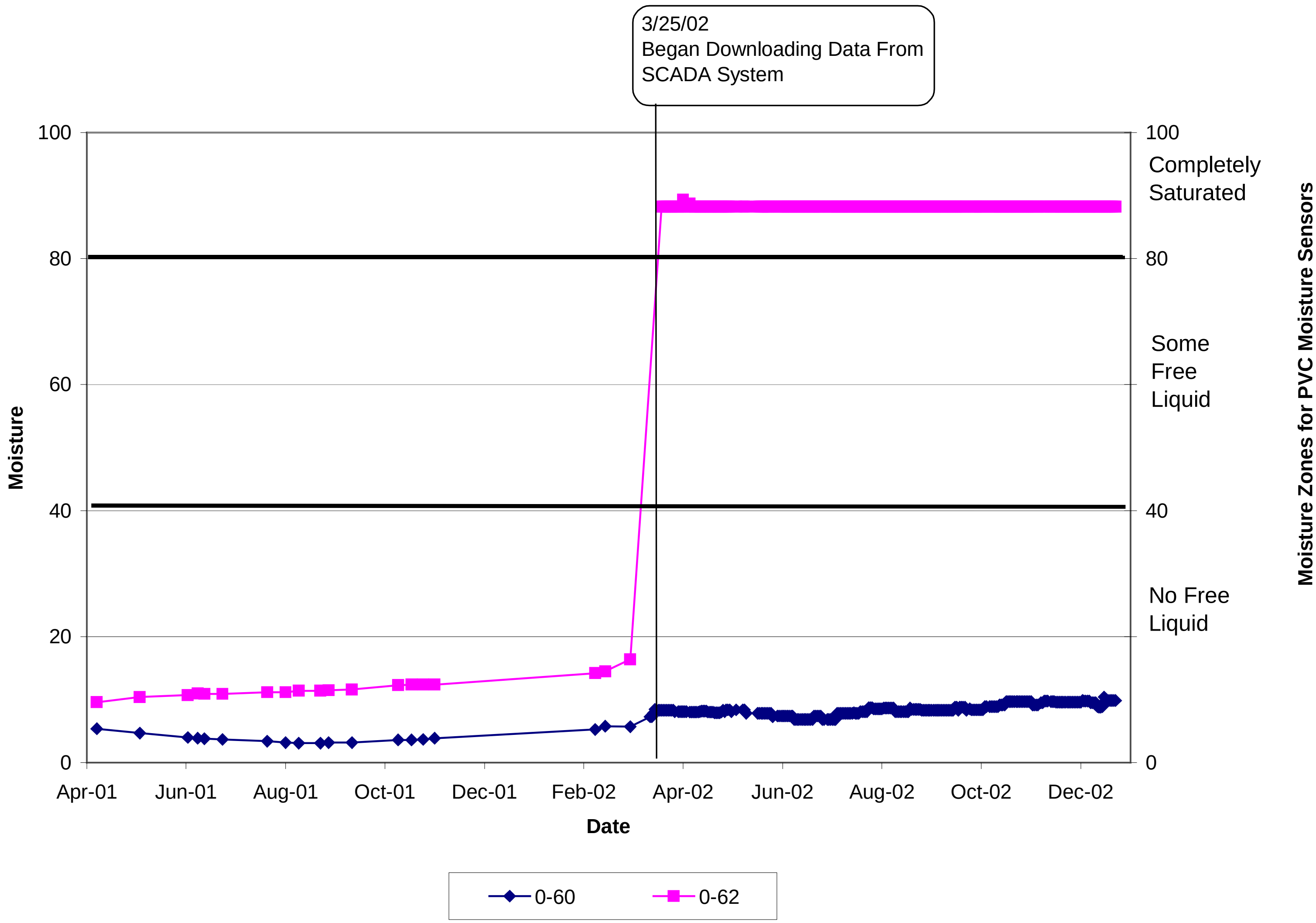


Figure 5-9. Module D Base Liner Average PVC Moisture Readings (Full Scale Project)

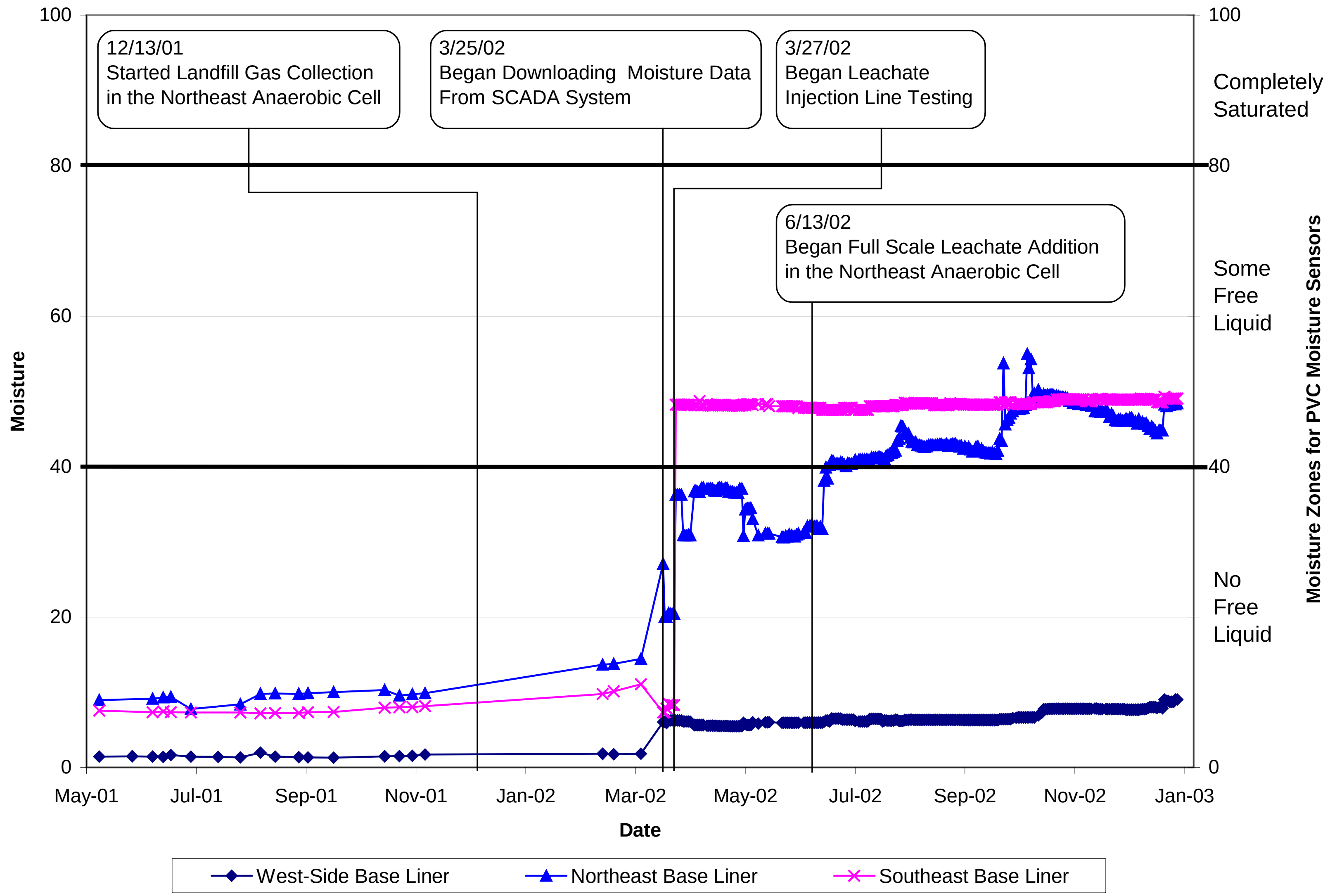


Figure 5-10. Module D Base Liner Pressure Transducers and Adjacent Tubes (Full Scale Project)

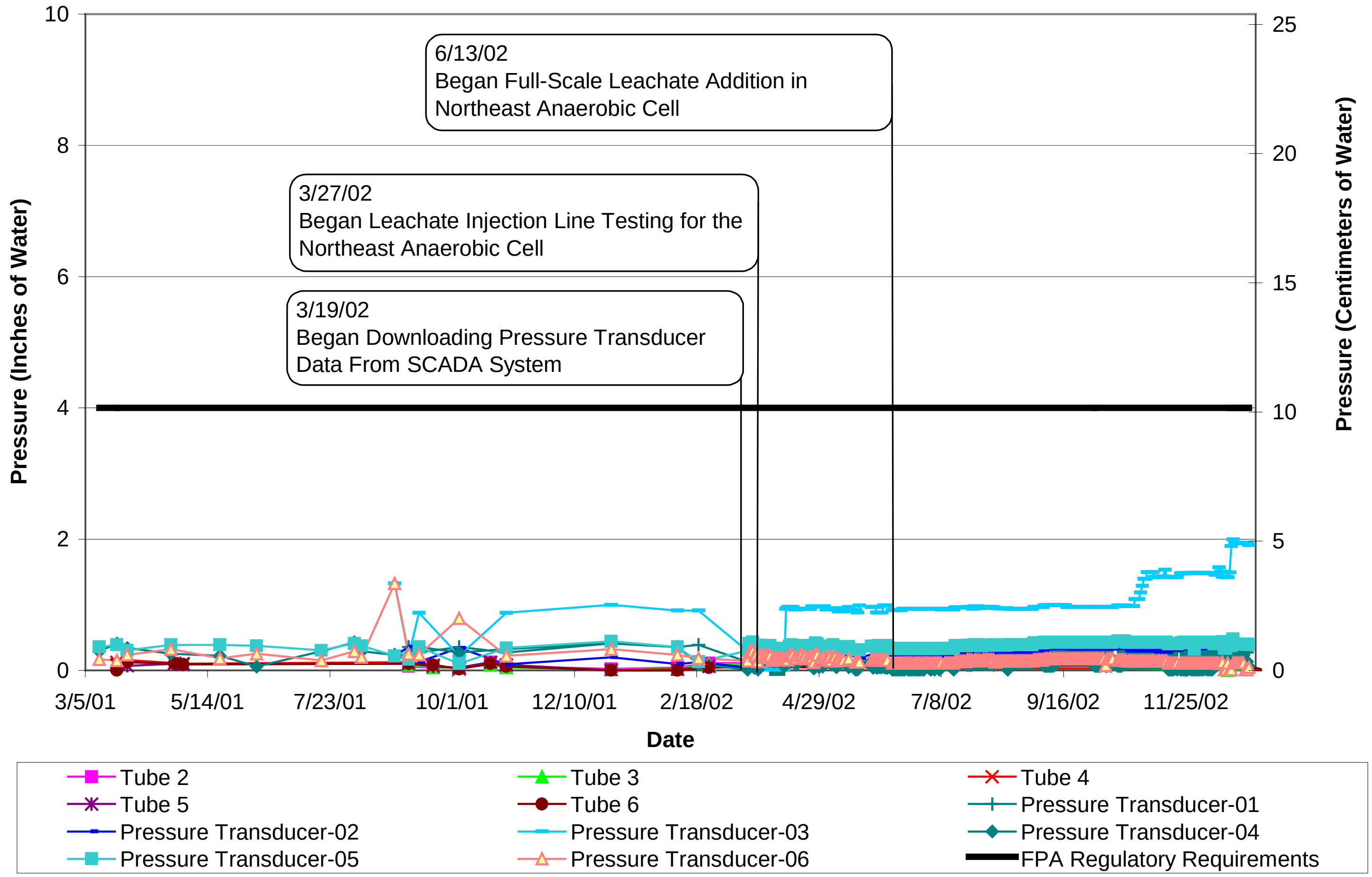
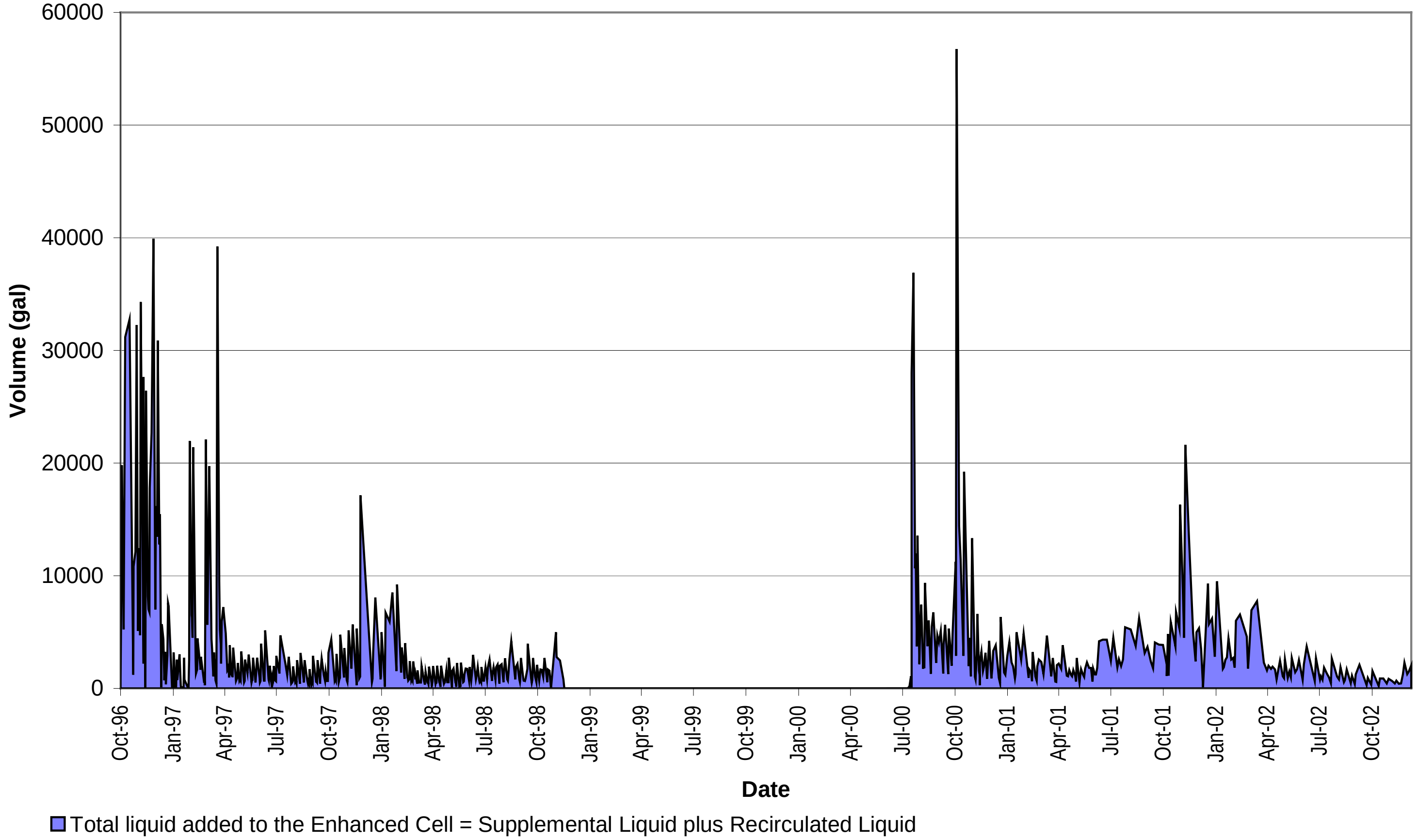


Figure 7-1. Enhanced Cell Leachate Recirculation Flow Rates (Pilot Scale Project)



Recirculation stopped between December 9, 1998 and July 25, 2000. During this time 59,618 gallons of leachate was sent to the LCRS.

Figure 7-2. Enhanced Cell Cumulative Leachate Added and Recirculated (Pilot Scale Project)

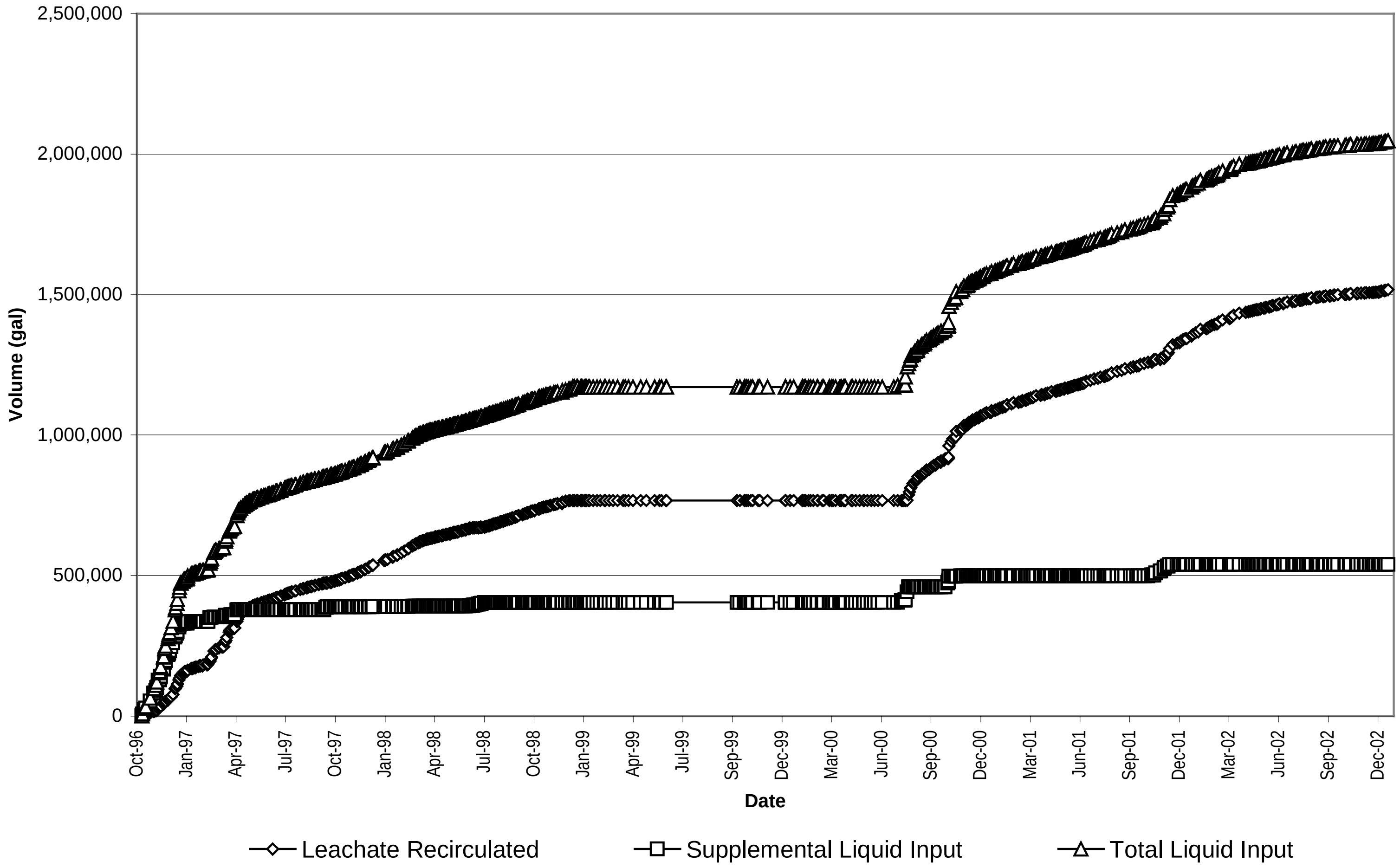


Figure 7-3. Enhanced Cell Average Temperatures (Pilot Scale Project)

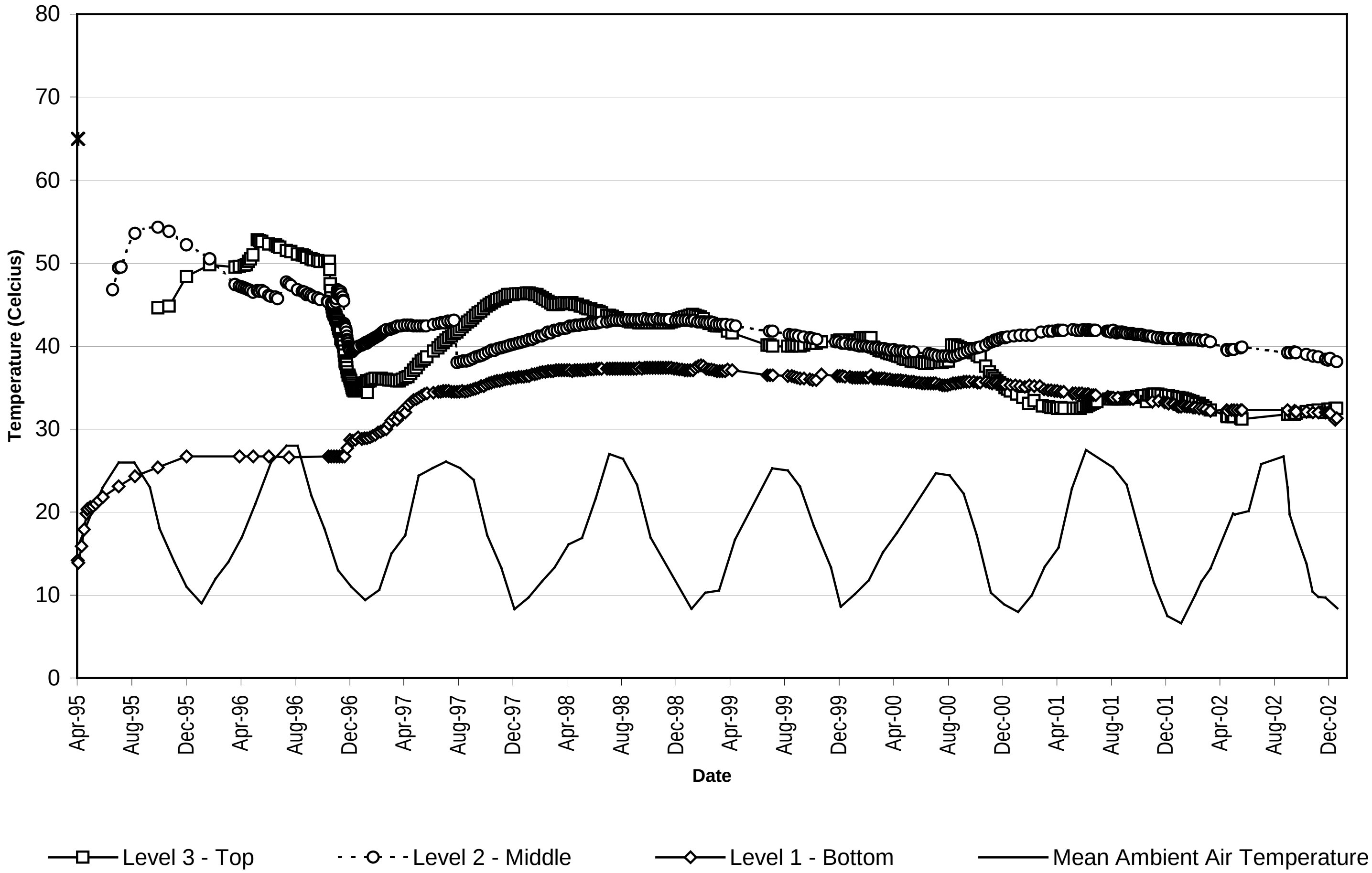


Figure 7-4. Control Cell Average Temperatures (Pilot Scale Project)

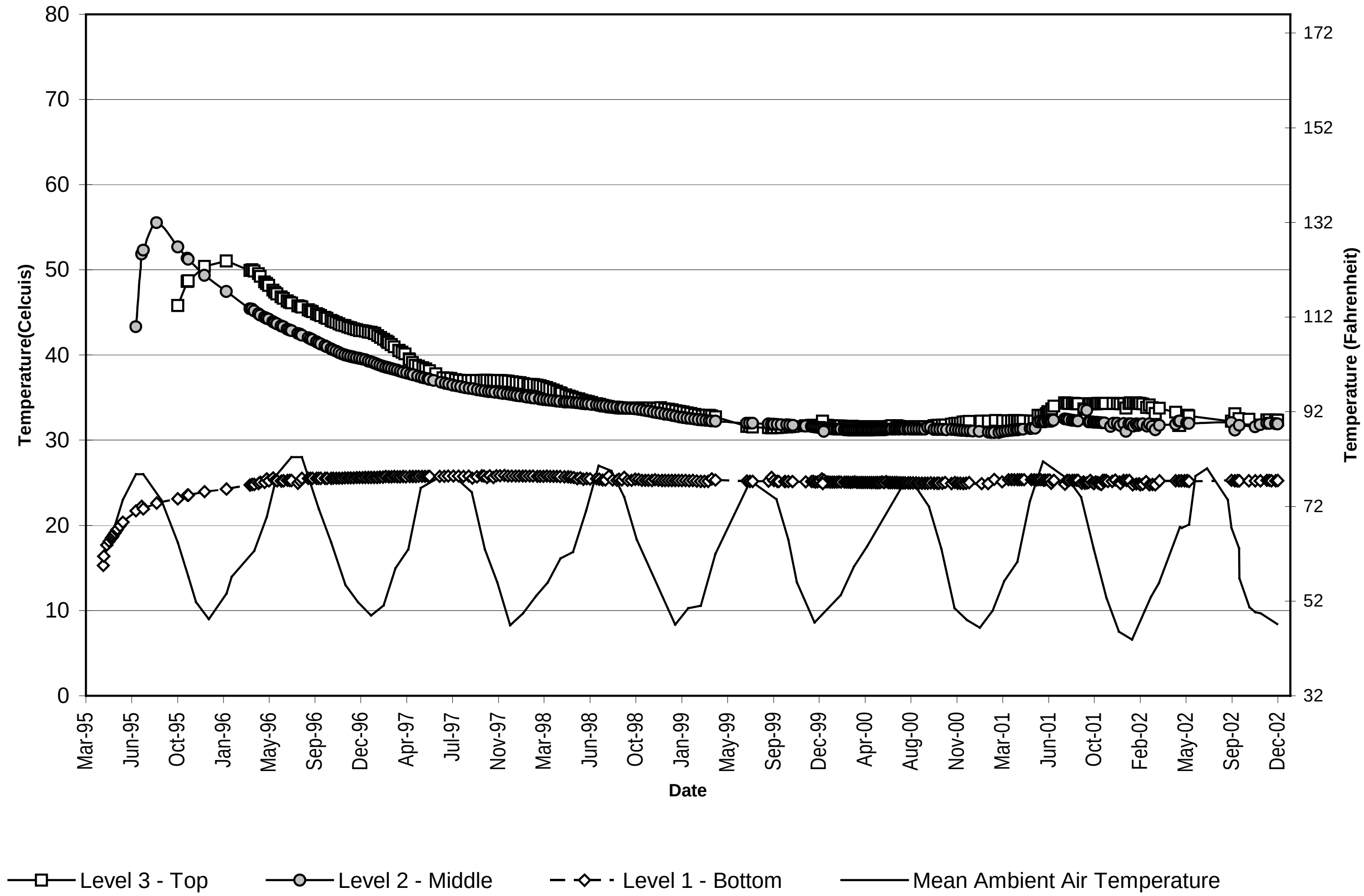


Figure 7-5. Enhanced Cell Average PVC Moisture Levels (Pilot Scale Project)

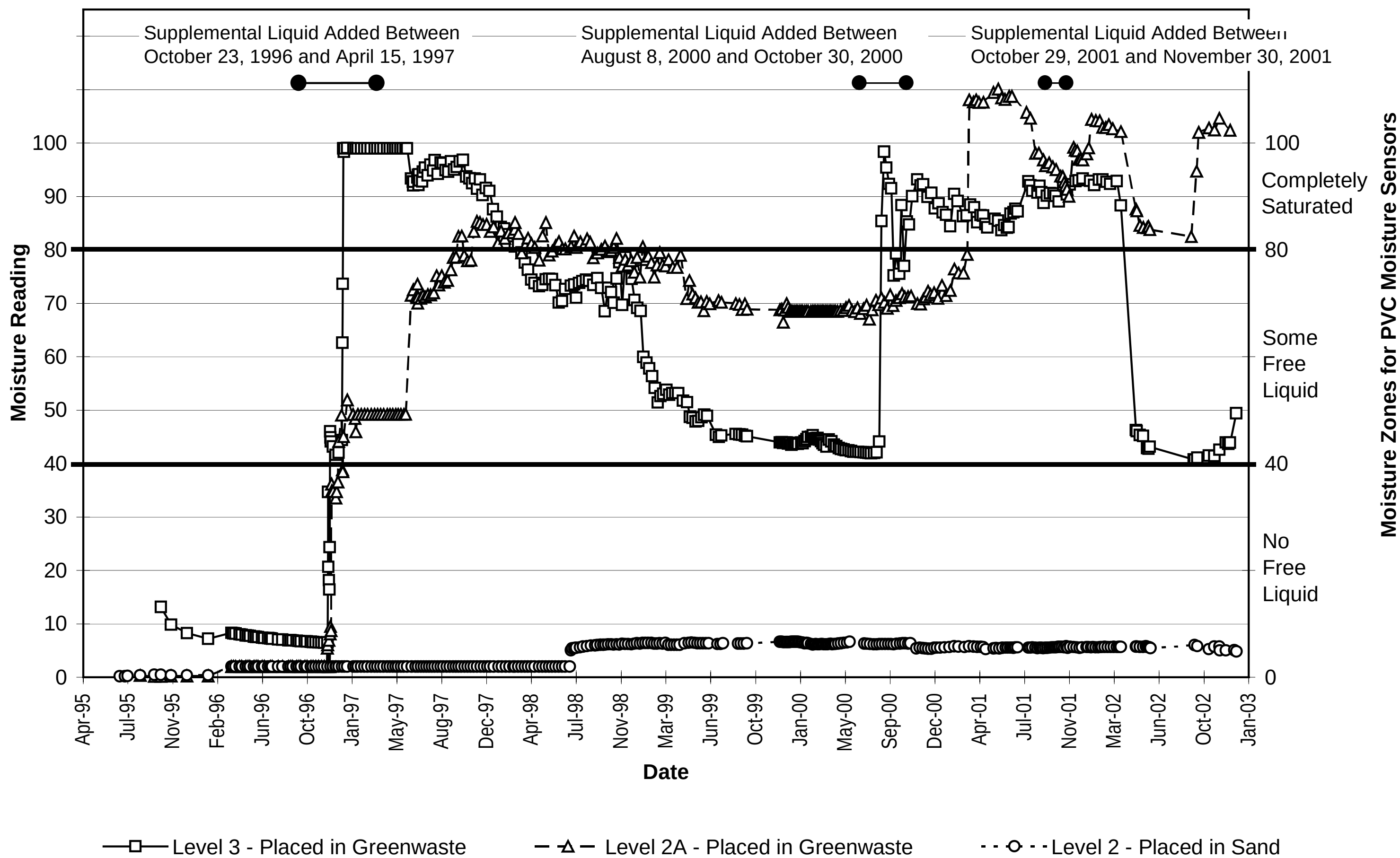


Figure 7-6. Enhanced Cell Average Gypsum Moisture Levels (Pilot Scale Project)

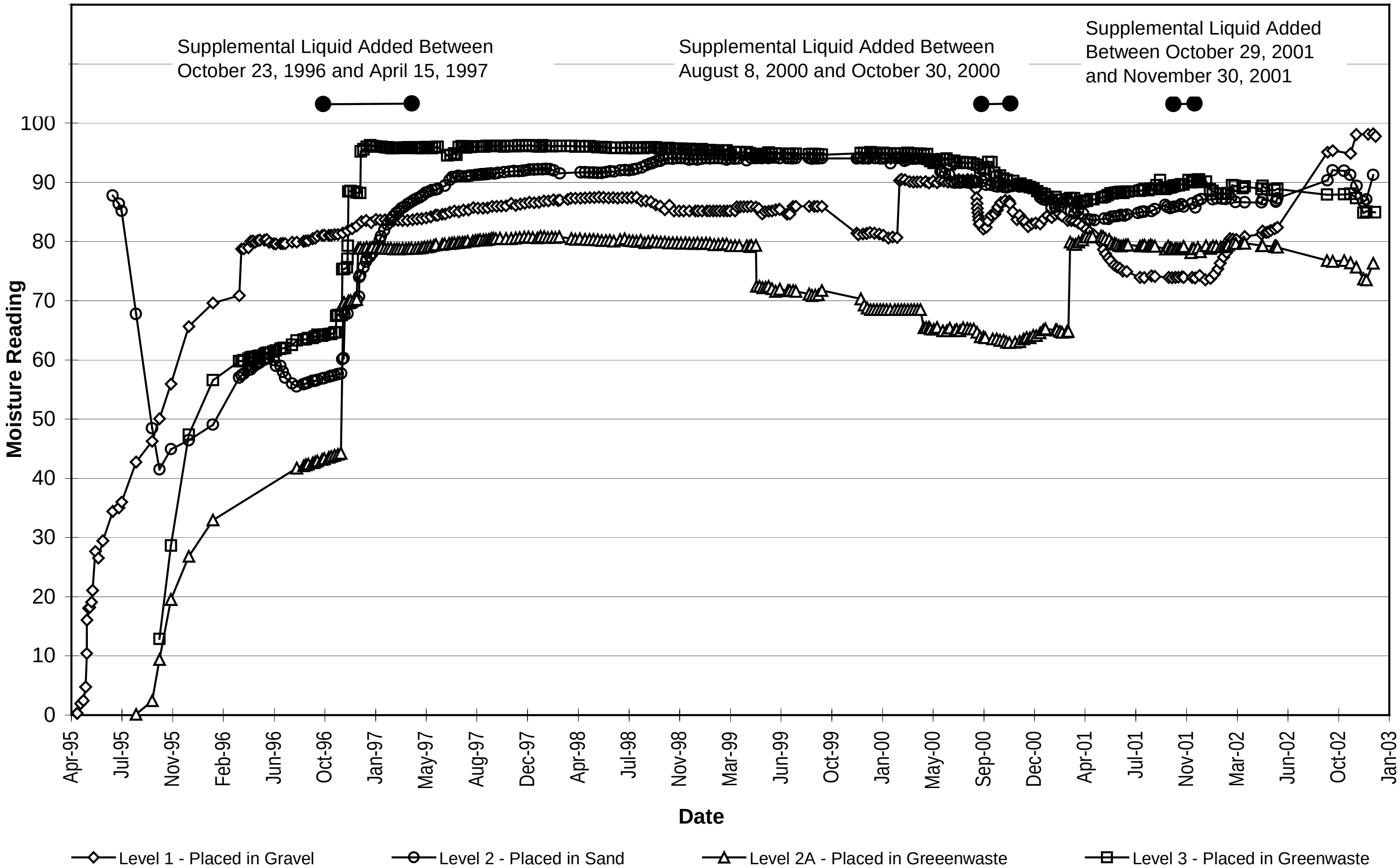


Figure 7-7. Control Cell Average PVC Moisture Levels (Pilot Scale Project)

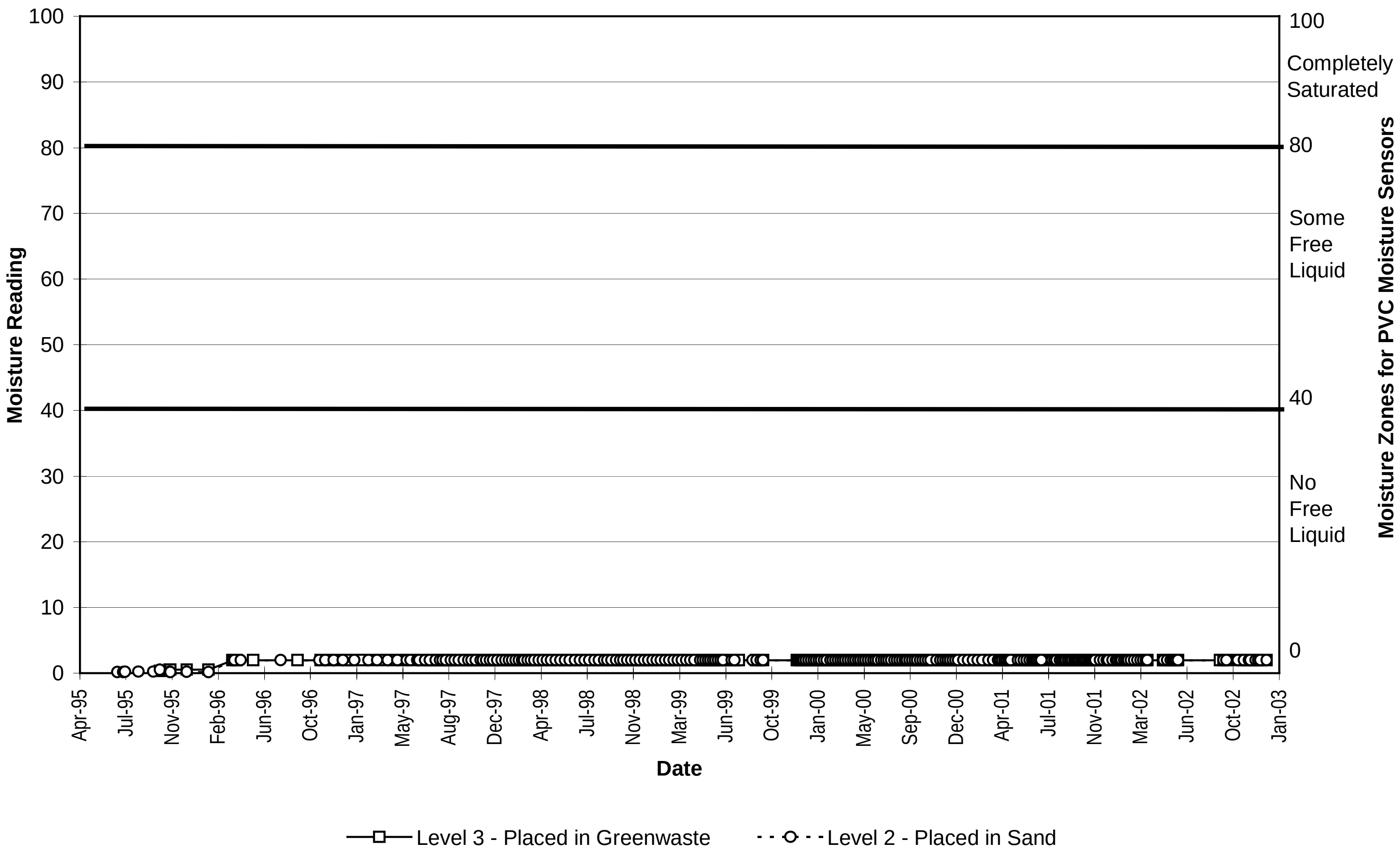


Figure 7-8. Control Cell Average Gypsum Moisture Levels (Pilot Scale Project)

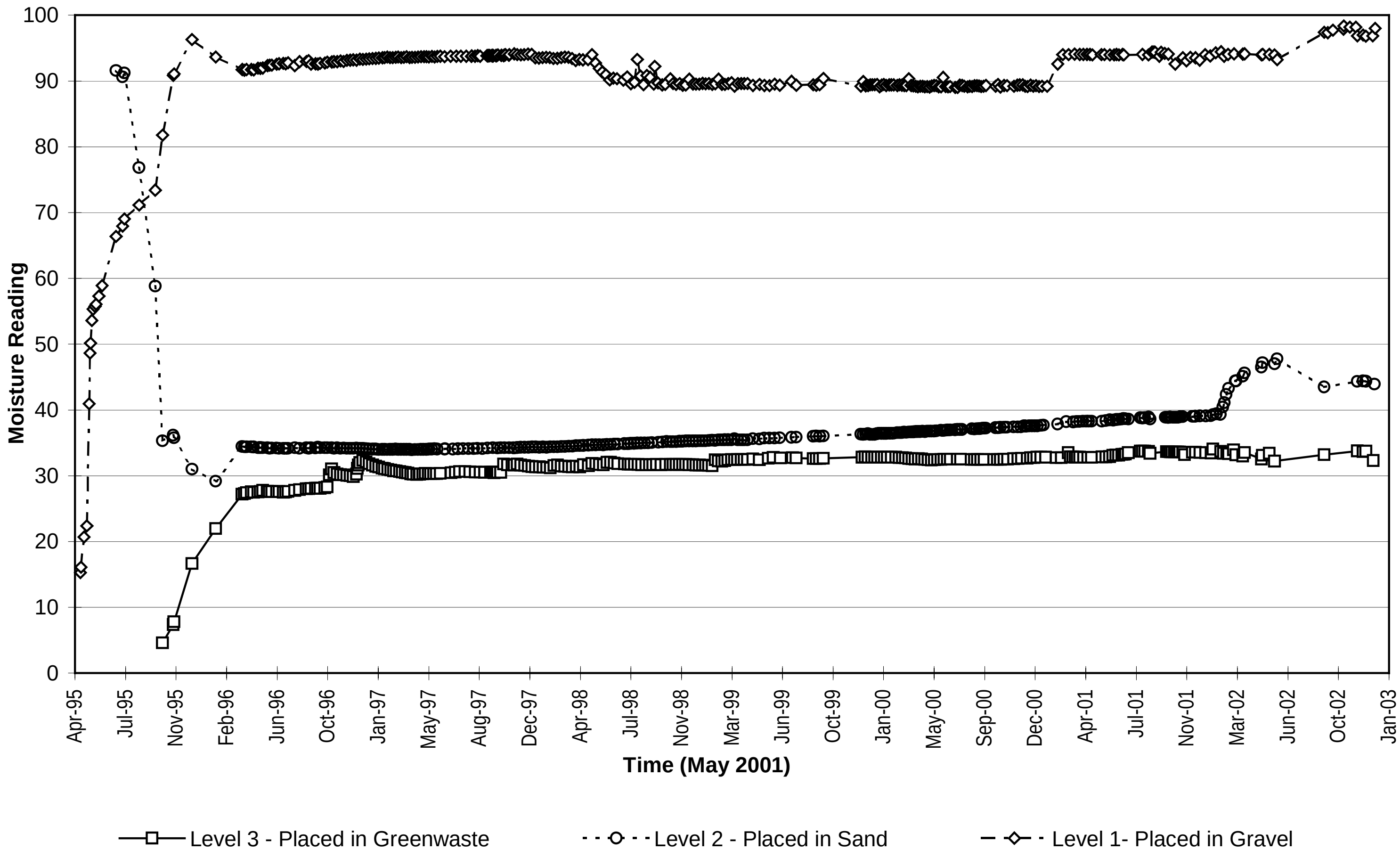


Figure 7-9. Methane Concentrations for the Enhanced Cell and Control Cell (Pilot Scale Project)

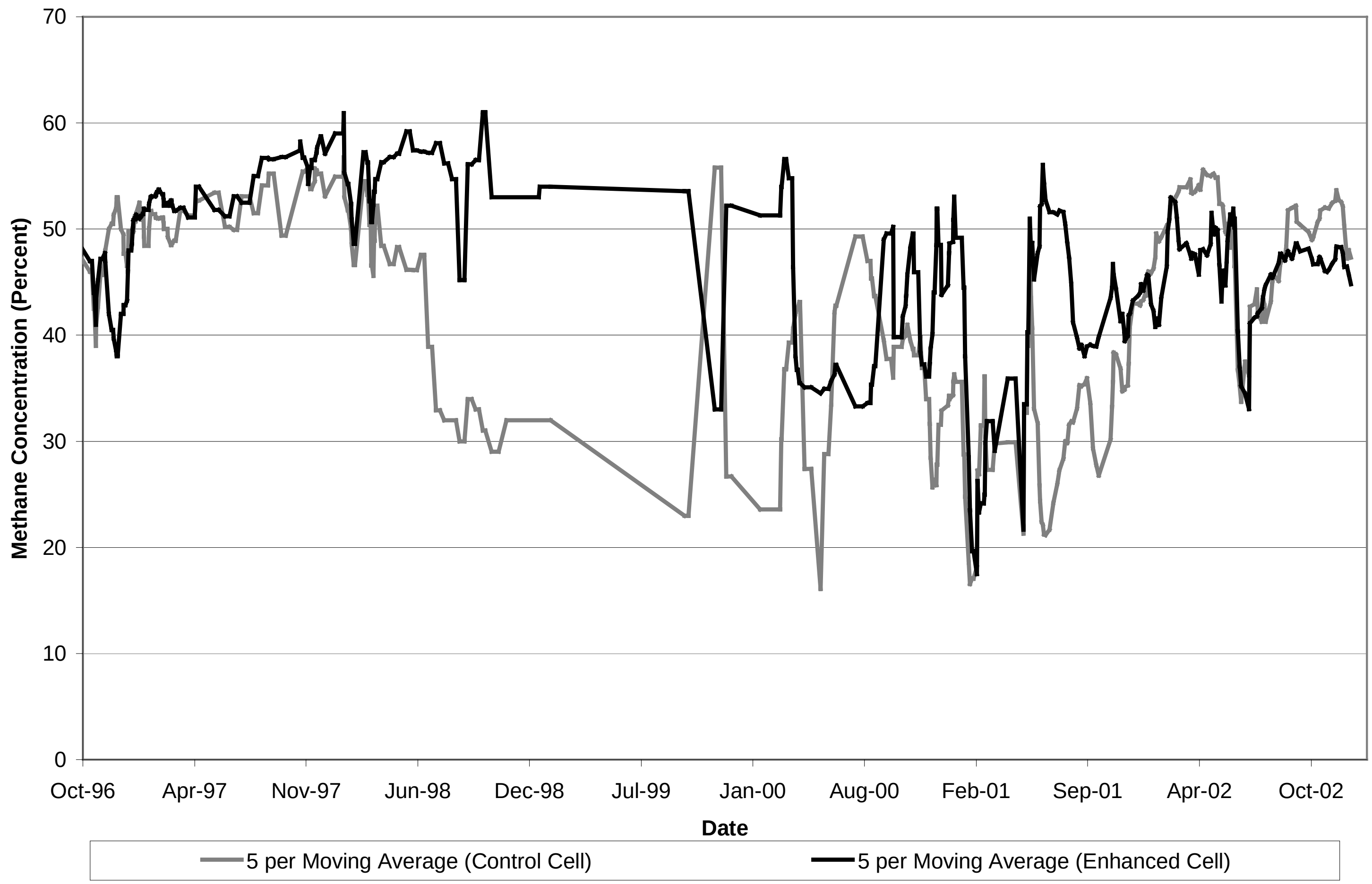


Figure 7-10. Methane Flow Rates for the Enhanced Cell (Pilot Scale Project)

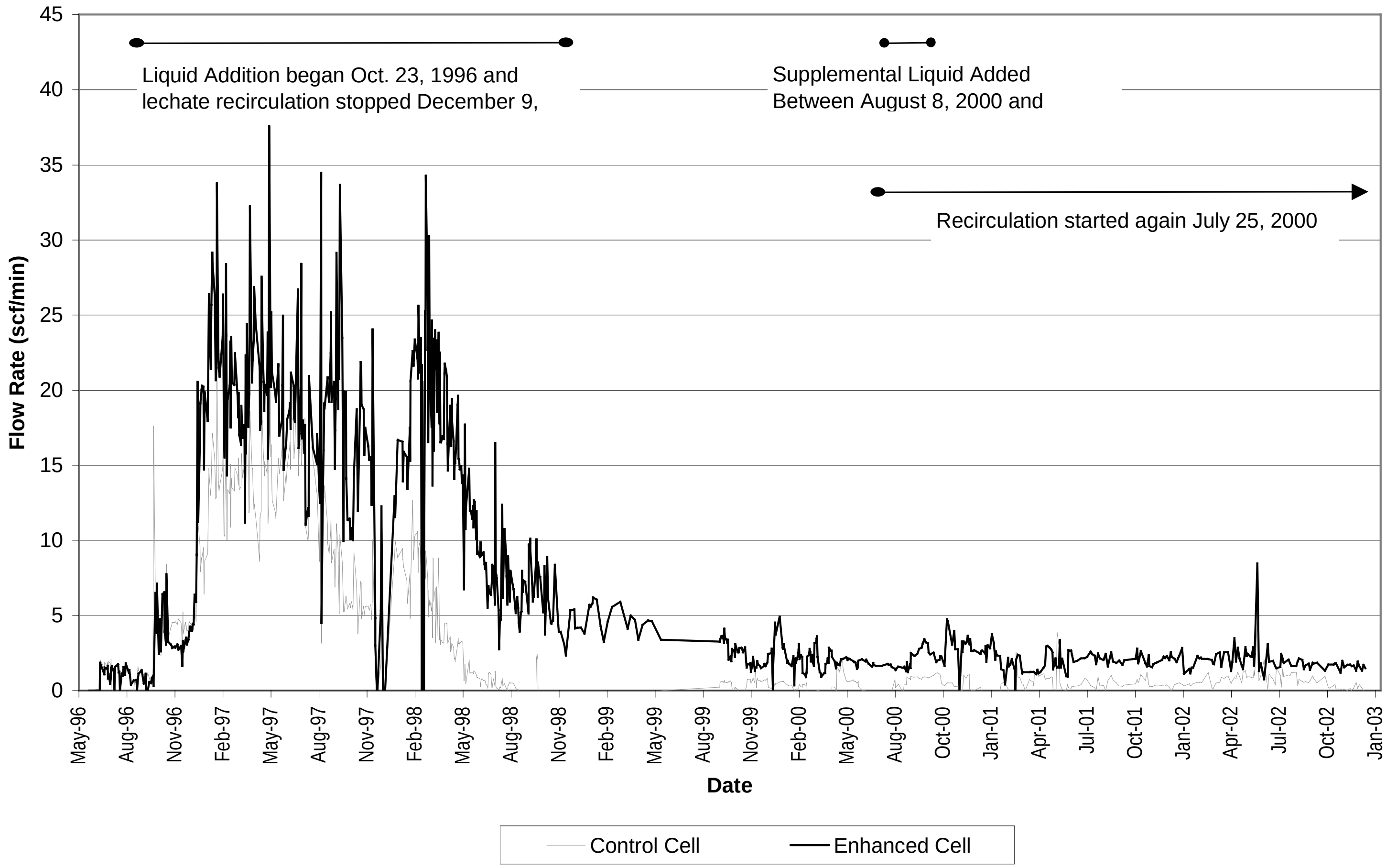


Figure 7-11. Cumulative Landfill Gas Volumes for the Pilot Scale Project

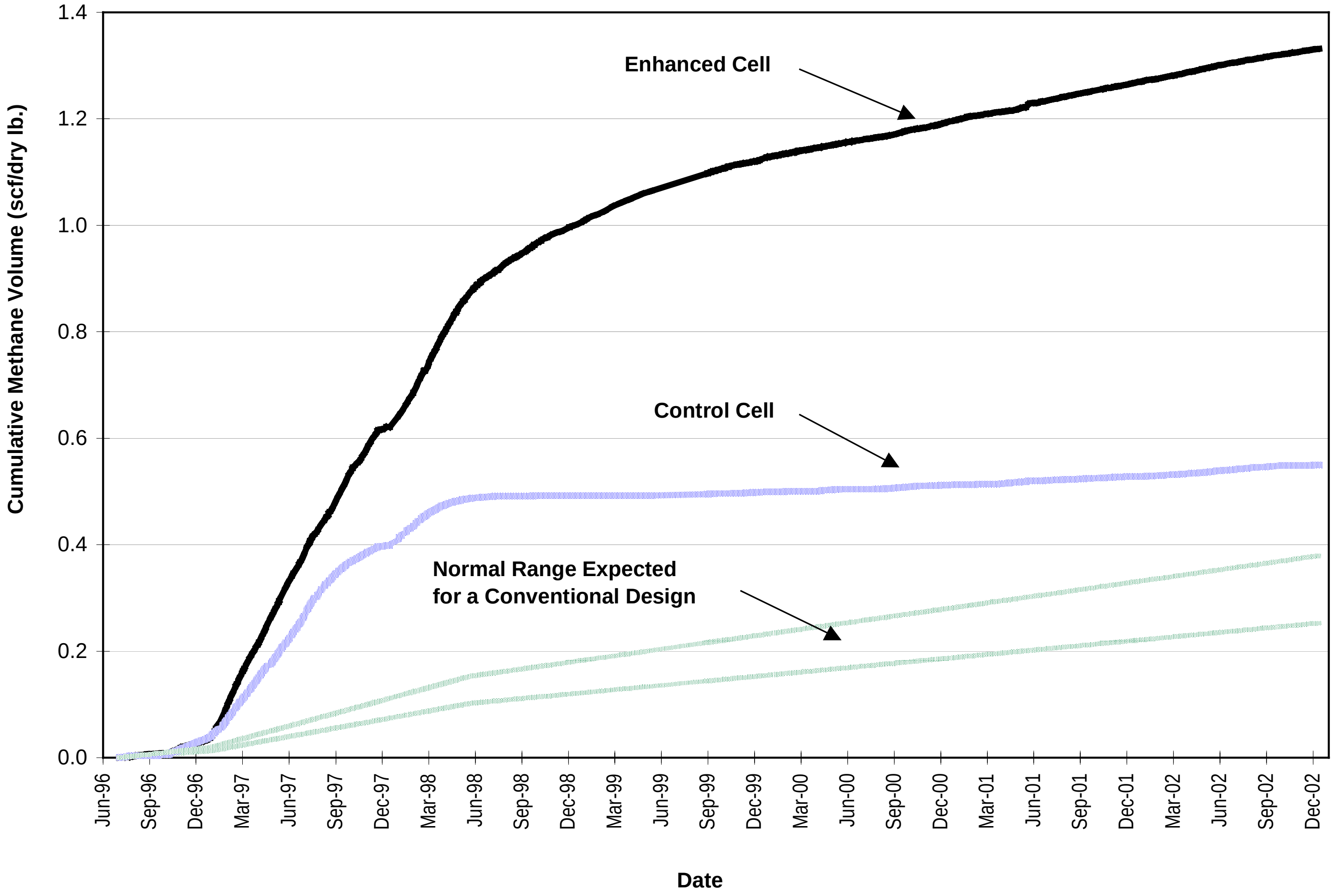


Figure 7-12. Change in Landfill Gas Constituents from the Enhanced Cell (Pilot Scale Project)

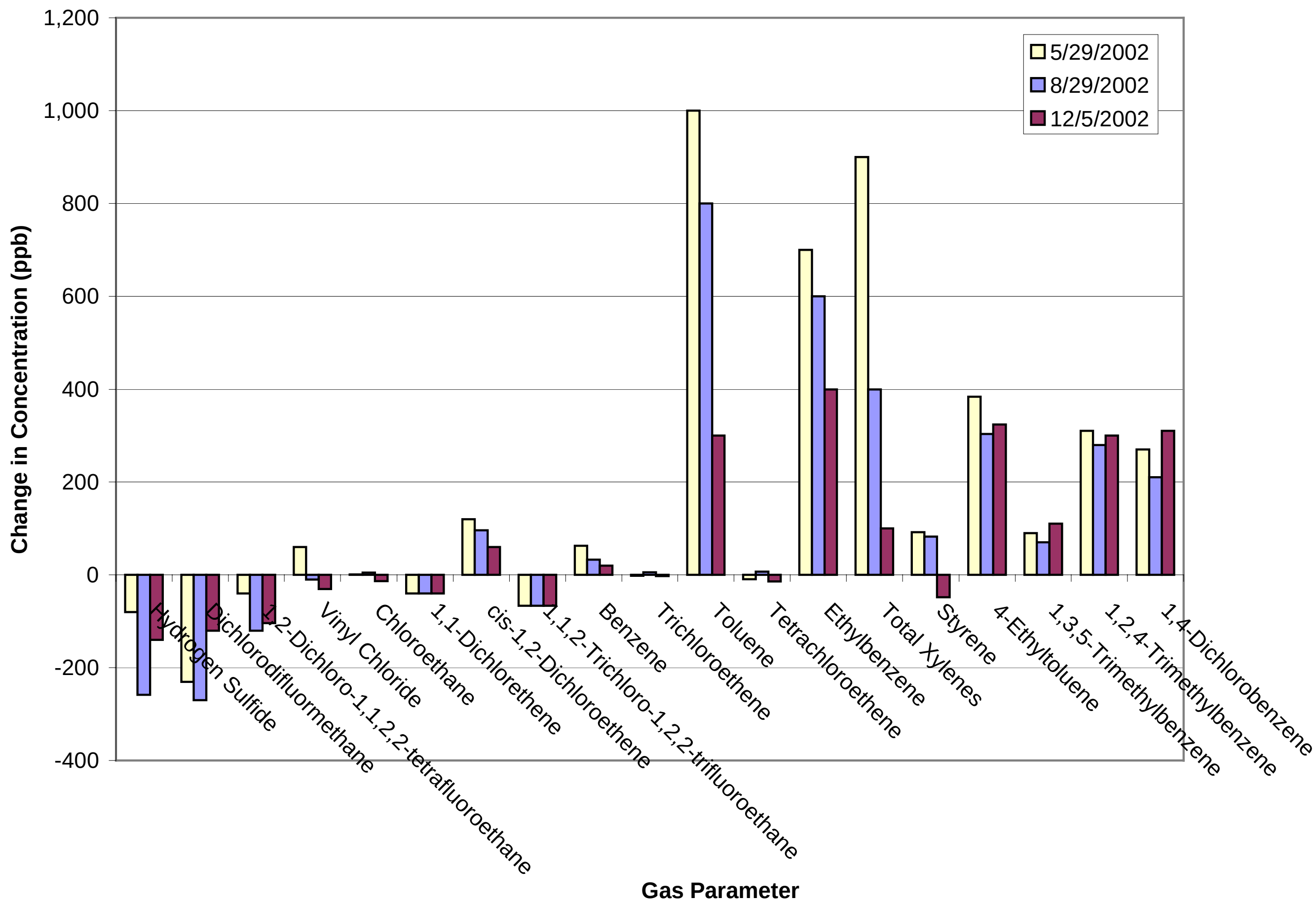


Figure 7-13. Change in Landfill Gas Constituents from the Control Cell (Pilot Scale Project)

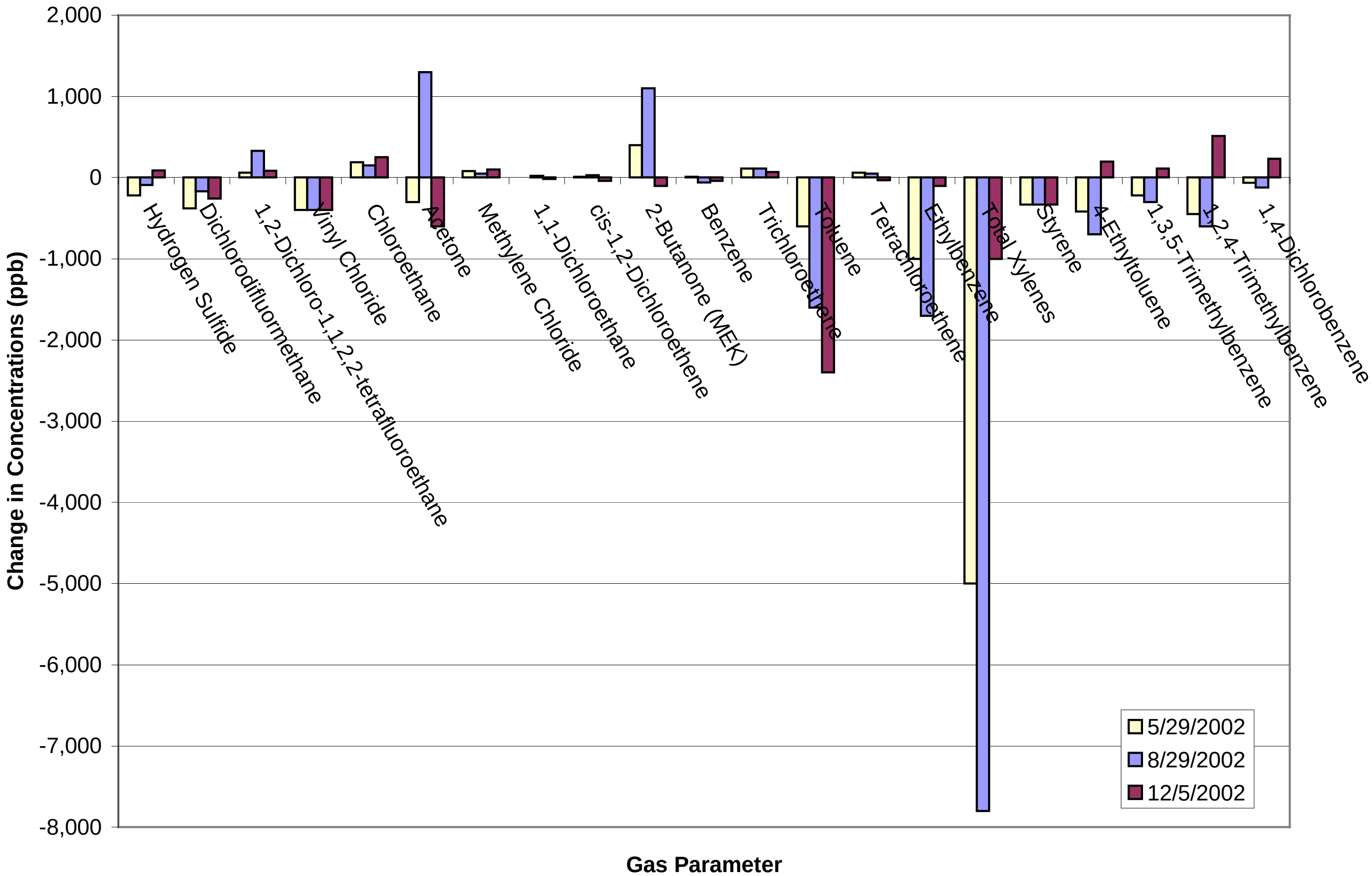


Figure 7-16. Results for Waste Sampled from the Enhanced Cell in June 2002 (Pilot Scale Project)