ESTIMATION OF LANDFILL SETTLEMENT FROM CONTROLLED AND CONVENTIONAL LANDFILLING

Project Report
for
Masters of Science in Civil Engineering

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INTRODUCTION

Landfills are one of the most economical methods for disposal of municipal solid waste. However, as development encroaches and environmental concerns limit the available space for landfill sites, there is a need to improve solid waste management. Current practices in most U. **S.** landfills, as defined as conventional landfills, consist of waste being placed, compacted, and then covered with an intermediate cover, usually soil, until final grade is reached. Regulations require complete containment of the landfill module through the use of a base liner system and placement of a final impermeable cover. Complete containment maintains the landfilled waste in a dry condition with the net effect of "entombing" the waste (Lee, 1990). Dry conditions result in slow and variable waste decomposition that extends over long periods of time, often decades. In conventional landfills, prolong waste decomposition and stabilization is realized in the continuous but gradually decreasing landfill settlement long after the 30-year post closure period. The rate and ultimate settlement achieved depends on site-specific conditions, which makes it difficult to predict. Complicated by the waste heterogeneity, landfill settlement is less understood than soil consolidation. Traditional soil consolidation models are not able to incorporate the large post-closure settlement. Selection of the appropriate settlement parameters is difficult due to solid waste properties that vary greatly and change with time. Often, the ultimate dedication of the land to more beneficial uses is delayed or limited by the variable post-closure settlement.

Yolo County Central Landfill (YCCL), located in Davis, California, is demonstrating an innovative solid waste management strategy known as "enhanced" landfilling or a landfill bioreactor. Enhanced landfilling is an operational practice that manipulates the landfill for optimal waste decomposition and accelerated methane production. Essentially the landfill becomes a biological treatment system to stabilize the landfilled waste. In Yolo County's Landfill Bioreactor Project this is achieved through liquid (groundwater) addition and recirculation of generated leachate. By accelerating waste decomposition, landfill gas generation and waste stabilization are completed within five to ten years, rather then the typical 30-50 years (or more). Newly created landfill space can then be reused, thereby extending the landfill life. Accelerated waste decomposition process minimizes post closure settlement and results in more predictable landfill settlement. Better landfill settlement prediction allows the land to be dedicated to more beneficial uses sooner.

This paper will conduct a comprehensive review of current methods for estimating landfill settlement. Landfill settlement associated with conventional landfill practices and enhanced landfilling will be estimated using traditional soil consolidation models. Field settlement data from Yolo County's Bioreactor Landfill Demonstration Project will be used to calibrate these models. This paper will also explore an alternative approach that estimates landfill settlement based on waste decomposition and overburden pressures. Landfill gas generation data will be correlated to a reduction in waste volume and, in turn, settlement. This method may allow landfill settlement to be estimated by monitoring landfill gas generation, rather than traditional settlement surveys. Application of these models to conventional landfill settlement and accelerated settlement achieved through enhanced landfilling will be evaluated.

FACTORS EFFECTING LANDFILL SETTLEMENT

Landfill settlement is commonly predicted using traditional soil mechanics models. Sowers (1968) was the first to propose using Terzaghi's one-dimensional consolidation theory to estimate landfill settlement. Yen and Scanlon (1975), Rao et al. (1977), Landva and Clark (1990), and others applied analytical models to improve predictions. Nevertheless, landfill settlement is complex and predictions often over or under estimate the final settlement. Less understood than soil settlement, landfill settlement is characteristically irregular due to the material's heterogeneity (Edil et al., 1990; Wall and Zeiss, 1995). Waste properties such as particle size, presence of voids, particle to particle contact, density, and organic content available for decomposition are difficult to determine in the field and may vary greatly within the landfill. These properties initially depend on operational practices but change with time as compression of the waste mass and decomposition of organic material progresses.

Operational practices such as waste separation, compaction, construction period, and loading patterns influence the ultimate settlement realized. Waste separation may reduce or increase the amount of organic material available for decomposition. The degree to which the waste is compacted will also effect the total settlement. Waste compacted to a high density will settle less than loose uncompacted waste (Sowers, 1968). Rapid construction periods shorten the time for the waste fill to complete the majority of settlement (Yen and Scanlon, 1975). Non-uniform loading patterns will result in non-uniform settlement patterns, with the greatest settlement occurring where there is the greatest loading. In general, the settlement rate increases with fill depth. However, in fill depths greater than 30 m (100 ft), the settlement rate stabilizes and does not increase significantly (Yen and Scanlon, 1975).

Once waste placement is completed, the settlement rate depends on waste age, leachate level, organic percentage, and environmental conditions within the landfill. Waste temperature and moisture content (Ling et al., 1998) are two factors that effect the rate of waste decomposition and landfill gas generation (Zimmerman, 1972). Biodegradation of the organic material has an important role in landfill settlement characteristics. Typically, landfill settlement curves are similar to organic soils and peats which exhibit rapid initial settlement followed by large, drawn out secondary compression (Oweis and Khera, 1990). The majority of settlement occurs in the first two years with settlement continuing indefinitely at a decreased rate (Sowers, 1968). Final settlement is known to range from 25% to 50% of the landfill initial thickness (Stearns, 1987) depending on operational practices and environmental conditions within the landfill.

MECHANISMS OF LANDFILL SETTLEMENT

Sowers (1973) characterized the mechanisms of landfill settlement as mechanical, raveling, physical-chemical, and bio-chemical. Each mechanism is described below:

1) Mechanical. This is the bending, reorientation and compression of particles due to the self-weight of the waste mass or the applied load of a cover system. Compression of the void spaces between and within particles corresponds to a change in volume.

2) Raveling. Raveling is the sudden, irregular movement of fines into the void spaces between or in larger particles resulting in the collapse of unsupported material (Sowers, 1968). The movement of liquid through the waste mass increases raveling by offering a mode for transporting supporting material into larger void spaces (Oweis and Khera, 1990).

3) Physical-chemical. This is the oxidation, corrosion or combustion of the waste material. Environmental conditions and waste composition control the amount of settlement realized through physical-chemical reactions.

4) Bio-chemical. This is the biodegradation of organic material within the waste mass. Initially this will occur under aerobic conditions. **As** the oxygen supply is depleted, this process will continue under anaerobic conditions. The process and rate of decomposition depends on the environmental conditions within the landfill.

STAGES OF LANDFILL SETTLEMENT

Similar to soil compression, landfill settlement may be described in three stages: 1) immediate or initial settlement, 2) primary or intermediate compression settlement, and 3) secondary compression settlement. Each stage is described below:

1) Immediate Settlement. Immediate settlement is the elastic deformation (Das, 1994) of the soil and compression of the void spaces without a change in the soil moisture content. This stage of soil settlement is used to describe the instantaneous settlement of solid waste as loads from the placement of either additional waste or cover system are applied to the underlying waste. Often this initial settlement occurs before settlement measurements are started and is rarely shown on settlement-time curves.

2) Primary Compression Settlement. In soil mechanics, primary or intermediate consolidation settlement is the volume change of saturated cohesive soils through the dissipation of pore water and gas from the void spaces (Gordon, 1986; Terzaghi and Peck, 1967). However, landfill settlement differs from soil consolidation. Soil consolidation assumes saturated conditions. Current landfill containment systems maintain the waste in a dry state with only inherent moisture. Since waste permeability is of the same magnitude of order as sand and gravel, liquid drains freely without pore water

pressure developing. Therefore, compression of the waste fill due to an applied load is used rather than consolidation to define this stage of settlement (Landva and Clark, 1990; Oweis and Khera, 1990). Even at increased moisture contents, Wall and Zeiss (1995) showed that settlement mechanisms remain relatively the same as dry waste. Sowers (1973) noted that primary compression occurs very quickly and is usually completely within the first month after application of a new load (Ling et al., 1998). During this first 30 days, secondary compression occurs simultaneously with primary settlement. However, primary settlement will dominate this stage and mask secondary compression settlement. The magnitude of load related settlement has been estimated to account for 5% to 30% of the total settlement (Edil et al,1990).

3) Secondary Compression Settlement. Secondary or long term settlement is due to a combination of mechanisms which include creep of the refuse skeleton, physical-chemical reaction, and waste decomposition (Strulgis et al, 1995; Morris and Woods, 1990; Wall and Zeiss, 1995). It is also known as the "plastic structural resistance to compression'' (Taylor, 1942). Secondary settlement of solid waste occurs over extended periods of time depending on the stabilization rate within the landfill. In conventional landfills, this settlement continues at decreasing rates long after the 30-year post closure period (Tang et al., 1994) and accounts for a significant portion of the total settlement (Dodt et al., 1987). As much as 40% of the total settlement may be attributed to secondary compression (Emberton and Parker, 1987; Rao 1974). Coduto and Huitric (1990) attributed 25% of the total settlement to creep of the refuse skeleton and 18% to 24% of total settlement to waste decomposition.

WASTE DECOMPOSITION PROCESS

Settlement attributed to waste decomposition and stabilization can vary greatly between landfills. In conventional landfills waste stabilization can vary between 10 and 80 or more years (Tchobanoglous et al., 1993; Augenstein and Pacey, 1991). The process of solid waste decomposition can be described in five phases; 1) Initial, 2) Transition, 3) Acid, 4) Methane Fermentation, and 5) Maturation Phase (Tchobanoglous et al., 1993; Yolo County, 1996). These phases are described below and presented in Figure 1.

1) Initial Adjustment Phase. During this phase the oxygen present in the recently landfilled waste supports aerobic waste decomposition. The amount of organic matter decomposed aerobically is a negligible fraction of the landfilled organic waste.

2) Transition Phase. During this phase the oxygen present in the landfill is depleted and anaerobic conditions develop. Bacteria reduce nitrates and sulfates to nitrogen gas and hydrogen sulfide. High levels of carbon dioxide are present in the landfill gas. Bacterial activity will convert organic material to organic acids causing leachate to have a low pH.

3) Acid Phase. During this phase microbial activity accelerates with the production of organic acids and some hydrogen gas. The pH of leachate will decrease to five or lower and heavy metals are solubilized. Carbon dioxide is the principal gas generated.

4) Methane Fermentation Phase. Methane production begins during this phase. Organic acids are removed and the pH of leachate rises to around neutral. With higher pH values less inorganic constituents are solubilized and the concentration of heavy metals in the leachate drops. Methane and carbon dioxide are the principal gases formed.

5) Maturation Phase. Most of the biodegradable organic matter has been decomposed and landfill gas production diminishes significantly. The leachate will continue to have near neutral pH.

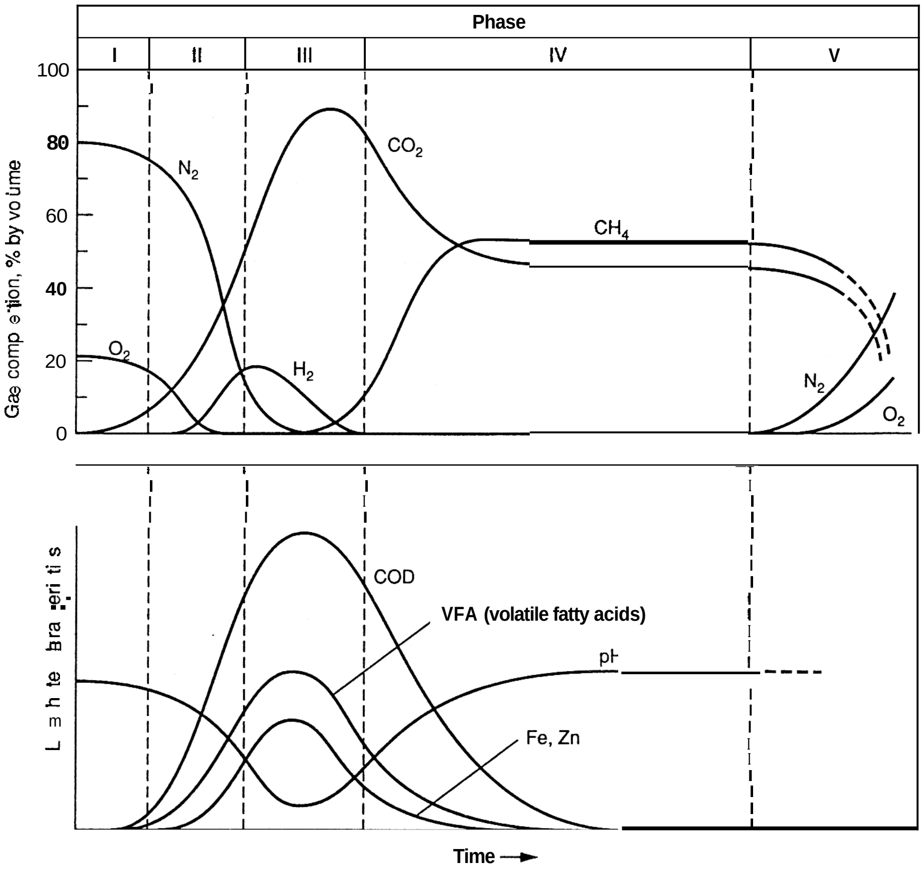


FIGURE 1. Phases of Waste Decomposition and Generation of Landfill Gas (Tchobanoglous et al., 1993).

ENVIRONMENTAL FACTORS AFFECTING WASTE DECOMPOSITION

The rate and stage of waste decomposition highly depends on environmental conditions within the landfill. Yen and Scanlon (1975) found that settlement rates were higher in landfills where conditions were favorable for waste decomposition (Wall and Zeiss, 1995). Accordingly, if conditions are unfavorable then biological decomposition will have little influence on the rate of secondary settlement (Rao et al., 1997). Environmental factors affecting the decomposition rate include: 1) moisture, 2) temperature, 3) pH management, and 4) nutrient supply (Reinhart, 1995). Each factor is described below:

1) Moisture. Moisture content and waste decomposition are strongly correlated with elevated moisture conditions being essential for accelerated biological activity (Halvadakis, et al., 1983). Once the readily soluble substrate is used the overall decomposition process is limited by moisture (Wall and Zeiss, 1995). Moisture addition is one of the most important and easiest factors to control for accelerated waste decomposition. Moisture addition, however, has the greatest effect on waste decomposition when combined with leachate recirculation. The continued flow-through of liquid provides transportation mechanisms for microbes to better access nutrients throughout the waste mass (Leckie and Pacey, 1979). Laboratory and field studies have shown that the decomposition rate is significantly improved with leachate recirculation as compared to an initial increase in moisture content alone (Leckie and Pacey, 1979). Moisture addition also increases secondary compression settlement due to the increase in bulk wet density. The addition of liquid causes the waste to be more plastic and susceptible to compression (Das and Keener, 1997) under the increased moisture weight.

2) Temperature. Temperature is a strong indicator of biological activity (Wise, 1987; Rees, 1980). Optimal temperature for waste decomposition is between 40 and 50 "*C* (Hartz and Ham, 1982). Temperatures above 55°C will inhibit microbial activity. Studies imply an approximate decomposition rate doubling for each 10 "*C* increase, over a temperature span of 10 to *50°C* (Ashare et al., 1977; Hartz and Ham et al., 1982). Temperature fluctuations can signal disturbances in the landfill environment related to microbial activity.

3) pH Management. Although not a significant factor, management of the pH between *6.5* and 7.5 has been shown to be beneficial for microbial activity. Below 6.2 methanogenic bacteria are not able to function properly, thus slowing the rate of waste decomposition (Tchobanoglous et al., 1993).

4) Nutrient Supply. The organic fraction of landfilled waste is the feedstock for microbe activity. The volatile solids or lignin content determines the amount available for decomposition. It is estimated that 30% to 40% of the landfilled waste is available for biological decomposition (Tchobanoglous et al., 1993).

LANDFILL BIOREACTOR DEMONSTRATION PROJECTS

The objective of a landfill bioreactor or enhanced landfilling is to bring the landfilled waste to the methane fermentation phase as quickly as possible through liquid addition, pH management and leachate recirculation. Benefits of this method include landfill life extension, more predictable settlement rates and shortened time period for secondary settlement. In planning the Yolo County Bioreactor Project, experiences and limitations of similar projects were explored. The following section will describe the results from two previous pilot-scale studies. The first demonstration project was conducted at the Sonoma County Landfill, California and the second demonstration project at Mountain View Landfill, California.

Sonoma County, CA

The objective of the Sonoma County project was to determine the effects of liquid addition and recirculation on waste stabilization. The study consisted of five demonstration cells. Each cell contained approximately 453.4 metric tons (500 tons) of municipal solid waste with a maximum depth of 2.44 m (**8** ft), covered with compacted clay. The cells were labeled Cell A through E. Cell A was used as a control cell, while various enhancement techniques were applied to the remaining four cells as outlined in Table 1. Five plates were installed on the surface of each cell to monitor the surface settlement. Periodic settlement surveys were performed from November 1971 to April 1974 (EMCON, 1975).

In Cells B and E the solid waste was brought to field capacity prior to the placement of the clay cover. Cell B received water and Cell E septic pumping. No liquid recirculation was implemented in either cell. Even though the moisture content was increased to field capacity, the settlement results for these cells were similar to Cell A, the control cell. Cell A settled an average of 0.049 m (0.16 ft) while Cells B and E settled an average of 0.052 and 0.061 m (0.17 and 0.20 ft) respectively. These results are in agreement with Wall and Zeiss (1995) who showed no increase in settlement when moisture content of the waste is initially increased to field capacity. Landfill gas composition for these cells remained about 90% carbon dioxide, indicating unfavorable conditions for waste decomposition and methane generation.

In Cells C and D the solid waste was brought to field capacity through recirculation. Water was recirculated in Cell C and leachate in Cell D. Settlement results from these two cells were the highest with Cell C settling an average of 0.107 m (0.35 ft) and Cell D 0.143 m (0.47 ft). Favorable conditions for decomposition were also evident by the landfill gas composition that remained stable at 50% methane. Accelerated waste decomposition was achieved through liquid recirculation rather than only increasing the initial moisture content. This may be attributed to the transportation mechanism provided by recirculation. In general, settlement was higher in the cells where liquid recirculation was implemented than in those cells where liquid was added initially (Leckie and Pacey, 1979). Cell settlement results are shown in Figure 2.

Table 1. Sonoma County Project Summary (EMCON, 1975).

Demonstration Cell	Enhancement Technique	Average Settlement' m (ft)
Cell A	No liquid added	0.049 (0.16)
Cell B	Added 155 m^3 (41,000 gal) of water initially to bring to field capacity but no recirculation.	0.052 (0.17)
Cell C	Recirculated water only at an average rate of 0.0122 m^3/m^2/day (0.3gal/ft^2/day).	0.107 (0.35)
Cell D	Recirculation of leachate only 1.8925m^3/day (500gal/day) to a high of about 18.925m^3/day (5000gal/day).	0.143 (0.47)
Cell E	Added 140m^3 (27,200 gal) of septic tank pumping initially to bring to field capacity but no recirculation.	0.061 (0.20)

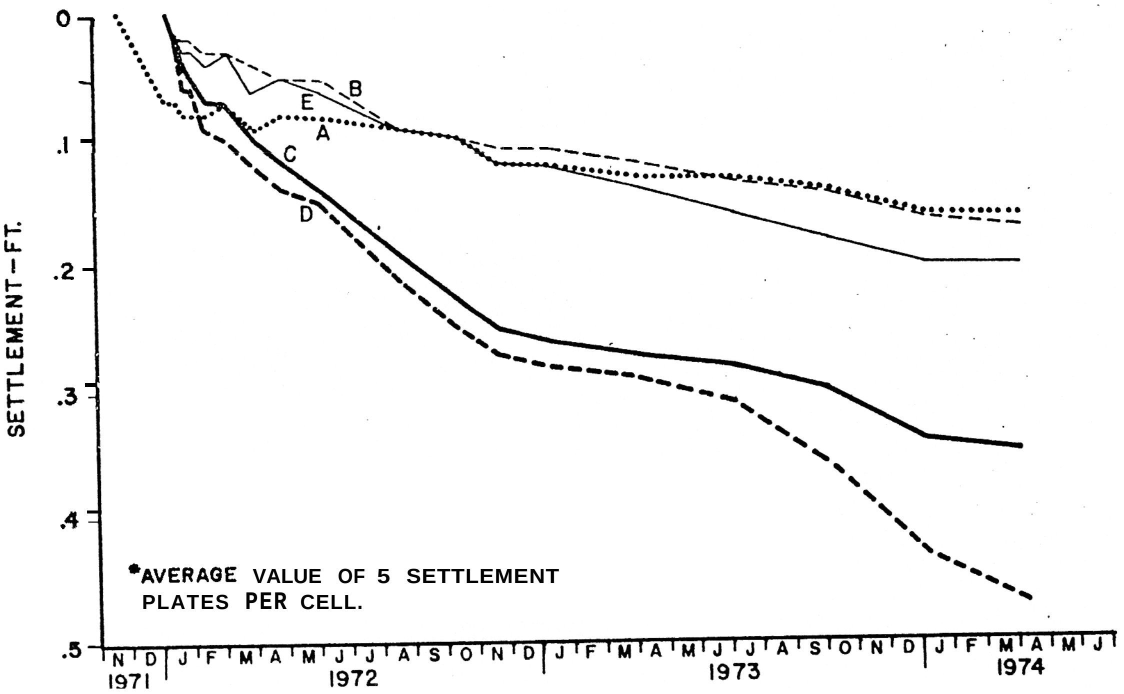


FIGURE 2. Sonoma County Project Cell Settlement Results (EMCON, 1975).

Mountain View, CA

The Mountain View Project was an extension of the Sonoma County study to further explore the effects of various enhancement regimes. It is recognized to be the first comprehensive demonstration project to have quantitative landfill gas generation results. The project consists of six demonstration cells each filled with roughly 8,000 metric tons (8,812 tons) of municipal solid waste (Pacey et al.,1987). Each cell was completely contained by compacted clay levees and covered with a Hypalon membrane. The cells were labeled as Cell **A** through F. Cells **A,** B, C, and E received sludge and buffers while Cell D received buffer only. Recirculation was implemented only in Cell **A.** Cell F was the project control cell and did not receive buffers or sludge. Table 2 gives a complete description of the enhancement techniques applied to each cell. Nine settlement monuments were installed on the surface of each cell to monitor surface elevations. Periodic settlement surveys were performed to assess the effect of enhancement techniques on waste stabilization. Landfill gas composition and volume were measured to assist in evaluating the stage and rate of waste decomposition. Settlement results for the Mountain View Project are shown in Figure 3. In general, the wetter demonstration cells, Cells **A,** B, and C, settled between 13% and 15% while the dryer cells settled between 8% and 12% (Reinhart, 1995). Higher settlement results for Cell E are attributed to the lower initial waste density (Reinhart, 1995). Overall, liquid addition and recirculation enhanced the waste stabilization rate, although quantification of the optimal enhancement technique is difficult.

Table 2. Mountain View Project Summary **(El-Fade1 and Al-Rashed, 1997; EMCON, 1987).**

Demonstration Cell	Enhancement Technique	Average Settlement
Cell A	Added 1,734m^3 (61,230 ft^3) of water over a 75-hour period to bring to field capacity. Added sludge and buffer. Applied leachate recirculation.	12.6% to 15.4%. Average 13.5%
Cell B	Added sludge and buffer, no water.	12.8% to 14.0% Averaged 13.7%
Cell C	Added 1,708 m^3 (60,305 ft') of water over a	10.7% to 15.6%
Cell D		
Cell E	buffers.	
Cell F (project control)	None.	11.1% to 12.8% Averaged 11.7%

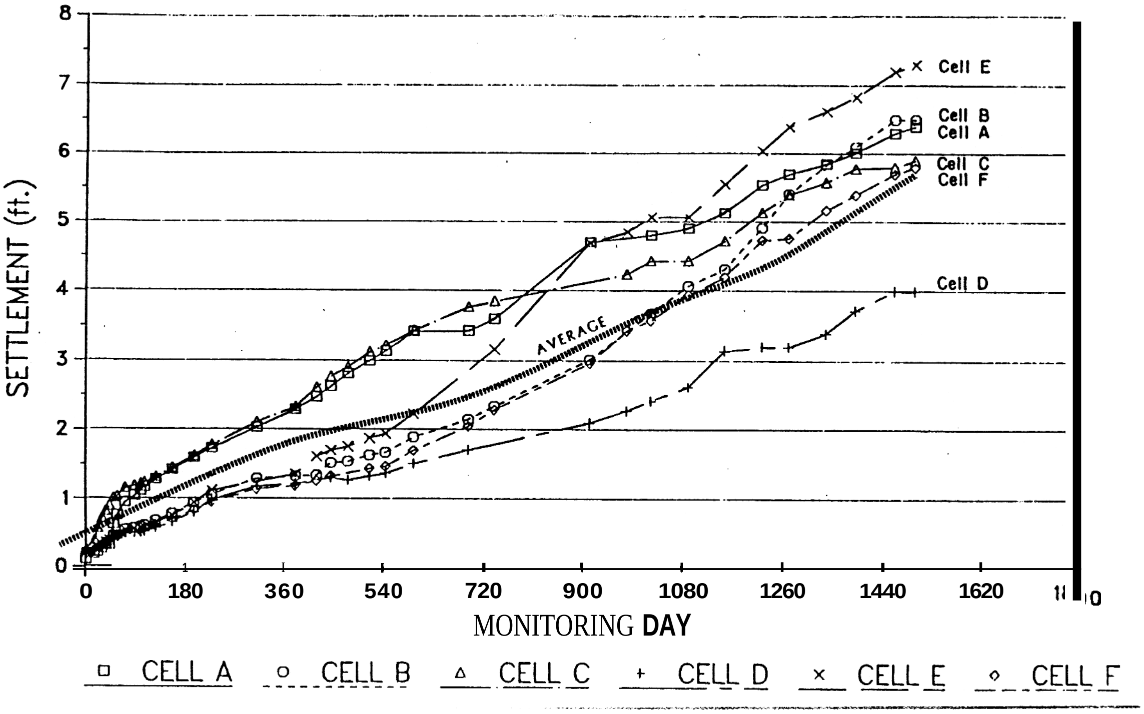


FIGURE 3. Mountain View Project Cell Settlement Results (EMCON, 1987).

YOLO COUNTY PROJECT SETUP

The overall goal of the Yolo County Project is to further investigate and quantify benefits that landfill bioreactors bring to solid waste management. Information gathered in this demonstration project may then provide guidelines for implementation of this technology commercially. The project setup duplicates conditions of a full-scale landfill for direct correlation of project results. A comprehensive monitoring system provides continuous measurement of parameters related to the decomposition process. Although similar projects were demonstrated in the Sonoma and Mountain View, results on enhanced landfilling technology are limited. The extent to which enhanced landfilling influences the decomposition process is not clearly defined. Before regulators and the solid waste industry accept landfill bioreactors as standard landfill practice, more operational data needs to be collected. The following section describes the Yolo County Project setup in detail.

The Yolo County Project consists of two demonstration test cells each filled with municipal solid waste. One cell serves as a control cell to represent a conventional landfill. Enhanced landfilling techniques are applied to the other cell, called the enhanced cell. The enhanced cell receives liquid (groundwater) addition and recirculated leachate. The design of the demonstration cells is similar to the Mountain View Project with average dimensions of 30 x 30 m (100 x 100 ft) and depth of 12 m (40 ft). Characteristics of a commercial landfill such as compaction and heat transfer at normal waste depth are duplicated at this project scale (Yolo County, 1996). Similar to conventional landfills, both cells were constructed with composite base liner systems. Since the enhanced cell receives liquid inputs, an additional composite liner system was constructed below the primary liner system to serve as a leak detection system.

A cross-sectional drawing of the control and enhanced cells is in Figure 4. Approximately 8,170 metric tons (9,000 tons) of municipal solid waste was placed in each cell. Large bulky items such as couches and mattresses were excluded from the cells. Waste filling occurred from April to October 1995. Waste was placed in 1.5 m lifts (5 ft) and covered with 0.3 m (1 ft) of shredded greenwaste. Shredded greenwaste was used as alternative daily cover rather than soil since the locally available soil has a high clay content and would have created barriers to moisture movement. Greenwaste is grass clippings and tree prunings shredded into a compost material. A total of nine waste lifts were placed in each cell. The final lift of waste was placed in a pyramid shape with 4:1 side slopes. The pyramid shape was designed to facilitate long-term surface drainage, which caused problems in the Mountain View Project.

Within each cell there are instrumentation layers to measure waste temperature and moisture. These layers are shown in Figure 4 as Level 1 through 3 with the enhanced cell having four levels and the control cell three. Temperature sensors provide information to evaluate the environmental conditions for waste decomposition. Moisture sensors provide a qualitative moisture measurement only, but assist in evaluating moisture movement within the enhanced cell (Augenstein et al., 1996). A datalogger collects the temperature and moisture measurements and automatically downloads the information to Yolo County's Davis office via the remote telemetry unit. A 40-mil linear low-density polyethylene (LLDPE) membrane liner covers each cell. Compacted clay levees surround each cell to prevent any migration of gas or liquid into or out of them. All gas and liquid entering or leaving each cell is collected and measured separately. Two vertical gas extraction wells collect the landfill gas from each cell. A layer of permeable shredded tires placed below the LLDPE liner serves to collect landfill gas that is not captured by the vertical gas wells. High precision temperature compensated gas meters are used to measure the landfill gas. Landfill gas generated from each cell has been measured continuously since July 5, 1996. A summary of the demonstration cells characteristics is presented in Table 3.

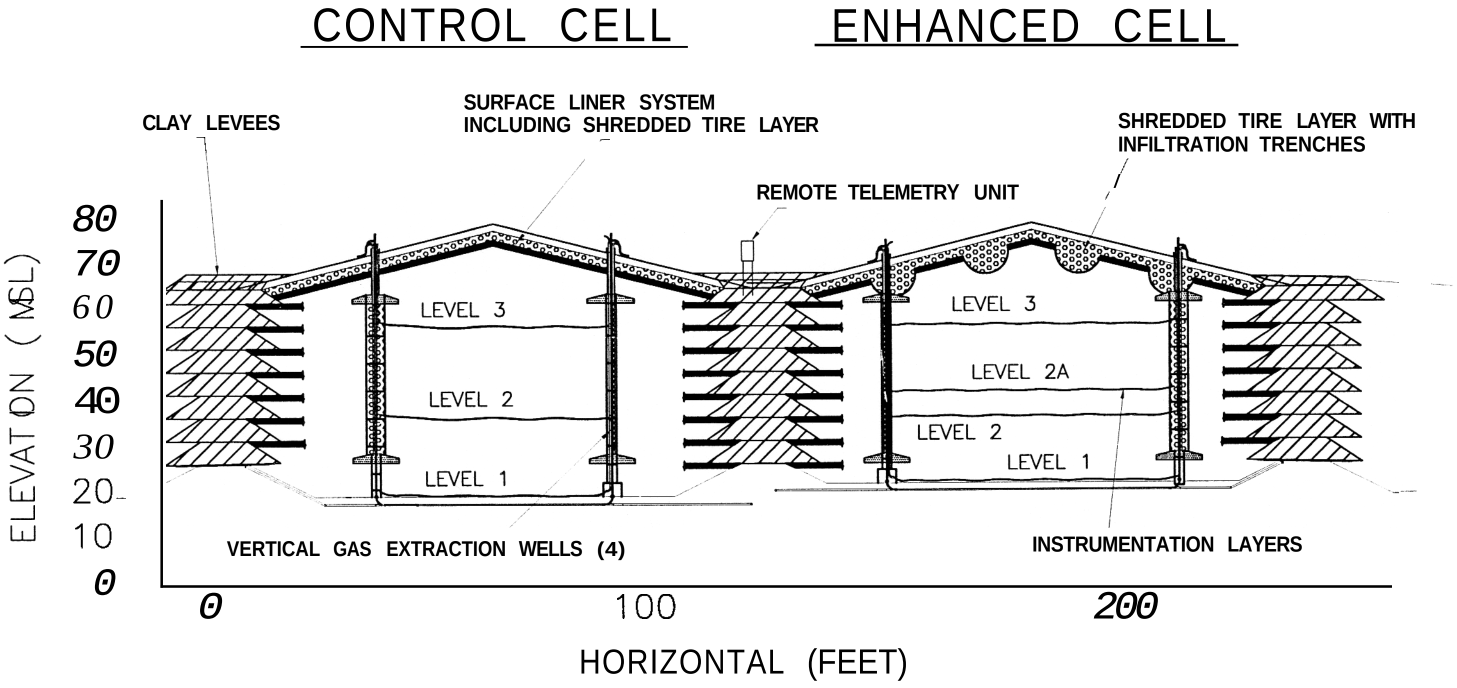


FIGURE 4. Cross-sectional Drawing of Demonstration Cells.

Table 3. Control and Enhanced Demonstration Cell Summary (Yolo, 1997).

Parameter	Control Cell	Enhanced Cell
Foot Print, m^2 (ft^2)	929 (10,000)	929 (10,000)
Total Waste Depth, m (ft)	13.72 (45)	12.80 (42)
Average Waste Depth, m (ft)	13.11 (43)	12.19 (40)
Total Weight, metric tons (tons)	7,921 (8,726)	7,768 (8,557)
Compaction Rate, kg/m^3 (lb/yd^3)	602 (1014)	609 (1027)
Rapidly Decomposable Material[1] (%)	51.1	51.0
Slowly Decomposable Material[1] (%)	16.6	16.4
Inert Material (%)	32.3	32.6
Waste Placement (months)	April to October 1995	April to October 1995
Water Content, Initial (%)	20% wet wt. Basis	20% wet wt. Basis
Water Content, Final[2] (%)	< 20% wet wt. Basis	38% wet wt. Basis
Liquid Volume, m^3 (gal)	None	1,430 (377,690)

[1] EBA Wastechnologies, 1993.

[2] As of June 1998.

Liquid Addition to the Enhanced Cell

In the enhanced cell, liquid addition and leachate recirculation accelerates waste decomposition. As previously discussed, moisture addition is the most important factor to accelerate waste decomposition (Leckie and Pacey, 1979). When combined with leachate recirculation, microorganisms have better access to nutrients and inhibitor concentrations are diluted (El-Fade1 and Al-Rashed, 1997). The objective of the demonstration project was to increase the moisture content of the waste to field capacity. Field capacity, as defined by Tchobanoglous et al. (1993), is the total amount of moisture that can be retained in a waste sample. In other words, it is the maximum amount of liquid that can be held by the waste without the formation of leachate. Field capacity varies with the overburden weight and stage of waste decomposition, but may be determined by the following empirical equation (Tchobanoglous et al., 1993):

$$FC = 0.6 - 0.55[W/(10000 + W)] \quad (1)$$

Where

FC = fraction of water in the waste based on dry weight

W = overburden weight calculated at the mid-height of the waste fill, lb.

The initial moisture content of the waste is assumed to be 25% on a dry weight basis (20% on a wet weight basis) based on waste characteristization studies conducted by Tchobanoglous at YCCL (Yolo County, 1993). Moisture content as defined on a wet weight basis is the weight of water divided by the wet weight of the waste. Due to the low initial moisture content, addition of liquid (groundwater) was required to increase the moisture content of the waste to field capacity. Field capacity was determined to be when about 344.44 m^3 (91,000 gal) of groundwater was added to the enhanced cell for moisture content of 30% on a dry weight basis. Liquid is added to the enhanced cell through an array of 14 infiltration trenches constructed on the shredded tire layer on the surface of the cell as shown in Figure 4. The infiltration trenches are roughly 3 m

(10ft) long, 1.5 m (5 ft) deep, 1 m (3 ft) wide and backfilled with shredded tires. Figure 5 shows the control and enhanced cell manholes. Groundwater is first added to the enhanced manhole and then pumped to the infiltration trenches. As leachate is generated in the enhanced cell, it drains into the same manhole. There it mixes with the groundwater and this mixture is then pumped to the infiltration trenches. The volume of groundwater added to the manhole and the volume of liquid (groundwater and leachate mixture) pumped into the cell are metered. A liquid mass balance on the manhole is used to determine the volume of leachate generated and the gross moisture content of the cell. The control cell manhole only accepts leachate as it is generated.

Liquid addition to the enhanced cell started on October 23, 1996. A total of 1,430 m^3 (377,690 gal) were added to the enhanced cell over a period of 174 days. Approximately 87% of the added water occurred during the first two months of liquid addition. The water addition ceased on April 15, 1997 and only generated leachate is currently being recirculated in the enhanced cell.

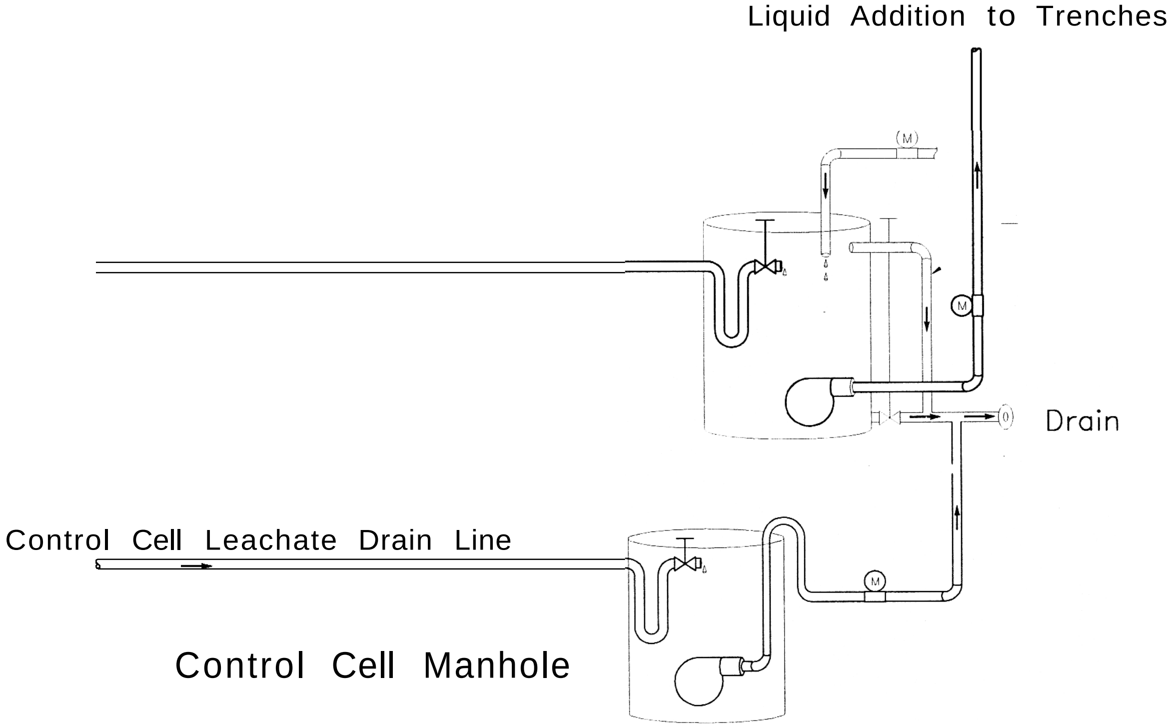


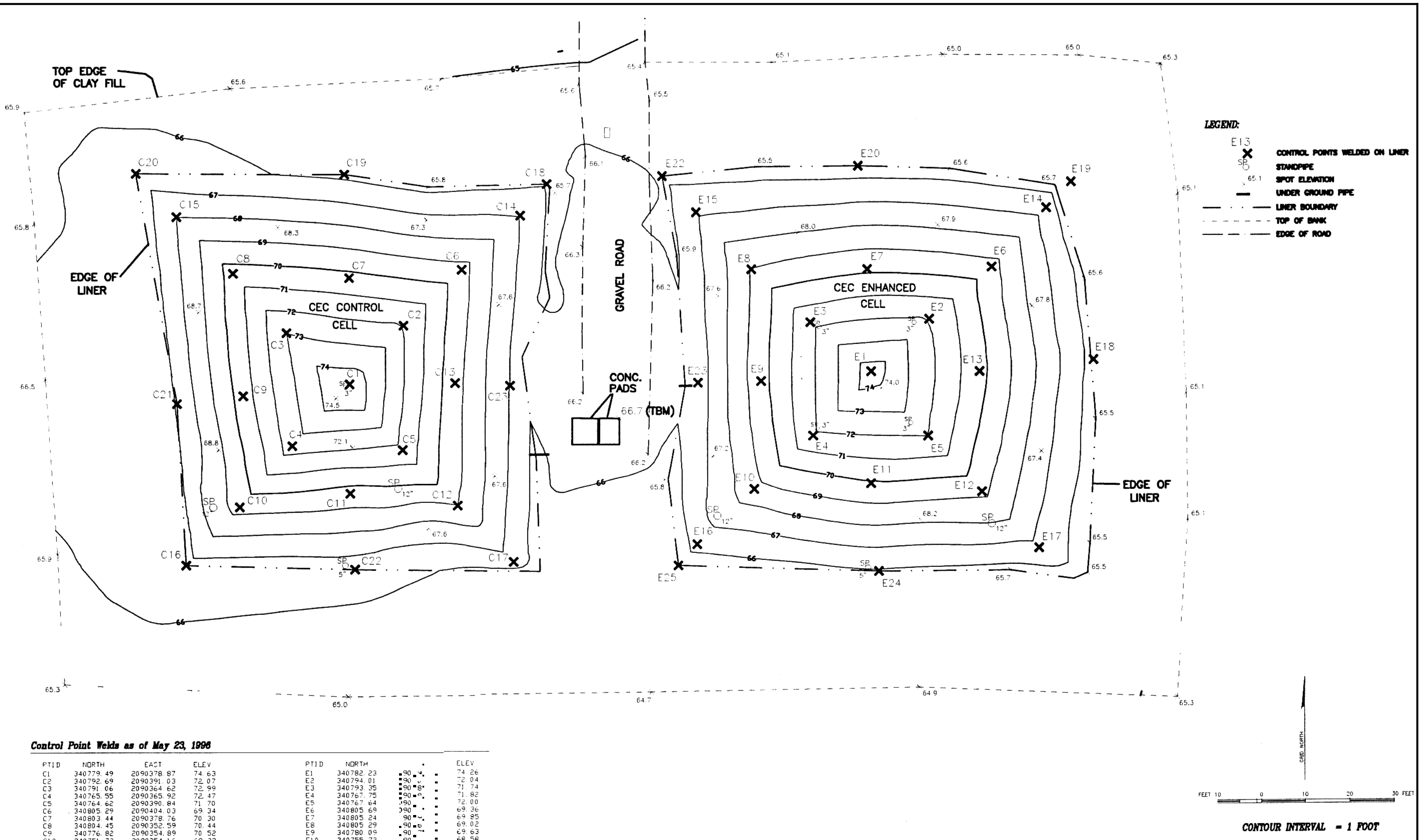
FIGURE 5. Control and Enhanced Cell Manholes.

YOLO COUNTY FIELD SETTLEMENT RESULTS

The Yolo County Project is currently in the second year of operation. Throughout this period a variety of parameters including cell settlement, gas production, leachate quality, temperature and moisture have been monitored. The control and enhanced cell results are compared to evaluate the level of waste decomposition and enhanced landfilling performance. The following section will discuss the control and enhanced cells settlement. Gas production and other related parameters are correlated to field settlement results.

Periodic settlement surveys are performed on the control and enhanced cells to determine the amount of landfill settlement from each operational practice. Changes in the surface elevations are tracked using an array of settlement markers that were welded to the surface liner of each cell during construction. There are 23 settlement markers on the control cell and 24 on the enhanced cell as shown in Figure 6. Settlement markers are labeled with an integer following either a "C" or "E" to represent either the control or enhanced cell, respectively. Surveys are conducted using a Lietz Sokkisha automatic level Model C3-A. Not all settlement markers were accessible for surveying throughout the monitoring period. The first settlement survey was performed on May 23, 1996, roughly seven months after completion of the cells' construction. The final construction and the first survey elevations at the center settlement survey markers, C1 and E1, differ by 1.8 m (5.9 ft) in the control cell and 1.9 m (6.2 ft) in the enhanced cell. This settlement is attributed to immediate and primary settlement due to the applied waste and cover system loads.

Field settlement results over a two-year period were collected for the control and enhanced cell. Table 4 lists the survey dates and the corresponding monitoring day. Monitoring day one (1) corresponds to May 23, 1996. The average settlement for the control and enhanced cells as of June 4, 1998 is shown in Figure 7 and listed in Table 5. Results from individual settlement markers are shown in Figures A1 and A2, and listed in Table A1, Appendix A. Settlement results were normalized by dividing the settlement with the average cell depth at the end of construction. All settlement results are compared to the first settlement survey conducted May 23, 1996. Since the first survey was conducted about seven months after the construction period, the total amount of immediate and primary settlement is not shown in the settlement curves. From the end of construction in December 1995 to October 22, 1996, no enhancement techniques were employed and the two cells displayed similar patterns with respect to waste temperature, moisture and landfill gas generation. Therefore, surface settlement in each cell is also assumed to be same for this time period, as shown by the extrapolated curves in Figure 7. The extrapolated settlement curves are based on the control settlement rate of 2.4×10^{-4} m/d (8.0×10^{-4} ft/d). On October 23, 1996, liquid addition was started in the enhanced cell; no liquid was added to the control cell. After this date, properties such as settlement, temperature, landfill gas generation and moisture changed dramatically between the two cells.



Control Point Welds as of May 23, 1996

PTID	NORTH	EAST	ELEV
C1	340779.49	2090378.87	74.63
C2	340792.69	2090391.03	72.07
C3	340791.06	2090364.62	72.99
C4	340765.55	2090365.92	72.47
C5	340764.62	2090390.84	71.70
C6	340805.29	2090404.03	69.34
C7	340803.44	2090378.76	70.30
C8	340804.45	2090352.59	70.44
C9	340776.82	2090354.89	70.52
C10	340751.73	2090354.16	69.32
C11	340754.79	2090379.02	69.61
C12	340752.08	2090403.11	68.98
C13	340779.77	2090402.56	69.39
C14	340817.45	2090417.29	66.96
C15	340817.17	2090339.87	67.99
C16	340738.57	2090342.11	66.65
C17	340739.34	2090415.78	66.56
C18	340824.50	2090423.26	65.93
C19	340826.65	2090377.65	65.79
C20	340826.88	2090330.71	66.40
C21	340775.06	2090340.02	67.10
C22	340737.62	2090380.08	66.38
C23	340779.18	2090414.99	66.98

PTID	NORTH		ELEV
E1	340782.23	[illegible]	74.26
E2	340794.01	[illegible]	72.04
E3	340793.35	[illegible]	71.74
E4	340767.75	[illegible]	71.82
E5	340767.64	[illegible]	72.00
E6	340805.69	[illegible]	69.36
E7	340805.24	[illegible]	69.85
E8	340805.29	[illegible]	69.02
E9	340780.09	[illegible]	69.63
E10	340755.72	[illegible]	68.58
E11	340756.93	[illegible]	69.91
E12	340755.00	[illegible]	69.24
E13	340782.20	[illegible]	70.31
E14	340818.95	[illegible]	66.64
E15	340818.10	[illegible]	66.85
E16	340743.27	[illegible]	66.29
E17	340742.32	[illegible]	66.72
E18	340784.77	[illegible]	65.67
E19	340824.77	[illegible]	65.51
E20	340828.38	[illegible]	65.49
E22	340826.24	[illegible]	65.73
E23	340779.78	[illegible]	66.51
E24	340737.07	[illegible]	65.90
E25	340738.46	[illegible]	65.51

YOLO COUNTY CENTRAL LANDFILL
MODULE B CEC CONTROL AND ENHANCED CELLS
AS-BUILT TOPOGRAPHIC SURVEY
DATE: 23 MAY 1996 *SCALE: 1 inch = 10 feet*

FIGURE 6. Control and Enhanced Cell Settlement Markers.

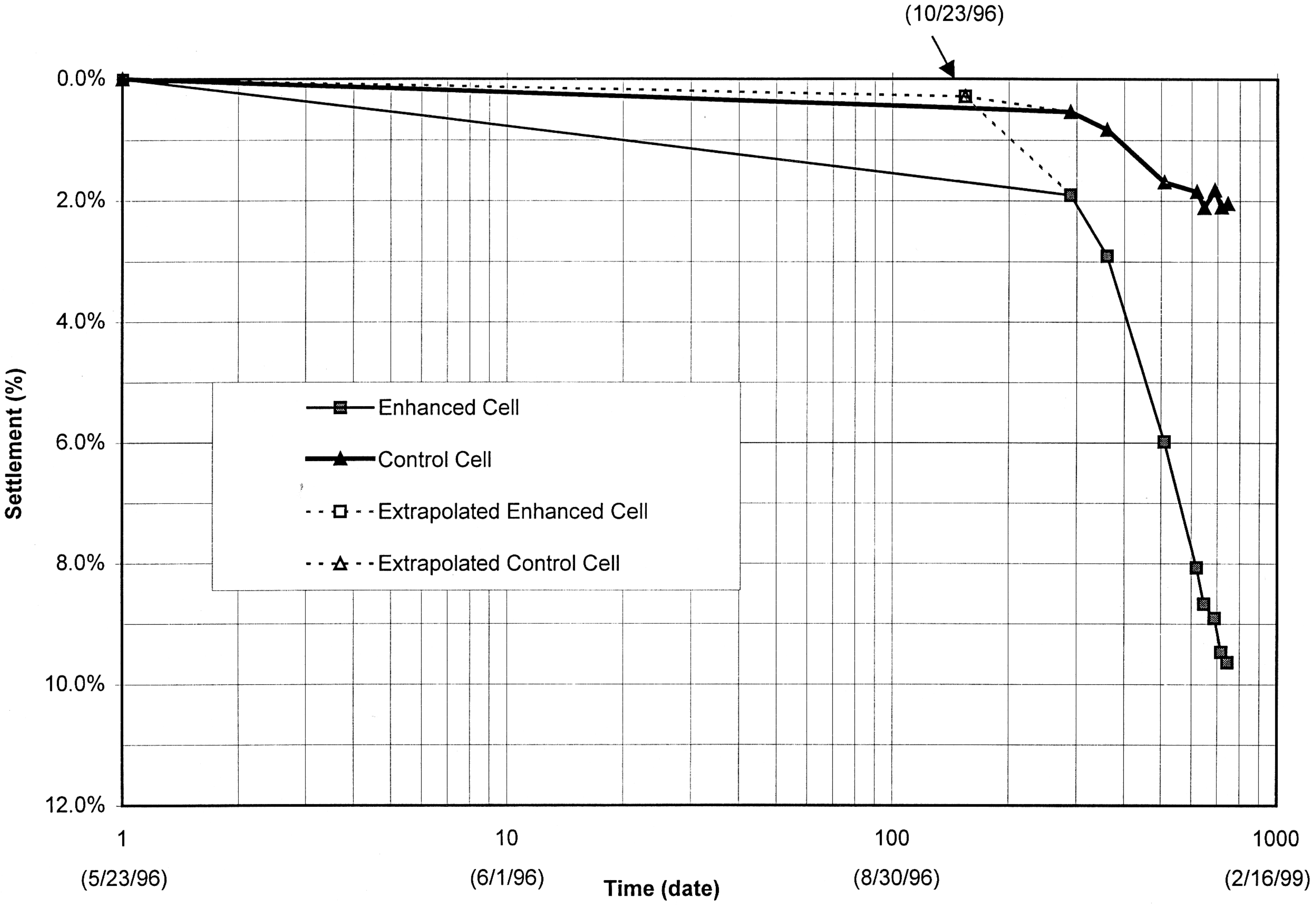


FIGURE 7. Control and Enhanced Cell Average Settlement.

Table 4. Survey Dates and Monitoring Day.

Survey Date	Monitoring Day
May 23, 1996	1
October 23, 1996*	154
May 17, 1997	360
October 13, 1997	509
January 30, 1998	618
Februarv 27. 1998	646
April 10, 1998	688
May 7, 1998	715
June 4,1998	743

Table 5. Control and Enhanced Cell Settlement Parameters, June 4,1998.

Settlement Parameter	Control Cell	Enhanced Cell
Minimum Settlement (%)	1.4	2.0
Maximum Settlement (%)	2.6	17.0
Average Settlement (%)	2.0	9.6

Control Cell Settlement

In general, the control cell settlement is a relatively smooth curve similar to conventional landfill settlement curves. Settlement is larger initially then gradually tapers to a lower rate. Settlement of individual survey markers ranges from 1.4% to 2.6% with an average of 2.0%. The largest settlement occurred in the center of the cell at survey markers C1 and C5. The least settlement occurred along the northeast corner at survey marker C18. In general, the settlement was the largest in the center, decreasing gradually as you move outward to the perimeter. Survey errors are responsible for the larger settlement results in February 1998. However, these errors do not detract from the general trend of the settlement curve and may be ignored. The settlement survey data is measured to the nearest 0.003 m (0.01 ft).

The generation of landfill gas and methane is related to waste decomposition and settlement. Trends in the control cell's landfill gas generation are reflected with a slight lag time in the cell's settlement. The landfill gas generation and settlement are plotted in Figure **8** and briefly described. The control cell experienced little settlement until March 1997. Between March 1997 and October 1997 the settlement rate increased from 2.4×10^{-4} to 8.2×10^{-4} m/d (8.0×10^{-4} to 2.7×10^{-3} ft/d). After October 1997 to the present, the settlement rate fluctuated between 1.8×10^{-4} and 1.4×10^{-3} m/d (6.0×10^{-4} and 4.5×10^{-3} ft/d) with an average of 6.1×10^{-4} m/d (2.0×10^{-3} ft/d). In recent surveys conducted in April and June 1998, the settlement rate was negligible. The landfill gas generation saw a low initial flow rate. From June 1996 to January 1997 the average landfill gas flow rate was 0.17 m^3/min (6 ft^3/min). In January 1997 the flow rate increased from 0.17 to 0.68 m^3/min (6 to 24 ft^3/min) and stabilized at 0.60 m^3/min (21 ft^3/min). After July 1997 the landfill gas generation rate decreased from 0.78 to 0.26 m^3/min (27.4 to 9.3 ft^3/min) in December 1997. The flow rate then increased for a short time between December 1997 and February 1998 but has been decreasing since March 1998. From March to June 1998 the landfill gas generation rate decreased from 0.36 to 0.050 m^3/min (12.7 to 1.78 ft^3/min). Fluctuations experienced in the settlement and landfill gas rate correspond to variable waste decomposition common in conventional landfills. Moisture and temperature sensors placed in the control cell remained stable throughout the monitoring period and give no indication of favorable conditions for waste decomposition.

Enhanced Cell Settlement

Liquid addition to the enhanced cell started on October 23, 1996. The enhanced cell settlement rate increased significantly over the control cell with the commencement of liquid addition. When plotted on a log-time scale, the accelerated settlement data is a linear curve. Settlement of the individual survey markers ranges from 2.0% to 17.0% with an average of 9.6%, nearly four times more than the control cell. The largest settlement occurred in the southwest corner of the cell at survey marker E10. The least settlement occurred along the northwest corner at survey marker E22. In general, the settlement was the largest in the southwest corner and center of the cell, decreasing gradually as you move outward to the north and perimeter. The southwest corner where the largest settlement occurred is also the location of the vertical gravel gas collection well. Construction of the vertical gas wells did not use standard industry practice of drilling the well after completion of waste placement. Rather, the wells were constructed in vertical sections while waste was being placed. The waste was compacted in-place with standard construction tractors and compactors. To avoid damaging the wells, it is thought that the waste surrounding the wells was compacted less than other areas. As liquid was added to the enhanced cell, moisture sensors at all levels along the south side of the cell measured an increase in moisture significantly before other sensors placed within each instrumentation level. The less compacted waste in the area surrounding the vertical gravel well provided preferential pathways for liquid to flow. The substantial settlement in this area is attributed to the increase in load from the liquid weight along with improved conditions for waste decomposition.

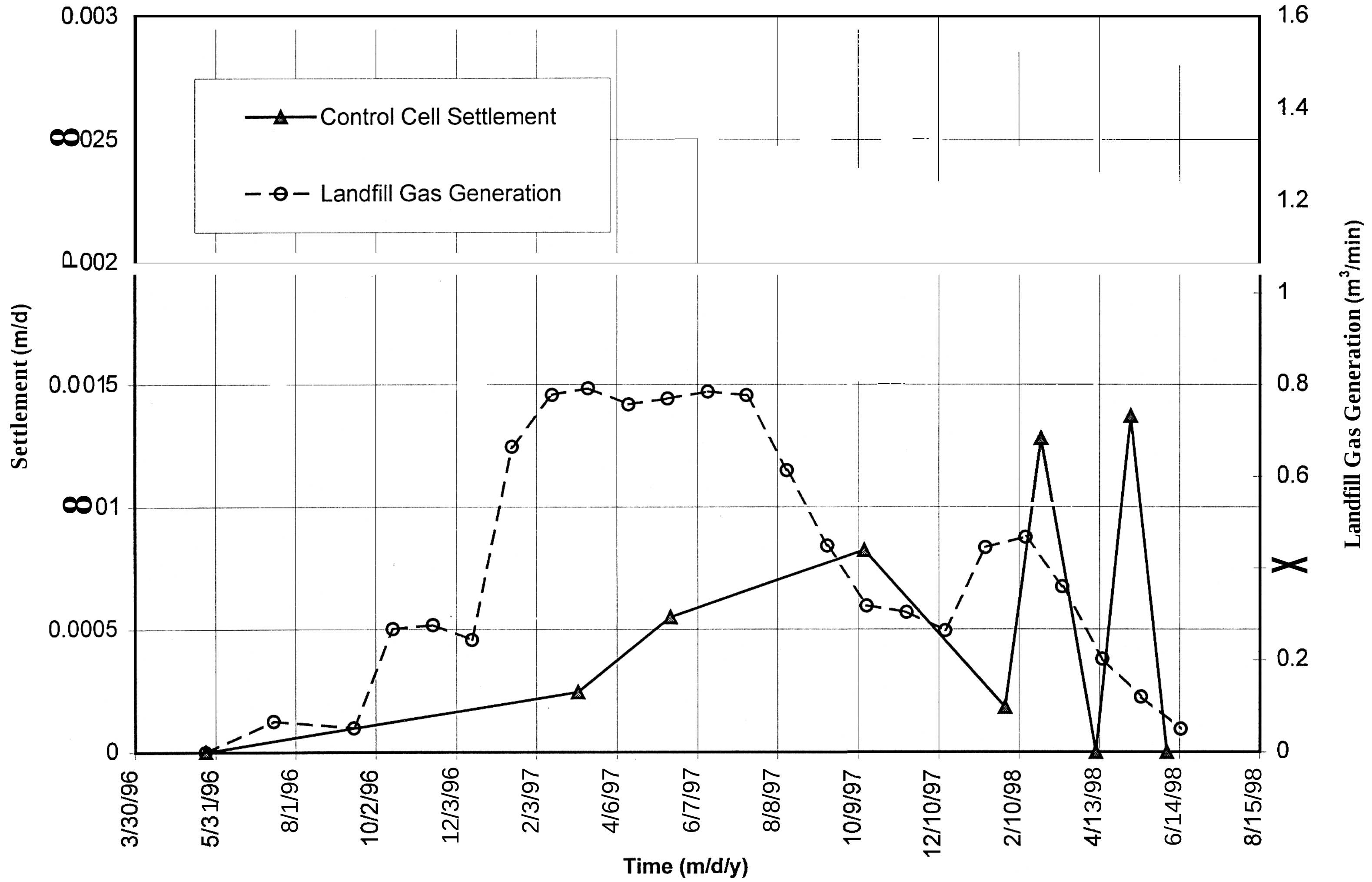


FIGURE 8. Control Cell Settlement and Landfill Gas Generation.

Initiation of liquid addition caused the settlement rate to increase from the assumed 2.4×10^{-4} to 7.9×10^{-4} m/d (8.0×10^{-4} to 2.6×10^{-3} ft/d). After March 1997 the settlement rate increased to 2.5×10^{-3} m/d (8.3×10^{-3} ft/d) in October 1997 and remained stable until the end of February 1998 at an average of 2.5×10^{-3} m/d (8.2×10^{-3} ft/d). The settlement rate then fluctuated greatly between April and June 1998. Elevated waste temperatures and improved leachate quality observed during this period indicate favorable conditions for waste decomposition. The landfill gas generation rate corresponded well to the settlement as shown in Figure 9. Approximately two months after the start of liquid addition, the landfill gas generation rate increased from 0.26 to 1.16 m^3/min (9.2 to 41 ft^3/min). From January to December 1997 the flow rate decreased from 1.16 to 0.58 m^3/min (41 to 20.6 ft^3/min) with an average of 0.97 m^3/min (34.1 ft^3/min). In January 1998 the flow rate increased until March 1998. After March 1998 the flow rate decreased from 1.37 to 0.49 m^3/min (48.4 to 17.5 ft^3/min). Further settlement surveys along with continued monitoring of landfill gas production will determine if the accelerated waste decomposition is decreasing or in a temporary decline. Overall, liquid addition and leachate recirculation significantly increased the settlement rate in the enhanced cell.

The enhanced cell settlement results are promising for landfill bioreactors. Accelerated settlement creates additional landfill space that may be reused before closure. Enhanced landfilling may potentially extend the landfill life by 20% through the placement of additional waste (Pacey, 1982). Accelerated waste decomposition shortens the time period for secondary settlement. Enhanced landfilling resulted in a higher, more predictable settlement rate in the enhanced cell. More predictable secondary settlement over a shorter time period allows the land to be dedicated to more beneficial uses sooner. The ultimate use of the land may be expanded since variable post-closure or differential settlement is reduced. Further investigation is still needed to determine the longer-term settlement rate from enhanced landfilling.

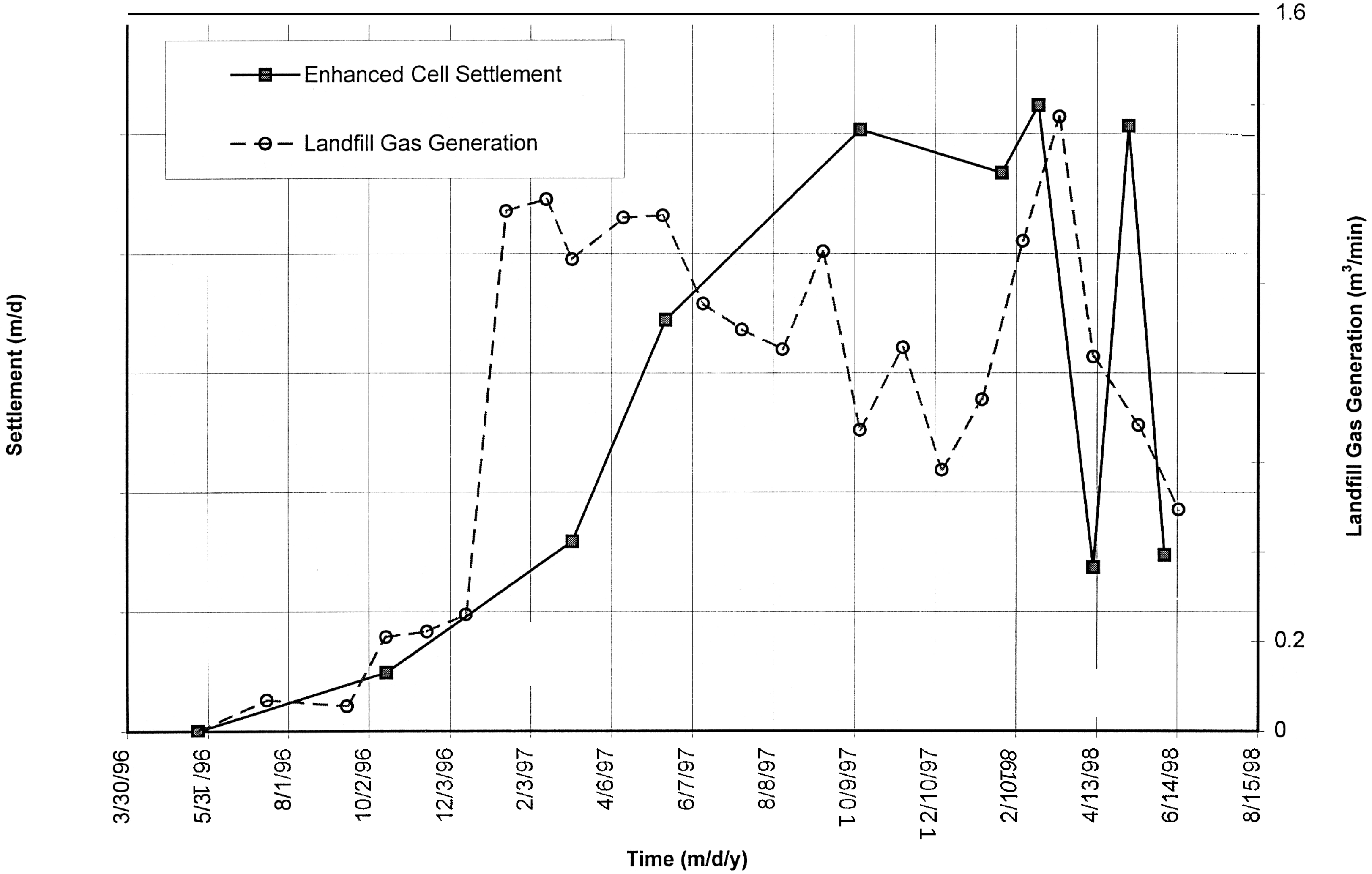


FIGURE 9. Enhanced Cell Settlement and Landfill Gas Generation.

SETTLEMENT MODELING

Conventional geotechnical techniques have been applied to model and estimate landfill settlement (El-Fade1 and Al-Rashed, 1997). A common aspect of all these models is their empirical nature. Although the models may differ in their approach, it is the selection of the appropriate values for the empirical constants that governs the result rather than the model itself (Tang et al., 1994). Values for empirical constants vary greatly depending on site-specific conditions. Model results and level of accuracy depend on the values selected. Therefore, model calibration with field settlement data enables the appropriate value to be selected. For modeling purposes, the total height of waste is treated as a single layer and the cover system is assumed not to compress. The following section will describe the approach of each model in further detail.

Logarithmic Model

Similar to soil consolidation, waste deformation is a linear curve when plotted against the log of time (Sowers, 1973). For this reason, a logarithmic function with a coefficient of compression will be used to model the secondary landfill settlement. Yen and Scanlon (1975) found this approach to correlate with landfill settlement for landfill depths up to 31 m (100 ft) based on field observations of three southern California landfills. Therefore, this approach is acceptable to apply to the demonstration cells with average height of 12 m (40 ft). A logarithmic function may be expressed by the following equation (El-Fade1 and Al-Rashed, 1997; Oweis and Khera, 1990):

$$S(t) = \Delta H/H = H_o C\alpha \log(t/t_{(1)}) \qquad (2)$$

Where
$S(t)$ = settlement, m
H_o = initial height of waste fill, m
$C\alpha$ = coefficient of secondary compression
t = end of settlement study, day
$t_{(1)}$ = time for primary compression to occur, day

The settlement study ended on June 4, 1998, day 743. The time for primary compression to occur is May 23,1996, day 1. Bjarngard and Edgers (1990) modeled primary and secondary settlement independently by separating $C\alpha$ into $C\alpha_{(1)}$ and $C\alpha_{(2)}$ to represent primary and secondary settlement, respectively, as show in the following equation:

$$S(t) = \Delta H/H = C\alpha_{(1)} \log(t_{(2)}/t_{(1)}) + Ca_{(2)} \log(t/t_{(2)}) \qquad (3)$$

Where
$Ca_{(1)}$ = coefficient of primary settlement
$C\alpha_{(2)}$ = coefficient of secondary settlement
$t_{(2)}$ = time at which the slope of stress-strain curve changes (days)

The model used in the analysis will only look at secondary settlement by the following equation:

$$S(t) = AWH = C\alpha_{(2)} \log(t/t_{(2)}) \qquad (4)$$

The logarithmic function used in study has similar characteristics of a one-dimensional consolidation analysis. A simple Kelvin model comprised of a linear elastic spring and dashpot connected in parallel may represent the one-dimensional consolidation concept. When a compressive force is applied to the model, the total load is first carried by the dashpot followed by the slow and progressive transfer to the spring. The transfer of load from the dashpot to the spring is analogous to the time dependent soil consolidation or secondary settlement. Although used in other landfill settlement analyses, Terzaghi's theory of one-dimensional consolidation over simplifies characteristics of solid waste. Assumptions used in a one-dimensional consolidation analysis are not applicable to solid waste for the following reasons:

1. The material is homogeneous. Solid waste characteristics are highly heterogeneous and change over time.

2. Saturated conditions. Except for a limited zone near the base liner that may be saturated with leachate, current containment systems maintain solid waste in a relatively dry state. Therefore, total stress relationship rather than effective stress is used in the waste settlement analysis (Stulgis and Telgener, 1995; Morris and Woods, 1990).

3. Consolidation is the change in volume due to liquid being squeezed out of the void spaces. In solid waste other mechanisms are responsible for volume change.

4. Darcy's law is valid. In solid waste a laminar flow may not be true for all cases.

5. Deformation occurs only in the direction of the load application. This is not always true in field settlement.

Power Creep Law Model

The Power Creep Law has traditionally been used to model transient creep behavior exhibited by engineered materials. This simple model combines primary and secondary settlement together to estimate the landfill settlement rate and magnitude. Estimates are a function of time and initial waste height under constant stress. The Power Creep Law models landfill settlement by the following equation (Edil et al., 1990):

$$S(t) = H_0 \, \Delta\sigma \, M \, (t/t_r)^N \qquad (5)$$

Where

$S(t)$ = settlement, m

H_o = initial height of waste fill, m

$\Delta\sigma$ = compressive stress, kPa

M = reference compressibility, 1/kPa

N = rate of compression

t = end of settlement study, day

t_r = reference time, day

The settlement study ended on June 4, 1998, day 743. A value of one day was used in this study for reference time. The compressive stress is due to the weight of the waste and cover system.

Rheological Model

The general trend of solid waste settlement resembles the time-dependent deformation of organic soils and peats more than inorganic soils. Upon loading, peats and solid waste exhibit rapid immediate and primary settlement followed by slow and continuous secondary compression. Secondary compression accounts for a large portion of the total settlement and is difficult to incorporate into traditional soil consolidation equations. Gibson and Lo (1961) proposed a Rheological model for estimating the secondary compression of peats with promising results. This same model will therefore be used to model solid waste settlement. The Rheological model is represented by a Hookean spring connected in series to the Kelvin model used in one-dimensional analyses. Immediate and primary settlement is analogous to the instantaneous compression of the Hookean spring connected in series to the Kelvin model. Compressive stresses are then taken by the dashpot to model the continuous process of secondary compression until it is progressively transferred to the parallel linear elastic spring. The Rheological model's time-dependent deformation is expressed in the following equation (Edil et al., 1990).

$$S(t) = H_o \, \varepsilon(t) = H_o \, \Delta\sigma \; \{a+b(1-\exp[-(\lambda/b)]\} \qquad (6)$$

Where

$S(t)$ = settlement, m

H_o = initial height of waste fill, m

ε = strain (settlement divided by the layer thickness)

$\Delta\sigma$ = compressive stress, kPa

a = primary compressibility parameter, 1/kPa

b = secondary compressibility parameter, 1/kPa

λ/b = rate of secondary compression

Hyperbolic Model

The Hyperbolic function is commonly applied to predict soil settlement. As the pore water pressure dissipates in soil consolidation, the settlement profile evidentially converges to a hyperbolic line (Tan and Lee, 1991). Once the hyperbolic line is established, the future settlement and rate may be extrapolated. The flexibility and simplicity of the hyperbolic function makes it ideal for landfill settlement prediction where in-situ properties are difficult to determine and change with time and space. If loading conditions change in the field, they are readily detected by the deviation from the established line. The hyperbolic function can then be reinitialized to incorporate these changes and a new hyperbolic line will be established. Application of this method is, however, limited by supporting settlement data, which must first approach a hyperbolic line. Previous studies have shown a hyperbolic line will be established once settlement reaches about 30-40% (Tan and Lee, 1991). Since the most problematic settlement occurs in the long-term, this method provides good estimation of the rate and ultimate settlement. The hyperbolic curve is defined by the following equation (Tan and Lee, 1991):

$$S = t / (a + \beta t) \qquad (7)$$

By taking the limit of settlement, the previous equation may be rewritten as a linear function when plotted in a t/S versus t.

$$t/S = a + \beta t \qquad (8)$$

Where

t = time difference between point of interest and start time, (i.e. $t = t_i - t_o$)

S = settlement difference between time t, and start time t_o, (i.e. $S = S_i - S_o$)

a = y-intercept

$1/\beta$ = inverse of the slope, ultimate settlement

Ling et al. (1998) expressed the hyperbolic curve in a similar equation:

$$S = t/(1/\rho_o + t/S_{ult}) \text{ and } t/S = 1/\rho_o + t/S_{ult} \qquad (9)$$

Where

ρ_o = initial rate of settlement (at $t = t_o$)

S_{ult} = ultimate settlement (i.e. as t approaches infinity).

The two equations may be related to each other with $a = 1/\rho_o$ and $\beta = 1/S_{ult}$.

Waste Decomposition and Biodegradation Model

An alternative method proposed by Tchobanoglous et al. (1993) and others (Das and Keener, 1997; Wall and Zeiss, 1995) estimates landfill settlement based on the waste decomposition and overburden pressure. The rate and total settlement achieved through biodegradation depends highly on the conditions within the landfill. Wall and Zeiss (1995) determined that biodegradation has little affect in short-term settlement but has a more significant role in the long-term. Enhanced landfilling manipulates the landfill environment for optimal waste decomposition and reduced long-term settlement.

As waste decomposes, the biodegradable organic material is converted into two by-products, landfill gas and leachate. The process results in a net reduction in the waste volume, which is realized as landfill settlement. As decomposition continues waste properties such as density, particle size and moisture content change with time and complicate landfill settlement prediction. Since waste decomposition is a dynamic process, the analysis incorporates these changes in the waste properties. The reduction in the waste weight due to decomposition is related to the volume of landfill gas generated over time. When combined with a liquid mass balance on the waste fill, the overburden pressure at mid-height is used to determine the compression of the fill over time. The overburden pressure is determined by the following equation (Tchobanoglous et al, 1993):

$$p(t) = W_c + W_w(t)/2 \qquad (10)$$

Where
$p(t)$ = overburden pressure at mid-height in the waste fill at time t
W_c = weight of cover system
$W_w(t)$ = weight of waste at time t

The specific weight of the waste is based on the calculated overburden pressure and is estimated by the following empirical equation:

$$SW, = \rho_i + p/(a + bp) \qquad (11)$$

Where
SW, = compacted specific weight of the waste at pressure p, lb/yd^3
ρ_i = initial waste density, lb/yd^3
P = overburden pressure at mid-height in the waste fill, lb/in^2
a = empirical constant, 0.0133 $(yd^3/in^2)(lb/in^2)$
b = empirical constant, 0.001 yd^3/lb

The height of the waste fill over time is then determined by the following equation:

$$W_w = SW_p\, h \qquad (12)$$

Where
h = height of waste fill, yd

CONTROL AND ENHANCED CELL MODEL RESULTS

In this study five models discussed above are calibrated with field settlement data collected from the control and enhanced cell. Since the first settlement survey was performed about seven months after the cells were constructed, the models do not include the effects of incremental loading during construction and immediate settlement is ignored. For the most part, primary and secondary settlement are modeled as a combined process due to the limited settlement data during the first year of monitoring. Settlement attributed to primary settlement, however, will be minimal since primary settlement is usually completed in less than one month of load application. For modeling purposes, the total height of waste is treated as a single layer and the cover system is assumed not to compress. Settlement results are expressed as a percentage of the original waste thickness. The following sections discuss the results from each model in detail.

Logarithmic Model

In general, the logarithmic model provided representative settlement curves for both demonstration cells. Figures 10 and 11 show the predicted and measured settlement from the control and enhanced cell, respectively. The predicted curve in the enhanced cell was a better representation of field measurements than in the control cell. Simulations in the enhanced cell slightly under estimated the initial settlement but provide accurate prediction after day 400 (June 26, 1997). In the control cell, simulations under estimated the initial settlement, then over estimated the later stages when the settlement rate decreased. The single simulation curve was not able to adjust to the control cell's lower long-term settlement rate typical of conventional landfills. The coefficient of correlation was in good agreement for the two simulations with 0.93 for the control cell and 0.99 for the enhanced cell.

The coefficient of long-term secondary settlement, $C_{\alpha2}$, for both cells is presented in Table 6. The estimated coefficient of long-term secondary settlement, $C_{\alpha2}$, is 0.056 in the control cell and 0.240 in the enhanced cell. The C„ for the control cell is within the accepted range reported in previous studies (E18). The C„ value for the enhanced cell is indicative of accelerated biodegradation and greatly exceeds values reported by Sowers. Sowers' (1973) lower limit for C„ is 0.025, which corresponds to low organic content and/or conditions unfavorable for biodegradation (Phillips et al., 1993). The upper limit of 0.075 corresponds to favorable conditions for biodegradation. Yen and Scanlon (1975) found a mean of 0.039 and upper bound of 0.062 for C„ in waste fills with the same height as the demonstration project. Watt and Charles (1990) however, reported values of 0.10 to 0.23 for C„ when looking only at the biodegradation creep in recent domestic waste fills. El-Fade1 and Al-Rashed (1997) estimated the Mountain View Project's C„ to vary between 0.132 for Cell C and 0.321 for Cell B. These higher values are comparable to the value calculated for the enhanced cell. Therefore, a higher C„ may be used when estimating secondary settlement in landfills that practice controlled landfilling. It is important to note that large variations in C„ may result depending on the start time assumed for secondary compression to begin, especially when analyzing creep of fresh landfill (El-Fade1 and Al-Rashed, 1997). In the analyses, secondary compression was initiated on March 1997, the second settlement survey. Primary settlement was ignored.

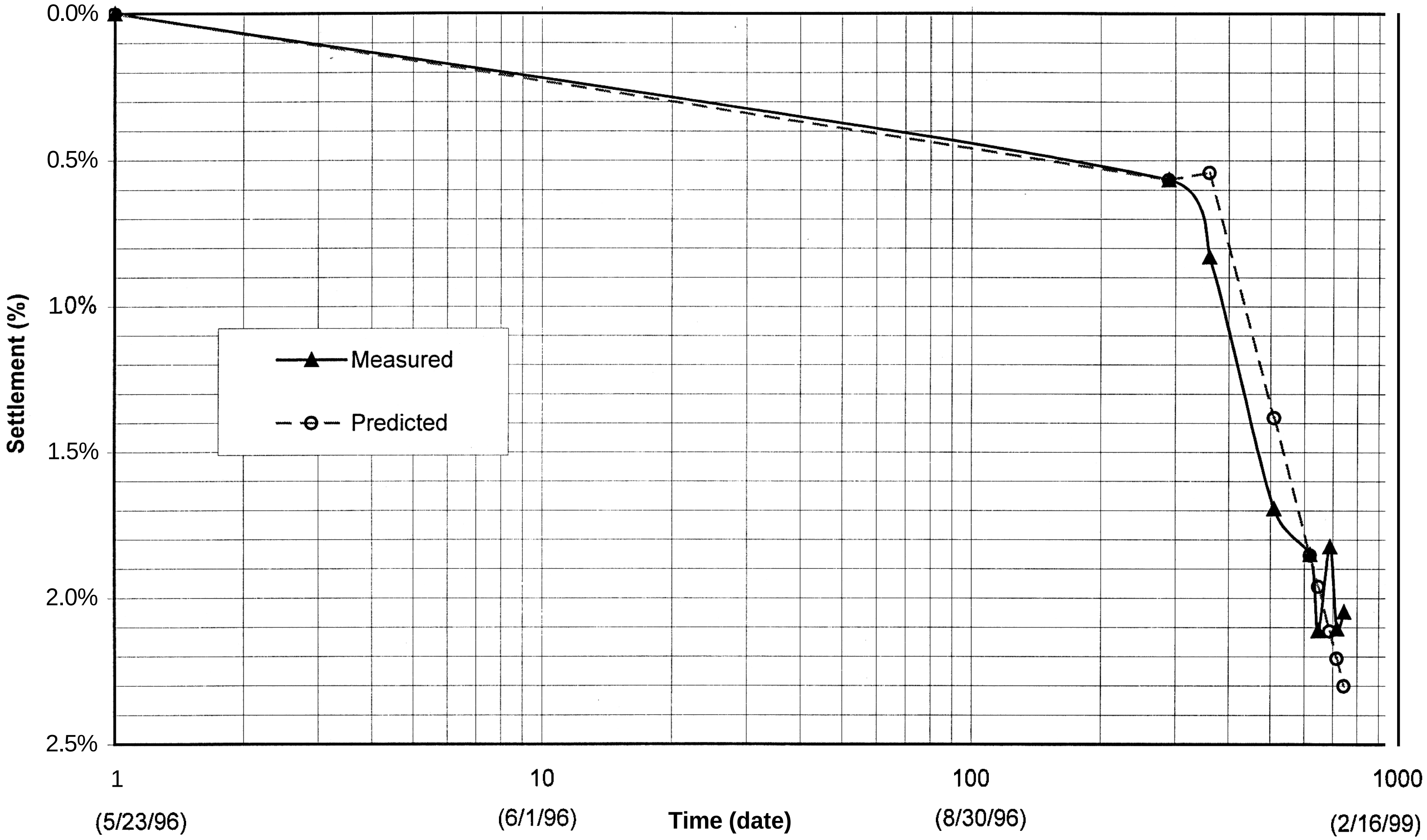


FIGURE 10. Control Cell Logarithmic Model.

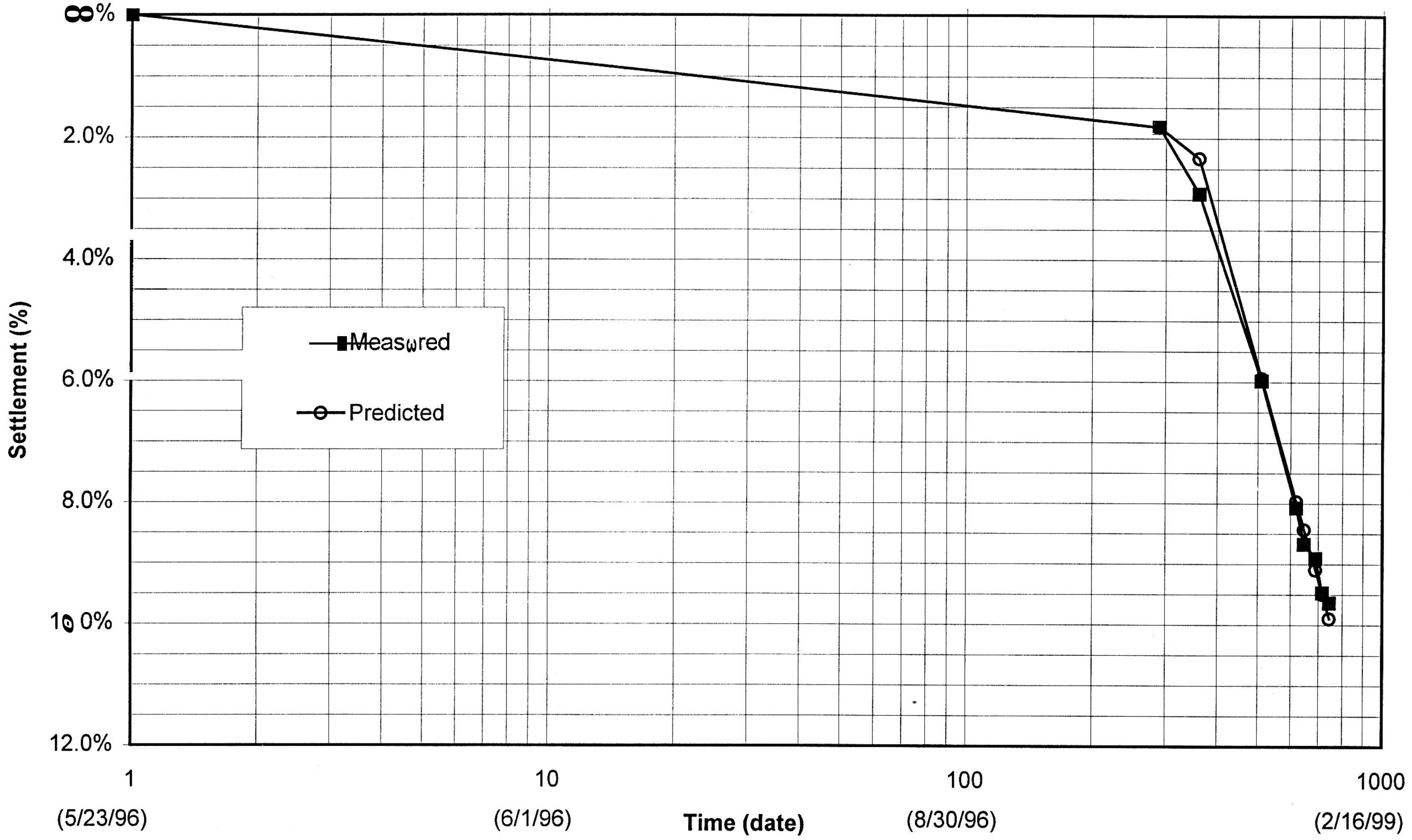


FIGURE 11. Enhanced Cell Logarithmic Model.

Table 6. Control and Enhanced Cell Logarithmic Settlement Parameter.

Demonstration Cell	**Coefficient of Long-term Secondary Settlement, $C_{\alpha 2}$**
Control Cell	*0.056*
Enhanced Cell	0.240

Power Creep Law Model

In general, the power creep function was able to simulate the field settlement realized in both the control and enhanced cell. Figure 12 shows the predicted and measured settlement in the control cell. The control cell's simulation slightly under estimated the settlement in the early stages, then over estimated the settlement rate after day 600. Two simulations performed for the enhanced cell are shown in Figures 13 and 14. The first simulation used initial waste properties to determine the compression while the second simulation incorporated the added weight of liquid into the analysis. Both simulations were similar to each other and provided reliable predictions of the enhanced cell settlement throughout the monitoring period. Further extrapolation of the predicted curves, however, may over estimate the long-term creep. The coefficient of correlation is 0.92 for the control cell and 0.99 for the two simulations for the enhanced cell.

Values for the reference compressibility, M, and rate of compression, N, for both cells are presented in Table 7. The reference compressibility, M, is equal to 1.47×10^{-11} 1/kPa for the control cell and 1.49×10^{-11} and 1.50×10^{-11} 1/kPa for the first and second simulations in the enhanced cell, respectively. The rate of compression, N, is 1.571 in the control cell and 1.800 for the first simulation and 1.780 for the second simulation in the enhanced cell. Values for the reference compressibility, M, for both cells were lower by several degrees of magnitude than reported values (Edil et al., 1990). Edil reported values ranging from 10^{-5} to 10^{-8} 1/kPa with an average of 2.5×10^{-5} 1/kPa. The reference compressibility is typically higher in older landfills than fresh refuse landfills. The rate of compression, N, for both cells was also higher than reported values. Average values reported range from 0.264 to 1.170 with fresh refuse landfills having a higher value than older landfills (Edil et al.,1990). The lower value for reference compressibility and higher rate of compression for the enhanced cell corresponds to accelerated waste decomposition. Values for the control cell are not representative of conventional landfill compression.

Table 7. Control and Enhanced Cell Power Creep Parameters.

Demonstration Cell	**Reference Compressibility, M (1/kPa)**	**Rate of Compression, N**
Control Cell	1.47×10^{-11}	1.571
Enhanced Cell	1.49×10^{-11}	1.800
Enhanced Cell plus liquid	1.50×10^{-11}	1.780

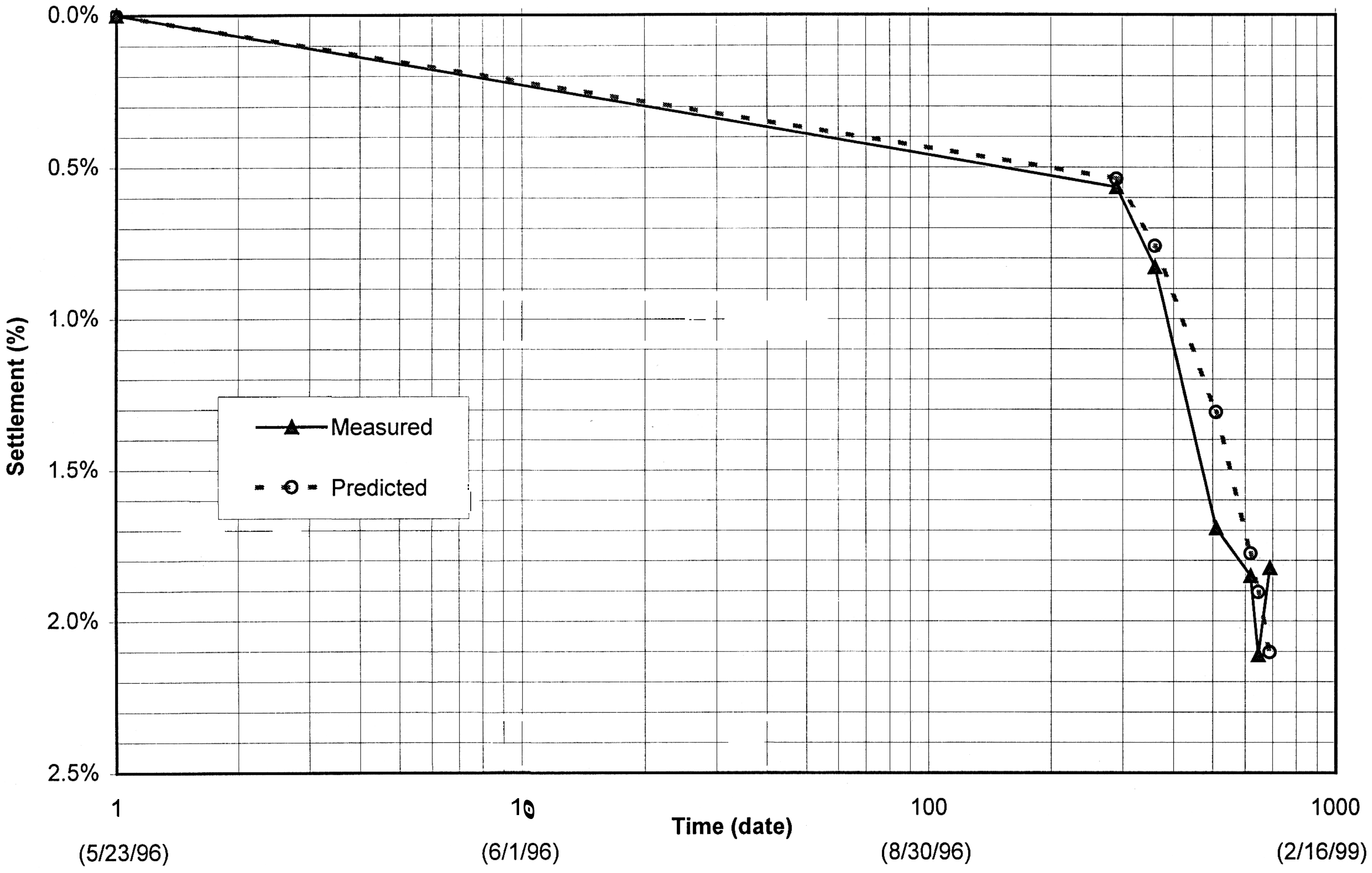


FIGURE 12. Control Cell Power Creep Law Model.

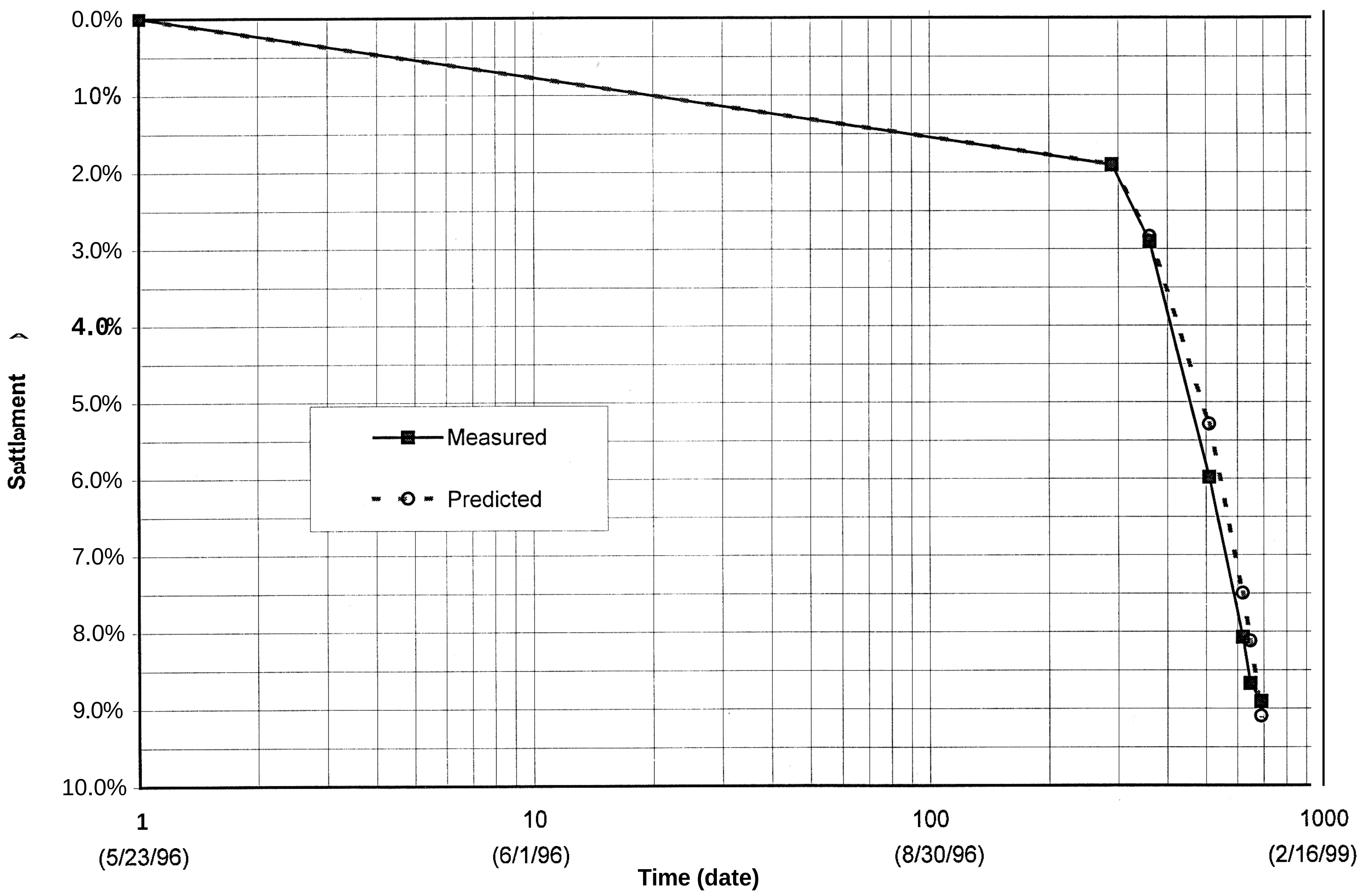


FIGURE 13. Enhanced Cell Power Creep Law Model.

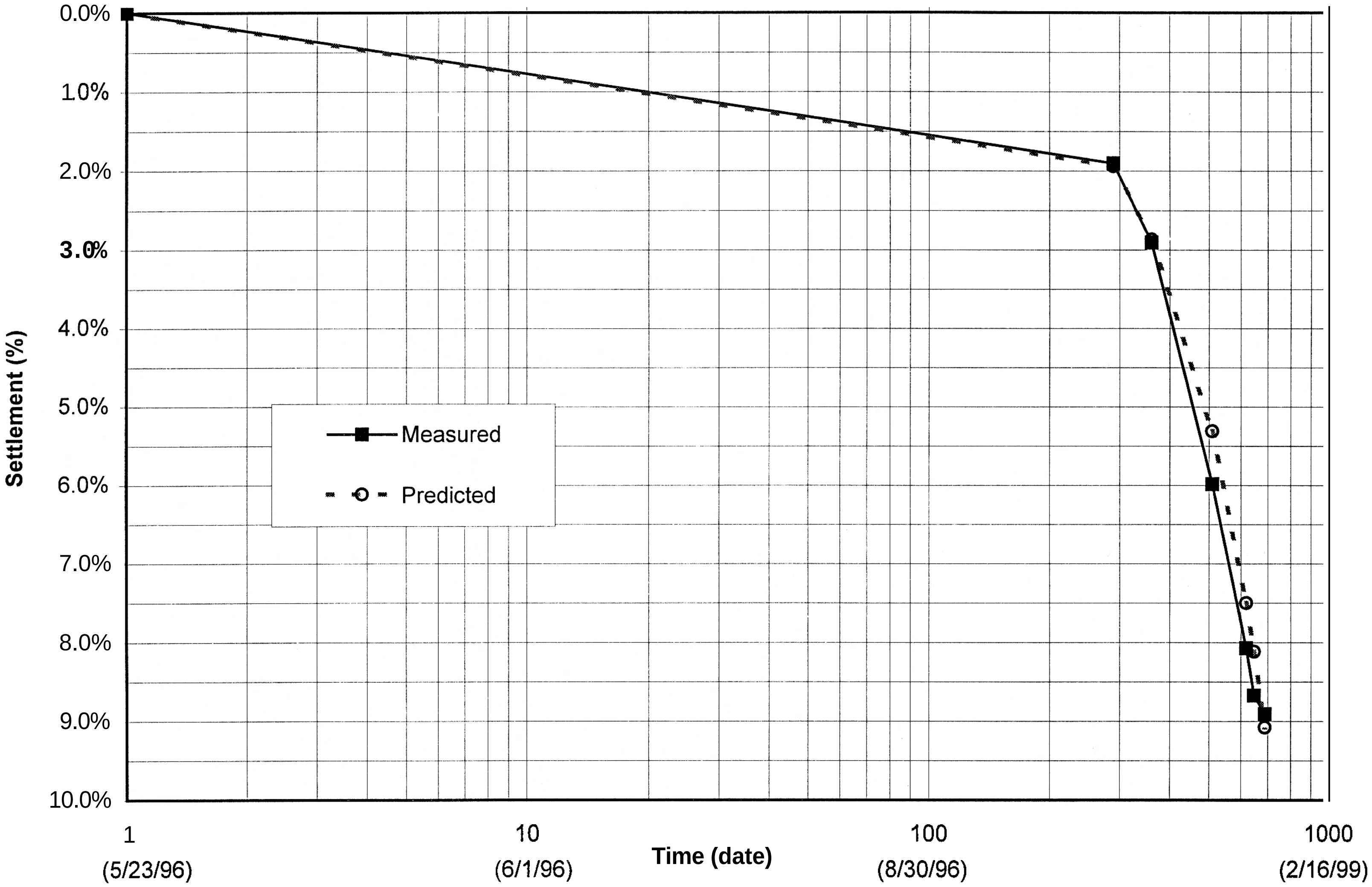


FIGURE 14. Enhanced Cell Power Creep Law Model Plus Liquid.

Rheological Model

The Rheological model provided relatively good estimation of the control and enhanced cell landfill settlement. The predicted and measured settlement curves for the control cell are shown in Figure 15 and for the enhanced cell in Figure 16. Similar to other models, the Rheological model provided a reasonable estimate from day 300 to 600 but over estimated the longer-term settlement in the control cell. In the enhanced cell the simulation provided a good estimation of settlement throughout the monitoring period. The coefficient of correlation for the two simulations are 0.88 and 0.95 for the control and enhanced cell respectively.

The Rheological model expresses primary and secondary landfill settlement rate with three empirical parameters. These parameters for both cells are listed in Table **8.** The primary compressibility parameter, a, is 1.0×10^{-14} 1/kPa for the control cell and slightly higher for the enhanced cell at 4.0×10^{-15} 1/kPa. These values are lower than reported values that range from 3.8×10^{-4} to 5.11×10^{-7} 1/kPa (Edil et al., 1990). The lower value may be attributed to the survey data not capturing all the primary settlement. This low value for primary compression has little effect on the shape of the predicted curves. The secondary compressibility parameter, b, is 5.9×10^{-7} 1/kPa for the control cell and 400 1/kPa for the enhanced cell. The corresponding rate of secondary compression, λ/b, is 1.58×10^{-3} for the control cell and 5.83×10^{-12} for the enhanced cell. Reported values for the secondary compressibility parameter range from 5.87×10^{-3} to 1.0×10^{-4} 1/kPa (Edil et al., 1990) while the rate of secondary compression ranges from 4.3×10^{-3} to 9.2×10^{-5}. Control cell values for these parameters are close to the reported values. The secondary compressibility and rate of secondary compression for the enhanced cell differ greatly from reported values. Manipulation of the secondary compressibility parameter in the enhanced cell showed the predicted curve was not sensitive to a change in values by several magnitudes lower. This indicates that the selection of the appropriate value for the parameter may not always significantly effect the prediction curve. However, selection of the appropriate value is highly dependent on site-specific conditions.

Table 8. Control and Enhanced Cell Rheological Parameters.

Demonstration Cell	Primary Compressibility, a (1/kPa)	Sccondary Compressibility, b (1/kPa)	Rate of Secondary Compression, λ/b
Control Cell	1.0×10^{-14}	5.9×10^{-7}	1.58×10^{-3}
Enhanced Cell	4.0×10^{-15}	400	5.83×10^{-12}

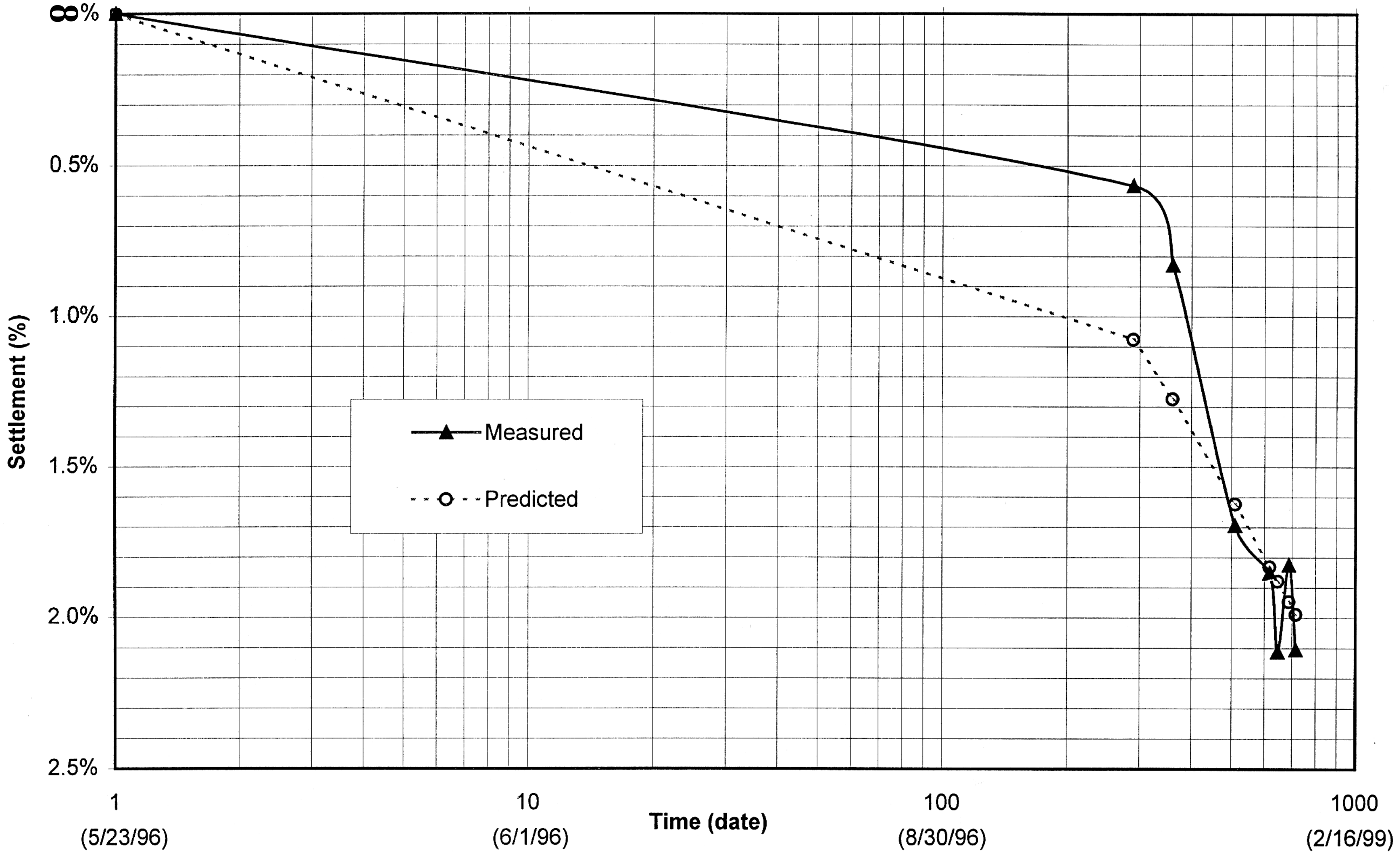


FIGURE 15. Control Cell Rheological Model.

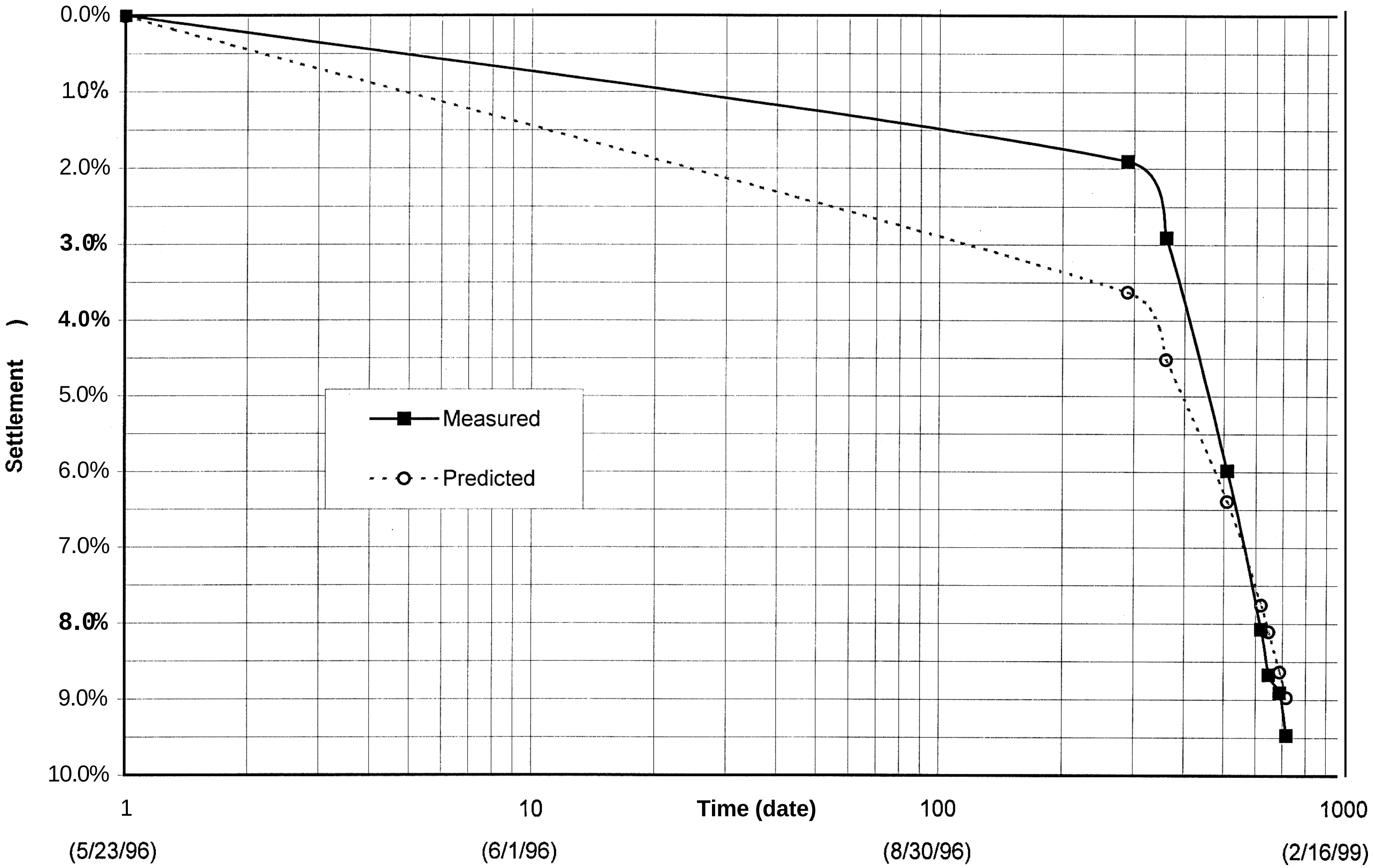


FIGURE 16. Enhanced Cell Rheological Model.

Hyperbolic Model

This approach differs from the other models because it does not simulate the actual settlement curve. Rather, the hyperbolic function looks at changes in the settlement rate to estimate future settlement. This approach clearly identified changes in the settlement trend in both the control and enhanced cell that are not evident in other analytical models. The hyperbolic curves from the control and enhanced cell exhibited the same general trend as shown in Figure 17. A negative sloped linear line was first established then changed to a positive sloped line. In both cases deviation from the initial hyperbolic line was at day 508 (October 13, 1997). No noticeable changes were recorded in the field during this time. The initial hyperbolic line in the control cell had a negative slope of 7.3 while the enhanced cell had a negative slope 2.7. A negative hyperbolic line is indicative of a settlement rate higher than the time duration. This is common for immediate and primary settlement, which occur over a short time period.

The hyperbolic function was then reinitialized at day 508. Table 9 summarizes the control and enhanced cell new hyperbolic line results. The control cell's new hyperbolic line is shown in Figure 18, clearly identifying settlement errors. Ignoring these errors, the hyperbolic line has a y-intercept of 1000 d/m (3,280 d/ft) and a positive slope of about 25, which correlates to an ultimate settlement of 0.04 m from day 508 to 743 (October 13, 1997 to June 4, 1998). Inconsistencies in the field data resulted in a hyperbolic trend line with a coefficient of correlation of 0.58. The reinitialized hyperbolic function for the enhanced cell, Figure 19, provided a relatively straight line with a y-intercept of 80 d/m (262 d/ft) and a positive slope of 2.2 which correlates to an ultimate settlement of 0.45 m. The positive slope is indicative of a settlement rate lower than the time duration. This is typical of long-term settlement where the settlement rate decreases with time. The trend line conformed to the hyperbolic line well with a coefficient of correlation at 0.93.

Application of the hyperbolic function to field settlement data clearly indicates any changes in the field conditions. Although no observational changes were recorded in the field, the gas production in the control cell decreased from an average of 0.57 m^3/min (20 ft^3/min) to less than 0.31 m^3/min (11 ft^3/min) in October 1997. The enhanced cell also saw a slight decrease in gas production in October 1997 from 1.08 m^3/min to 0.65 m^3/min (38 to 23 ft^3/min). The hyperbolic function was able to incorporate into the analysis changes in the field settlement. This method may provide the best estimate for long-term settlement provided the supporting field settlement data continues to approach a hyperbolic line.

Table 9. Control and Enhanced Cell Hyperbolic Parameters after Day 508.

Demonstration Cell	**Y-intercept, α (d/m)**	**Ultimate Settlement, $1/\beta$ (m)**
Control Cell	1000	0.04
Enhanced Cell	80	0.45

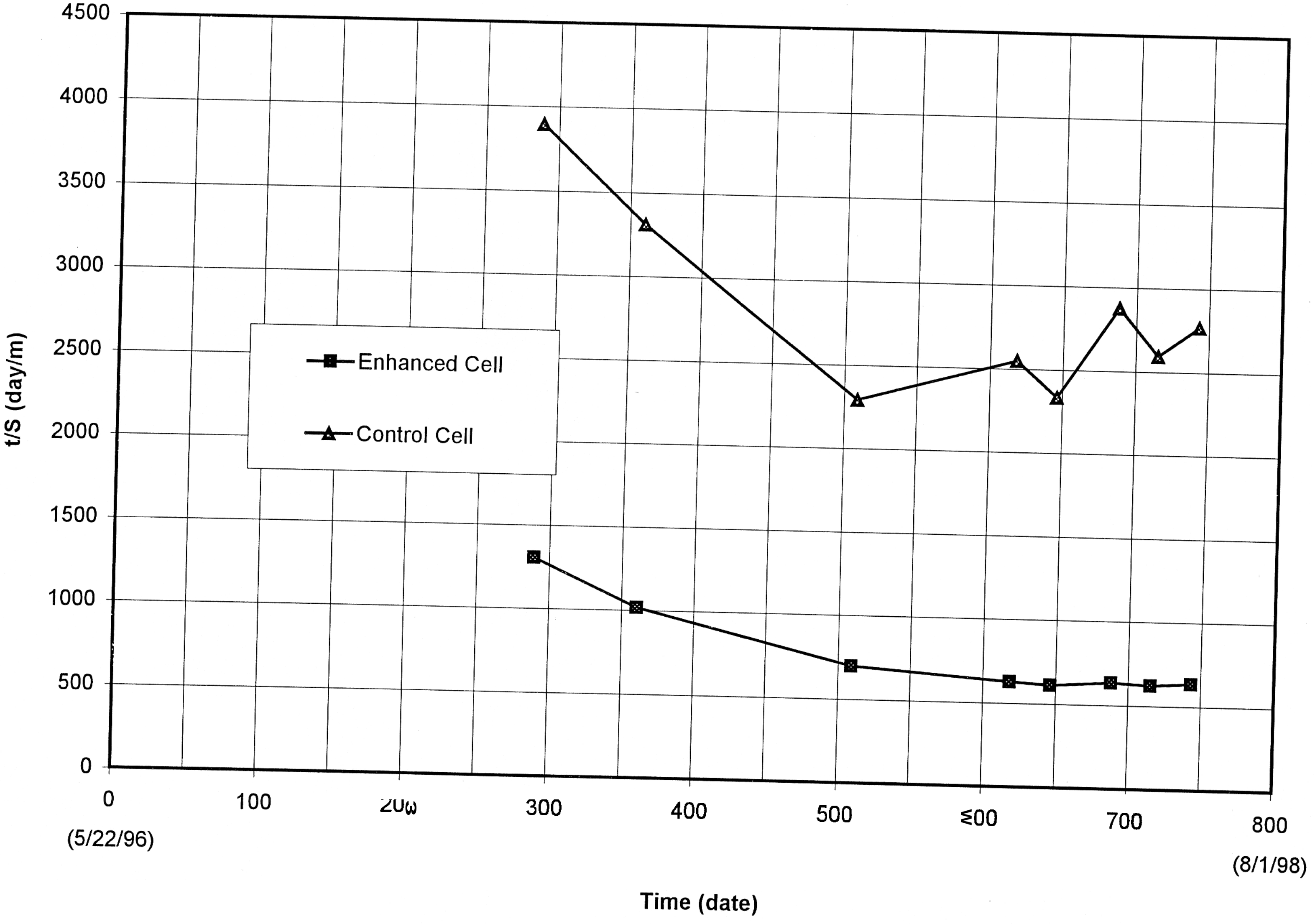


FIGURE 17. Control and Enhanced Cell Hyperbolic Model.

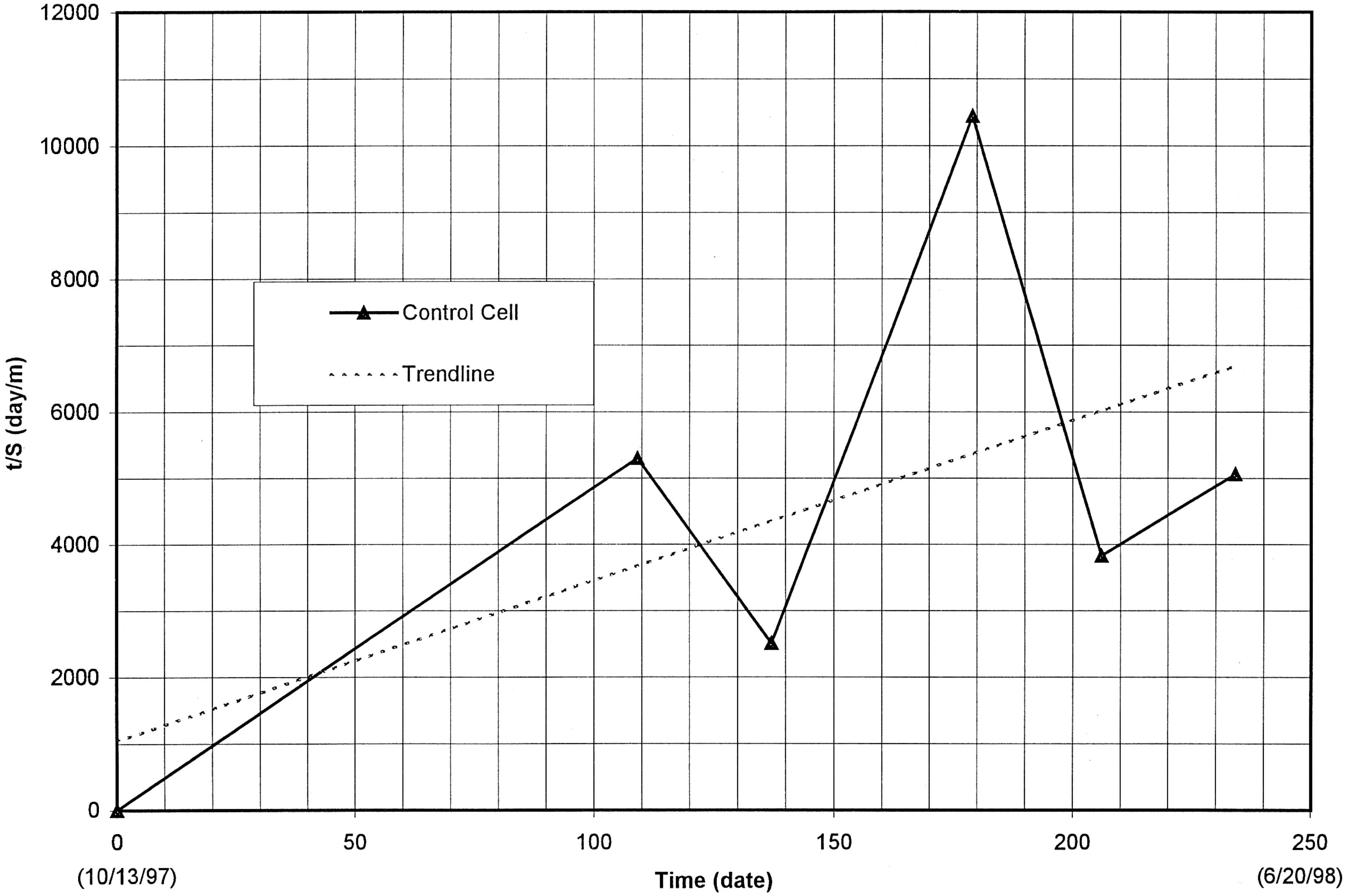


FIGURE 18. Control Cell Reinitialized Hyperbolic Model.

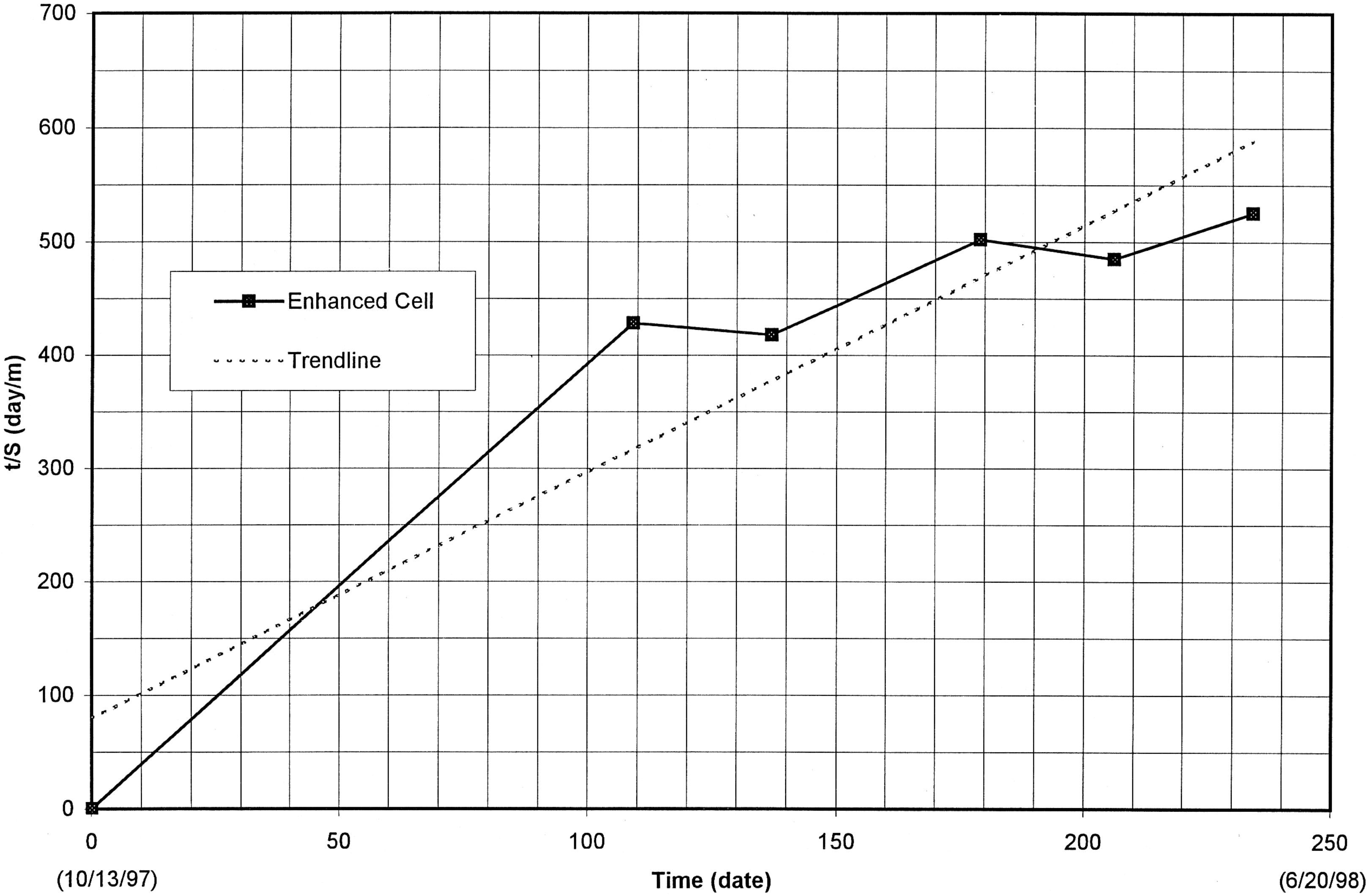


FIGURE 19. Enhanced Cell Reinitialized Hyperbolic Model.

Waste Decomposition and Biodegradation Model

In general, this approach provided good estimation of landfill settlement for the enhanced cell while it over estimated the settlement in the control cell. Figure 20 shows the predicted settlement for the control and enhanced cells based on the biodegradation settlement. The measured settlement in the control and enhanced cells used the same initial height as the predicted settlement curves for comparison purposes. Although the control cell's predicted curve over estimated the actual settlement, the curve did follow the general settlement pattern. The predicted curve estimated a larger settlement between March and September 1997, which caused the 4.3% over estimate. The settlement rate for the control cell from June 1996 to March 1997 is 0.002%/day while the predicted rate was slightly higher at 0.006%/day. The settlement rate then increased slightly to 0.004%/day from March 1997 to June 1998. The predicted rate increased to 0.011%/day but tapered to a near horizontal, zero settlement rate similar to the measured curve during May and June 1998.

The predicted and measured settlement for each cell is summarized in Table 10. The predicted settlement curve for the enhanced cell over estimated the final settlement by 3.8%. Ignoring the added liquid weight, the predicted settlement curve over estimated the settlement by only 1.5%. In both cases the predicted curves provide good settlement prediction. The predicted curves for the enhanced cell followed the same trend as the measured settlement data. From June 1996 to March 1997 the measured settlement rate was 0.008%/day. The predicted settlement rate including the added liquid weight was 0.017%/day, while ignoring the added liquid weight was 0.009%/day. The settlement rate then increased to 0.018%/day from March 1997 to June 1998. Similarly, the predicted settlement rate increased to 0.021%/day for both analyses. In general this approach provided good estimation of the actual field settlement. For the enhanced cell, the volume of landfill gas generated provides sufficient information for the analysis and the added weight of the liquid may be ignored.

Table 10. Control and Enhanced Cell Biodegradation Settlement.

Demonstration Cell	Measured Settlement (%)	Predicted Settlement (%)	Error (%)
Control Cell	2.33	6.67	186
Enhanced Cell	10.49	11.98	14.2
Enhanced Cell plus liquid	10.49	14.30	36.3

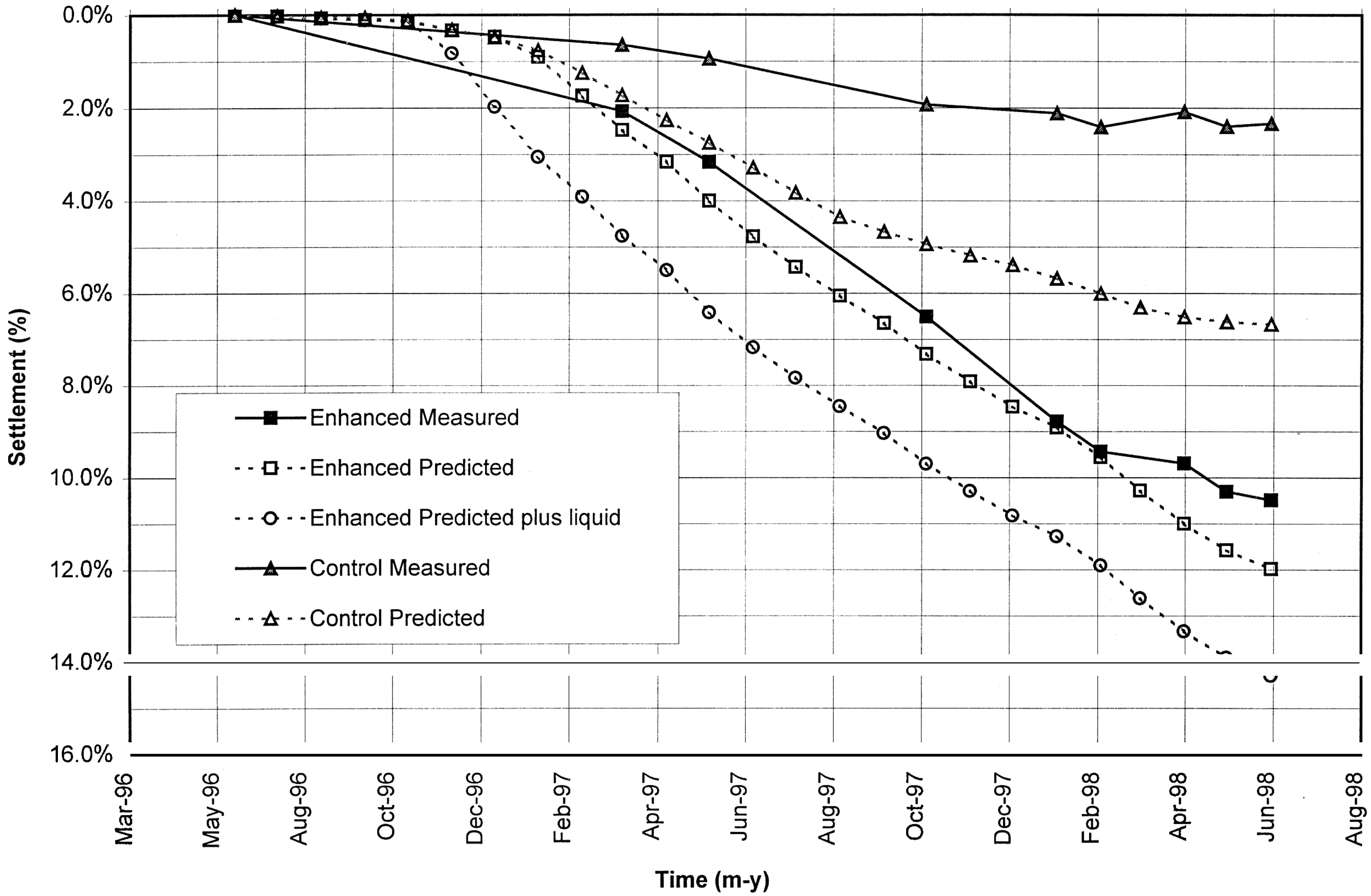


FIGURE 20. Control and Enhanced Cell Biodegradation Model.

SUMMARY OF MODEL RESULTS

In general, each model simulated the field settlement data well for the control and enhanced cells. Models used to predict the control cell settlement generally under estimated the initial settlement and then over estimated the settlement after day 600 (January 1998). Enhancement techniques applied to the enhanced cell to accelerate waste decomposition resulted in more predictable settlement in all models. A summary of each model is listed in Table 11 for the control cell and Table 12 for the enhanced cell. The logarithmic model provided to be the best model to simulate the settlement of the control and enhanced cell throughout the monitoring period. The power creep and rheological simulations were also acceptable settlement predictions. The best estimate of the final settlement as of June 4, 1998 came from the rheological model for the control cell with less than 1% error. For the enhanced cell, the logarithmic model predicted the final settlement the best with less than 0.03% error. Model settlement parameters for the control cell were consistent with reported values. Values for the enhanced cell were indicative of accelerated waste decomposition and not within ranges reported in literature. The hyperbolic function clearly identified field settlement changes and incorporated these changes into the analyses. This method may provide the best estimate for long-term settlement depending if field settlement data continues to approach a hyperbolic line. Although the biological degradation simulation over estimated the control and enhanced cell settlement, the predicted curves did follow the general field settlement pattern. Results from this model were the worst for both cells. The model's approach depends not only on reliable landfill gas generation data but also other factors that are difficult to quantify. The work necessary to improve the prediction does not justify the effort since other models provide reasonable results.

Table 11. Control Cell Measured and Predicted Settlement, June 4,1998.

Average Settlement	Logarithmic	Power Creep	Rheological	Hyperbolic	Biological Degradation
Measured (%)	2.04	2.04	2.04	0.04 m	2.33
Predicted (%)	2.30	2.37	2.03	0.05 m	6.67
Coefficient of Correlation	0.93	0.92	0.88	0.58	______

Table 12. Enhanced Cell Measured and Predicted Settlement. June 4.1998.

Average Settlement	Logarithmic	Power Creep	Rheological	Hyperbolic	Biological Degradation
Measured (%)	9.64	9.64	9.64	0.446 m	10.49
Predicted (%)	9.89	10.45/10.41	9.32	0.45 m	11.98/14.30
Coefficient of Correlation	0.99	0.99/0.99	0.95	0.93	_______

CONCLUSIONS

Current landfill practices maintain the landfilled waste in a dry state. Dry conditions result in slow and variable waste decomposition and settlement. As landfill sites become more limited, new strategies for solid waste management need to be investigated. Yolo County Central Landfill, California, is demonstrating a new and innovative landfill practice known as enhanced landfilling. Enhanced landfilling is an operational practice that actively manages the landfill environment for rapid waste decomposition. The goal of the Yolo County Project is to provide quantifiable data on the benefits of this technology. Benefits of this management strategy include extended landfill life, accelerated landfill gas generation and shorter time period for secondary settlement. The project is currently in the second year of operation with promising results. Two demonstration cells were constructed and filled with municipal solid waste. One cell serves as the project control and represents a conventional landfill while the other cell is managed with enhanced landfilling techniques. Enhancement techniques used in the project include liquid addition and leachate recirculation to the enhanced cell. Moisture addition is the easiest and most important environmental factor to improve waste decomposition. When combined with leachate recirculation, optimal waste decomposition may be achieved.

The project setup and cell design duplicates conditions of a full-scale landfill for direct correlation of project results. **A** comprehensive monitoring system provides information on an array of waste decomposition parameters. This information is used to evaluate the extent to which enhanced landfilling accelerates waste decomposition. Settlement surveys and landfill gas data are used in this study to determine the amount of settlement achieved through enhanced landfilling. Settlement results from the control cell are consistent with the general behavior of conventional landfills. The cell exhibited a large initial settlement, and then gradually decreased to a slower settlement rate. Large settlement fluctuations measured in the control cell are characteristic of variable waste decomposition. Settlement characteristics between the two cells were similar until liquid addition and leachate recirculation started in the enhanced cell. After this point, the settlement rate in the enhanced cell increased dramatically. Throughout the monitoring period the enhanced cell exhibited a constant accelerated settlement rate. As of June 1998, enhanced landfilling resulted in the enhanced cell settling nearly four times the control cell.

Information on waste decomposition and settlement was also provided in the landfill gas generation data. Landfill gas flow rates for each cell correlated well to the settlement rates. A lag-time between changes in the gas flow rate and settlement were evident for both cells. Further investigation in the inter-relationship between these two factors is needed. Results from this study confirm previous finding that enhanced landfilling accelerates waste decomposition and landfill gas generation. However, the longer-term settlement rate for each demonstration cell is required before creditable conclusions on enhanced landfilling may be drawn.

This study evaluated the ability of five settlement models to predict landfill settlement from conventional and enhanced landfilling practices. Results from the Yolo County Project were used to calibrate each model. In general, all models were able to predict the enhanced cell settlement more accurately than the control cell. Each model was able to simulate the cell settlement well but the logarithmic model provided the best fit to field settlement data throughout the monitoring period. The hyperbolic model proved to be the easiest model to manipulate and was able to incorporate changes in the field conditions. The alternative approach of using landfill gas generation data provided a surprisingly good estimate of settlement from enhanced landfilling and marginal results for conventional landfill settlement. Application of this approach, however, highly depends on accurate landfill gas generation data as collected in the Yolo County Project. The settlement model parameters estimated for the control cell are within the range reported in literature and consistent with conventional landfills. Parameters for the enhanced cell indicate favorable conditions for waste decomposition and are not consistent with reported values for typical landfills. The enhanced cell model parameters may be applied to other landfill bioreactor projects with similar waste characteristics to estimate the magnitude and rate of accelerated secondary settlement.

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APPENDIX A

Table A1. Individual Settlement Results. June 4. 1998.

Settlement Marker Control/Enhanced	Control Cell (%)	Enhanced Cell (%)
1	2.6	13.5
2	2.3	10.4
3	2.3	14.0
4	2.5	16.1
5	2.6	12.2
6	1.9	6.6
7	1.9	11.0
8	1.8	9.8
9	2.1	14.4
10	2.0	17.0
11	2.3	14.6
12	2.2	11.0
13	2.3	9.5
14	1.6	3.0
15	1.8	4.0
16	1.8	10.6
17	2.2	4.3
18	1.4	
20	1.6	2.3
22	2.0	2.0
23	2.0	
24		8.9
25		7.3
AVERAGE	**2.0**	**9.6**

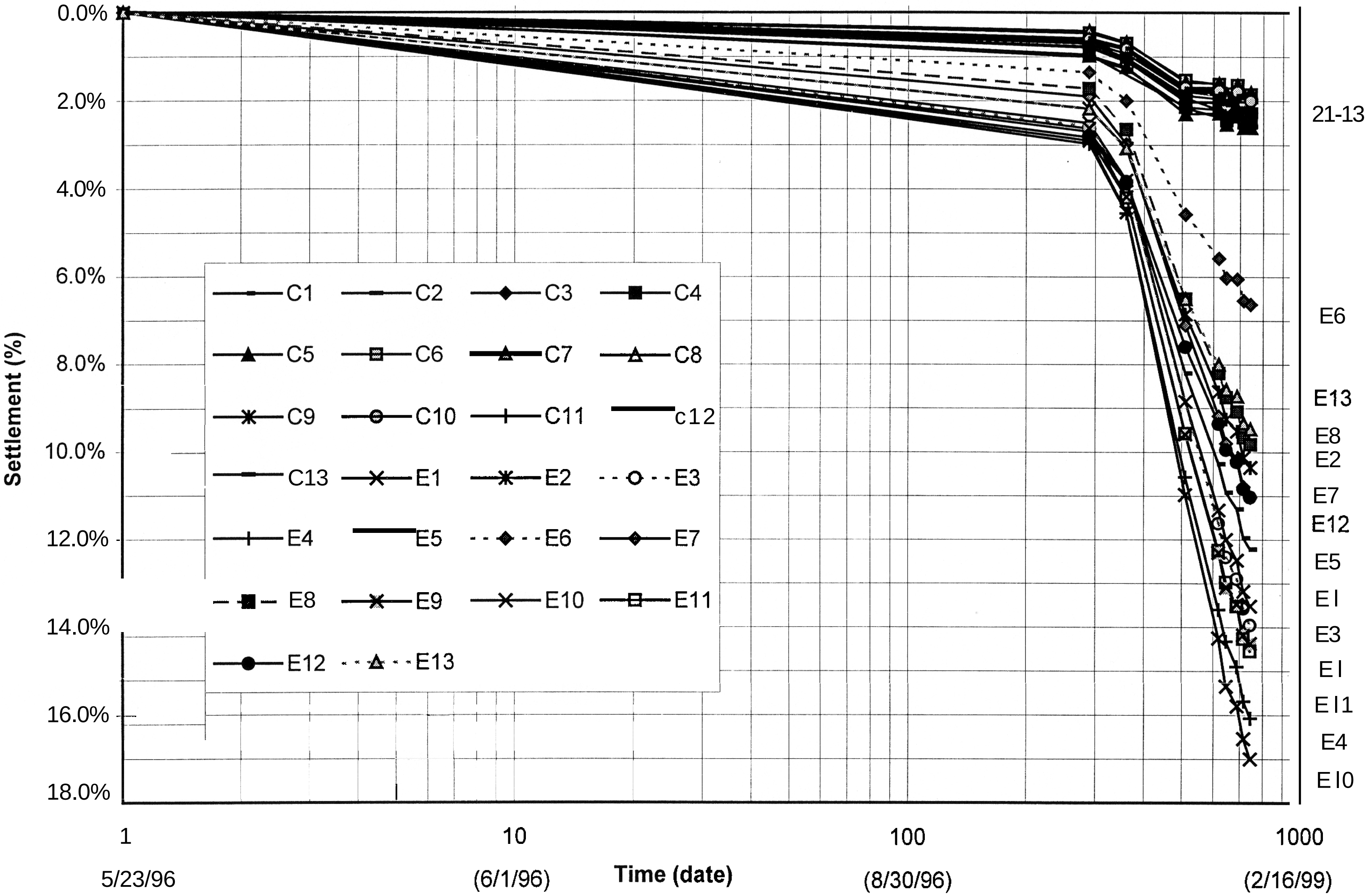

FIGURE A l. Control and Enhanced Cell Settlement, Markers 1-13.

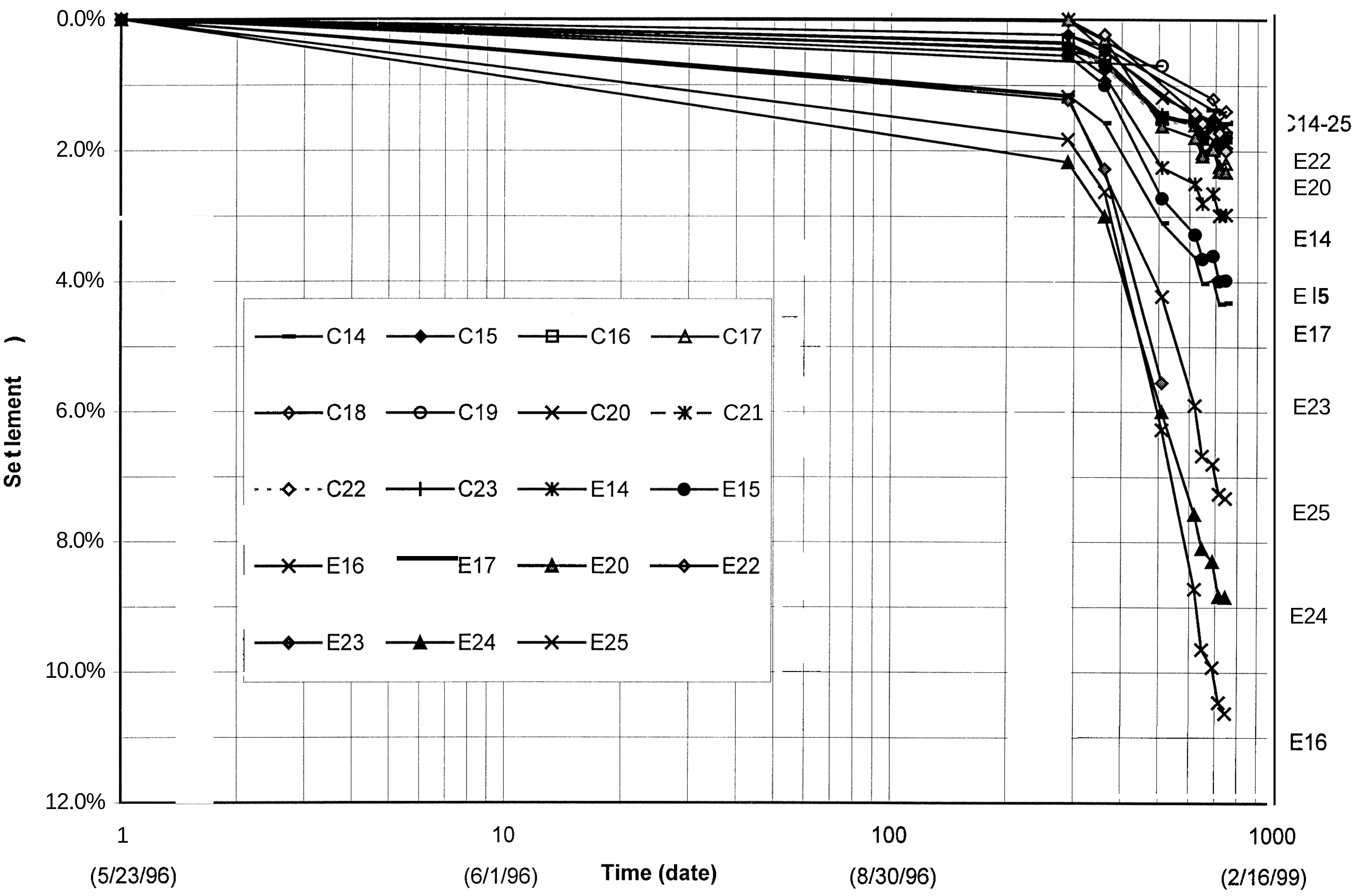

FIGURE A2. Control and Enhanced Cell Settlement, Markers 14-25.