# INSIGHTS TO ENHANCED LANDFILL GAS GENERATION

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**SUMMARY:** Two test projects demonstrate enhanced landfill gas generation yield and rate. Quantitative moisture addition and temperature management are the keys to success. Normalized data allow comparison of test cell results with values for operating landfills where moisture and temperature are naturally enhanced.

## 1. INTRODUCTION

Modern landfills are designed and managed to provide environmental security. The protective measures (liners, etc.) tend to maintain the contained refuse in a dry state, which significantly slows decomposition. Liquid addition and temperature management can be used to accelerate refuse decomposition. These activities generate significant landfill gas (LFG) over a short time and in an environmentally secure manner. This procedure for enhancing LFG production — for example, as part of an LFG-to-energy project — is technically sound. It is necessary, however, to carefully manage moisture content and temperature.

This paper describes two controlled-enhancement landfill projects, both in central California, USA. The first is the Mountain View demonstration project, which ran between 1980 and 1986 (EMCON, 1987). The second is the Yolo County demonstration project, begun in 1995 (Yazdani et al., 1997). The Mountain View project involved six test cells, each containing around 8,000 metric tons (tonnes; 8,800 tons) of municipal solid waste **(MSW).** At Yolo, two similarly sized cells are being tested.

Both projects demonstrate that high moisture and temperature are very significant parameters in enhancing LFG generation rate and yield. The LFG generation test data are normalized for comparison with data from actual operating landfills, some of which have naturally occumng moisture and temperature conditions conducive to high LFG generation.

## 2. MOISTURE MANAGEMENT

### 2.1 Moisture and density relationships

This section presents a fundamental understanding of the refuse moisture and density relationships necessary for developing a protocol to achieve enhanced LFG generation. The moisture content of the refuse must be increased with additional liquids to realize a significant gain in LFG yield and flow rate. The amount of additional liquid necessary to achieve the desired moisture content can be determined from the refuse placement moisture and density, combined with appropriate formulae. The moisture and density relationships will change over time as a result **of** additional placement of refuse lifts, decomposition, settlement, or **as** liquid additions occur, naturally or artificially. Figure 1 illustrates the refuse volume **and** weight relationships; it separates a unit **mass** into its three phases: solid, liquid, and gas.

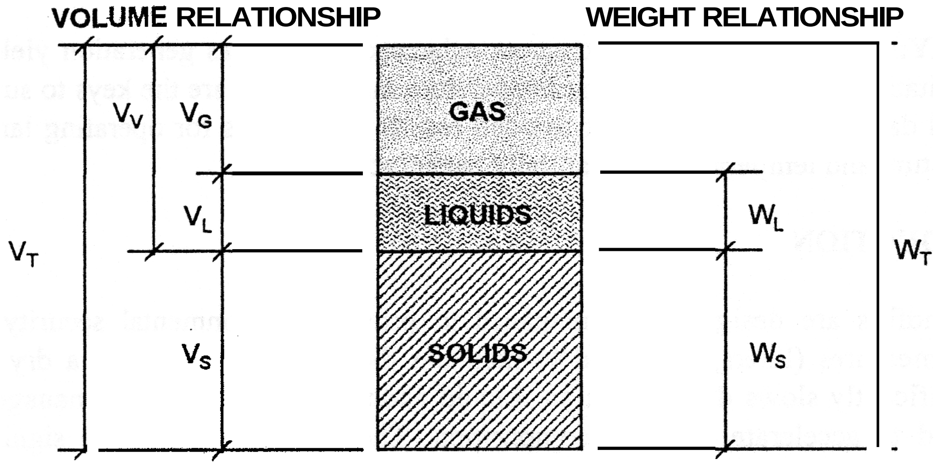


**Figure 1. Three phase diagram: refuse volume /weight relationships**

| | Volume Relationship | Weight Relationship |
|---|---|---|
| Formulae: | Moisture content $= W_T/W_L$ | Void ratio $= V_V/V_S$ |
| | Density $= W_T/V_T$ | Porosity $= V_V/V_T$ |
| | Saturation $= V_L/V_V$ | |
| Where: | $W_T$ = Total weight | $V_T$ = Total volume |
| | $W_S$ = Solids weight | $V_S$ = Solids volume |
| | $W_L$ = Liquids weight | $V_L$ = Liquids volume |
| | w = Moisture content | $V_G$ = Gaseous volume |
| | $G_S$ = Solids specific gravity | $V_V$ = Voids volume |

The generic geotechnical soil formulae for moisture content, saturation, void ratio, porosity, volume, and weight are applicable to refuse. EMCON (1987) used a refuse solids specific gravity of 1.00 for **US MSW.** This value was based on laboratory work performed for EMCON (ca. 1975), associated with refuse sampling at three San Francisco Bay Area landfills. The refuse solids specific gravity can vary significantly for different refuse compositions.

Initial values for total weight, total volume, and average moisture content are measured in a test cell program. All other quantification values are then calculated. Table 1 summarizes Mountain View and Yolo weight and volume characteristics for a unit total volume, assuming a specific gravity of 1.00 for both dry refuse and liquid.

| Table 1. Summary of Cell Unit Characteristics at Completion of Construction | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mountain View Cells | | | | | | Yolo Cells | |
| | Units | A | B | C | D | E | F | $Y_C$ | $Y_E$ |
| Total Weight | kg | 765 | 746 | 711 | 693 | 687 | 704 | 593 | 593 |
| Solid Weight | kg | 505 | 507 | 498 | 513 | 488 | 521 | 433 | 433 |
| Liquid Weight | kg | 260 | 238 | 213 | 180 | 199 | 183 | 160 | 160 |
| Total Volume | $m^3$ | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Solid Volume | $m^3$ | 0.505 | 0.507 | 0.498 | 0.513 | 0.488 | 0.521 | 0.433 | 0.433 |
| Liquid Volume | $m^3$ | 0.260 | 0.239 | 0.213 | 0.180 | 0.199 | 0.183 | 0.160 | 0.160 |
| Gas Volume | $m^3$ | 0.235 | 0.254 | 0.289 | 0.307 | 0.313 | 0.296 | 0.407 | 0.407 |
| Void Volume | $m^3$ | 0.495 | 0.493 | 0.502 | 0.487 | 0.512 | 0.479 | 0.567 | 0.567 |
| Void Ratio | | 0.98 | 0.97 | 1.01 | 0.95 | 1.05 | 0.92 | 1.31 | 1.31 |
| Porosity | % | 50 | 49 | 50 | 49 | 51 | 48 | 57 | 57 |
| Saturation | % | 53 | 48 | 42 | 37 | 39 | 38 | 28 | 28 |

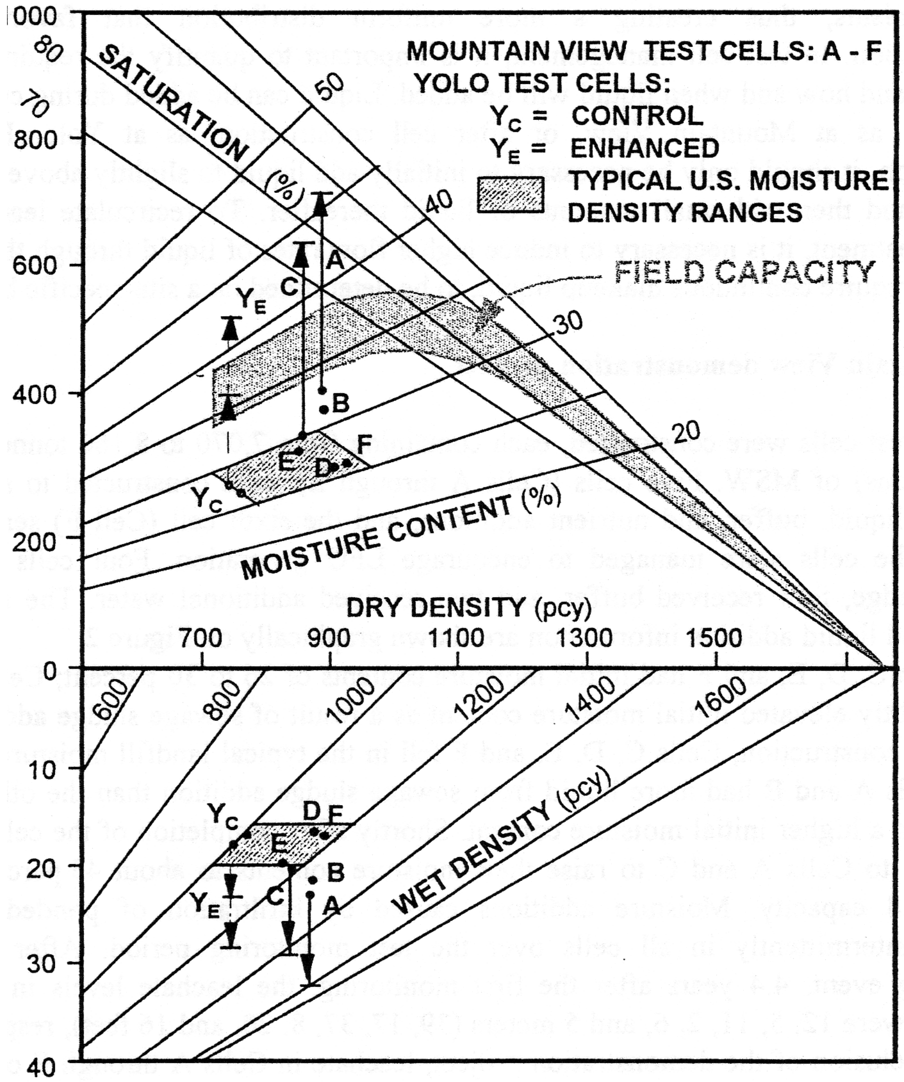


**Figure 2. Moisture content and liquid weight vs. density relationships**

The lower portion of Figure **2** plots MSW density, both in the total and dry conditions, vs. average moisture content (total weight basis). Weight of water, moisture content, dry density, saturation, and range of field capacity (moisture content after all free moisture has drained by gravity from a saturated mass) are shown in the upper portion of Figure **2.** Typical as-placed US landfill moisture density ranges are indicated by the cross-hatched areas. Figure **2** provides the weight of liquid per unit MSW mass at time of placement, at full saturation, and in the range of field capacity (shaded zone) for a selected dry density value. In the early 1970s, a rule of thumb for the amount of liquid that could be added to refuse before it reached field capacity was 10 percent by weight. Campbell (ca. **1982)** states that the initial absorptive capacity of the waste before significant leachate generation at typical site refuse densities is about 50 kg/wet tonne (130 pounds per cubic yard [pcy]), a value comparable with **US** findings.

Figure **2** is valuable for determining the amount of liquid addition necessary to achieve field capacity, i.e. the condition when leachate is first observed. As leachate moves by gravity from upper levels to lower levels it transports nutrients and microorganisms, thus creating a more uniform distribution that favors refuse decomposition. In test cell management, it is important to quantify the required liquid additions, and how and when liquid will be added. Liquid can be added during cell refuse placement, as at Mountain View, or after cell construction, as at Yolo. For LFG optimization, it should only be necessary to initially add liquid to slightly above the field capacity, and then add small amounts of liquid thereafter. To recirculate leachate for internal treatment, it is necessary to induce higher flow rates of liquid through the refuse. This may require continuous makeup liquid, to be determined on a site-specific basis.

## 2.2 Mountain View demonstration project

Six test cells were constructed, each containing from 7,070 to 8,160 tonnes (7,800 to 9,000 tons) of MSW. Five cells (Cells **A** through E) were constructed to study the effects of liquid, buffer, and nutrient additions, and the sixth cell (Cell F) served as a control. The cells were managed to encourage LFG generation. Four cells received sewage sludge, four received buffer, and two received additional water. The moisture, density, and liquid addition information are shown graphically on Figure **2.**

Cells C, D, E, and F had initial moisture contents of 26 to 30 percent; Cells C and E had slightly elevated initial moisture content as a result of sewage sludge addition. At the end of construction, Cells C, D, E, and F fell in the typical landfill moisture content range; Cells A and B had more liquid from sewage sludge addition than the other cells, resulting in a higher initial moisture content. Shortly after completion of the cells, liquid was added to Cells **A** and C to raise their moisture contents to about 45 percent, well above field capacity. Moisture additions caused by infiltration of ponded rainfall occurred intermittently in all cells over the test monitoring period. After the last monitoring event, 4.4 years after the first monitoring, the leachate levels in Cells A through F were 12, 5, 11, 2, 6, and 5 meters (39, 17, 37, 8, 20, and 16 feet), respectively. At the conclusion of the demonstration project, leachate in Cells **A** through F composed 88, 38, 84, 16, 47, and 36 percent of the cell depths, respectively. Note also that high temperatures and LFG generation rate occurred, even when much of the refuse was inundated with leachate. This result supports the contention that very high moisture content and a high LFG generation rate are sustainable, even without externally induced liquid circulation.

If this project were rerun, it would be desirable to add sufficient liquid to maintain a moisture content of about 40 to 42 percent for the leachate recirculation cell (Cell A) and a moisture content of 35 to 38 percent for Cell C. Cell A would use the additional liquid to make up for liquid lost internally during recirculation. Cell C would receive only enough liquid to be in the upper field capacity range. It would also be advantageous to manage rainfall run-on and runoff to prevent ponding in the test cell area, precluding any unplanned additions of liquid.

### 2.3 Yolo demonstration project

Two 8,160-tonne (9,000-ton) cells were constructed, one designated as control Cell $Y_C$ and the other as enhancement Cell $Y_E$. Refuse was placed between April and October 1995. The refuse is about 12 meters (45 feet) deep and each cell has an average density of about 593 $kg/m^3$ (1,000 pcy). The cells were designed to demonstrate that it is possible to manage liquid additions and achieve rapid refuse decomposition, increased methane generation and yield, and internal leachate treatment. The cells were well instrumented to measure moisture content, temperature, methane composition, gas pressure, and flow. Both cells were allowed to equilibrate to normal landfill conditions for roughly a year. The moisture and density of the two cells were initially within the typical landfill range shown on Figure 2. In October 1996, moisture addition to Cell $Y_E$ began. By January 1997, the Cell $Y_E$ moisture content had risen to above field capacity, as shown on Figure 2. The monitoring data suggest that field capacity was encountered at a moisture content of about 36 percent.

### 2.4 Operating landfills

Liquid is added during and after refuse placement at many US landfills. Annual rainfall infiltration may be high, or the landfill may receive significant disposal rates of wastewater or plant sludges. An obvious high-moisture condition is typified by a continuous leachate effluent. Most landfills where annual rainfall exceeds 1020 mm (40 inches) may have potentially high refuse moisture contents. Many exhibit high LFG generation rates, the most famous being the Fresh Kills landfill in New York. Many of these landfills were developed before currently adopted standards, and may not be lined or environmentally secure.

With the requirements for secure environmental containment of leachate and LFG now in effect, liquid addition and management to achieve enhanced LFG generation should see increasing application. Roosevelt landfill in the state of Washington, a large landfill under development, is now seeking approval for a major LFG enhancement project. The project has a composite base liner for environmental security and is in an arid region where annual precipitation is 152 to 229 mm (6 to 9 in.). Because of projected future heavy demand for enhancement water, it was necessary to secure well water rights to assure an adequate liquid supply. If approvals are received, the LFG generation rate is expected to exceed 51,000 $m^3/h$ (30,000 din) by the year **2020.** Without enhancement., the rate would be less than 17,000 $m^3/h$ (10,000 cfm). This project **is** completing a 0.8-hectare (2-acre) demonstration of moisture management procedures for state approval.

## 3. TEMPERATURE

### 3.1 General

Temperature plays a significant role in controlling LFG yield and rate. EMCON (1987) found that the upper temperature limit at Mountain View for anaerobic landfill microorganisms appears to be 60°C (140°F). Cecchi et al. (1991), in research on high solids anaerobic digestion of MSW, found that the semi-dry thermophilic process at 55°C (131°F) has a gas generation rate of two to three times the mesophilic process at 37°C (99°F). Huitric and Soni (1997) state that thermophilic temperature effects increase methane generation by 50 percent relative to mesophilic temperatures. Ham *et* al. **(1982)** report an optimum temperature for LFG generation from MSW of 41°C (106°F) over the short-term. Pfeffer (1974) studied the effect of temperature on digestion of solid waste over short periods (3 to 30 days), at temperatures of from 35°C to 60°C (95° to 140°F). Total gas produced at 60°C (140°F) was 1.5 to 2.6 times the production at 35°C (95°F). Except for a modest drop at 45°C (113°F), production increased with temperature. It should also be noted that Campbell (1995) did not find a good correlation between temperature and generation rate.

High temperatures were developed and maintained at both Mountain View and Yolo (Yolo is still in the early stages). Commentators have felt that it would be difficult to achieve and maintain the high temperature that is necessary for substantial enhancement in full scale landfills. The Mountain View and Yolo projects have both demonstrated, however, that a LFG generation temperature can be obtained and maintained with little, if any, capital expenditure.

Where the primary goal of the test cell project is to optimize LFG generation (flow rate and yield), the key management parameters are liquid additions and high temperatures. The author believes that when MSW moisture is less than 20 percent, temperature has little influence on generation rate. Significant temperature impact on LFG generation commences at about 30°C (86°F), when the associated moisture content is about 25 percent. Enhancement has its greatest potential for achievement at higher temperatures and moisture contents, in the range of 40" to 60°C (104" to 140°F) and 35 to 45 percent, respectively. Temperature impact increases as moisture content gradually increases to MSW field capacity, beyond which point temperature may have its strongest impact. When temperature is near the upper limit of 60°C (140°F), caution must be exercised that the temperature results from the decomposition process and not an underground fire. **A** fire condition can be verified by testing the LFG for carbon monoxide, which is associated with incomplete combustion.

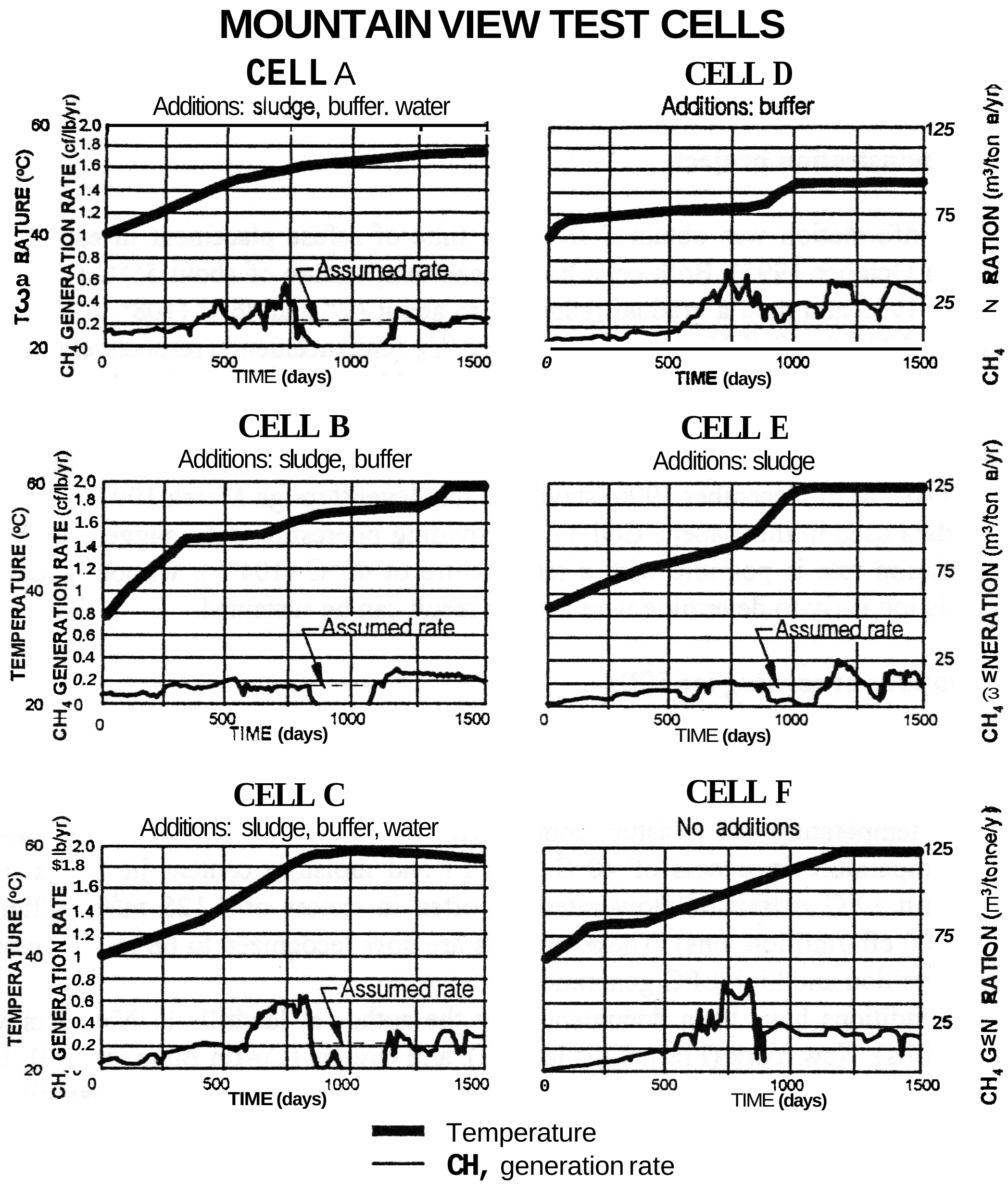


**Figure 3. Temperature and $CH_4$ generation rate vs. time**

## 3.2 Mountain View demonstration project

The relation between temperature data and methane generation for the Mountain View project cells is illustrated in Figure 3. The resultant flow rates for all six cells are significantly higher than reported for operating landfills sharing similar regional characteristics. The temperature for each cell was in the mesophilic range (35° to 40°C [95° to 104°F]) at the beginning of the monitoring program, three months after final refuse placement. The temperatures in each cell climbed into the thermophilic range within a year and maintained high levels of 50° to 60°C (122° to 140°F) until the project terminated at year 4.4.

The unit flow rates for each cell are among the highest reported in the literature. The cells generated methane in the range of **8.7** to 21.2 $m^3$ per *dry* tonne per year (0.14 to 0.34 cf per dry pound per year).

### 3.3 Yolo demonstration project

Temperature information was obtained from the time of refuse placement in each cell (May through October 1995). Both cells had a peak temperature of about 55°C (131°F) in September 1995 and then a gradual reduction to about 42° and 46°C (108" to 115°F) by November 1996 for Cell $Y_C$ (control) and Cell $Y_E$ (enhancement), respectively. The temperature of Cell $Y_C$ has continued to decline. ***As*** of March 1997, it was about 40°C (104°F). Cell $Y_E$ received sufficient liquid addition in October 1996 to increase moisture content slightly above field capacity. The temperature then began to drop and reached about 40°C (104°F) in December 1996, staying at that level through March 1997 (the last monitoring data used in this paper). Cell $Y_C$ is providing interesting data, suggesting that a high generation rate is possible with a temperature of 40°C (104°F), without adding moisture. It is too early to determine whether this result can be sustained.

### 3.4 Observations at existing landfills

The author prepared and reviewed numerous LFG estimates for operating landfills, with the aid of mathematical models. Two of the principal model input parameters to be calibrated are temperature and moisture content. At landfills where these parameters are high, e.g., temperature in excess of 40°C (104°F) and moisture content in excess of 35 percent, unit LFG extraction flow rates are often in excess of 1,125 $m^3$/h/million (M)tonnes (600 cfm/million tons). These landfills are now recognized to be in a state of rapid decomposition and high LFG generation.

Such conditions have been documented by the author at landfills in New Jersey (HMDC landfills), New York (Fresh Kills landfill), and Oregon (Coffin Butte landfill). It is becoming clear that enhanced landfill temperatures are present in numerous landfills, without operational, or design, planning.

## 4. DATA NORMALIZATION

### 4.1 General

Data normalization converts LFG generation flow data to a common measurable mass unit coupled with a selected methane concentration. Data normalization facilitates comparisons between full scale landfills and test cells. For the purpose of this paper, a normalized unit is considered 1 Mtonnes (1.1 million tons) of refuse, assuming a LFG methane concentration of 50 percent by volume.

### 4.2 Mountain View demonstration project

**LFG** generation rates were **determined** by volume measurement and corrected to standard temperature and pressure values. Figure 4 depicts the yearly **flow** rates for each cell measured **from** the *start* of monitoring. The average normalized **rate** of LFG flow from these cells ranged from 1,990 to 4,840 $m^3$/h/Mtonnes (0.28 to 0.68 cf/wet lb/yr) over a 4.4-year term. By **comparison,** the non-normalized values ranged from 1,780 to 4,270 $m^3$/h/Mtonnes (0.25 to 0.60 cf/wet lb/yr). The difference between actual **values** and normalized values would be zero if the actual methane concentrations were 50 percent.

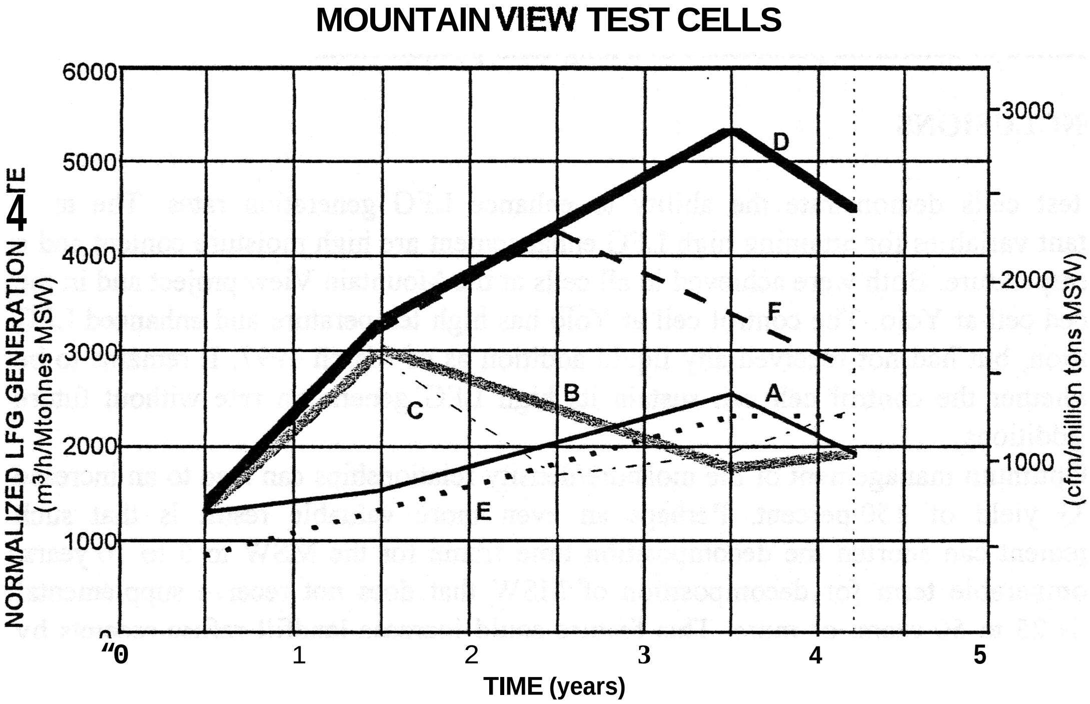


**Figure 4. Normalized LFG generation rate vs. time**

### 4.3 Yolo demonstration project

The Yolo test cells are in the first two years of study, and liquid was only recently added to the enhanced cell. As of March 1997, the enhanced and control cell were providing LFG flow rates of 63 and 46 $m^3$/h (37 and 27 cfm), respectively. Extrapolating these data to a yearly basis for the enhanced and control cell provides a normalized LFG flow rate of 5,720 and 8,150 $m^3$/h/Mtonnes (3,050 and 4,350 cfm/million tons) for Cells $Y_E$ and $Y_C$, respectively. The non-normalized values, by comparison, were 5,600 and 7,680 $m^3$/h/Mtonnes (2,990 and 4,100 cfm/million tons) for Cells $Y_E$ and $Y_C$ respectively. Figure 3 for the Mountain View test cells shows many significant short-term peaks in the data, which reflect extremely high generation rates. Because of this potential short-term variability, it is best to have at least one full year of rate data before drawing conclusions.

Nevertheless, the early Yolo data suggest that this demonstration project will contribute new insights about landfill gas enhancement.

Note that a project to convert LFG to energy is active at the Yolo landfill. The project has for the past seven years extracted between 1,360 and 1,870 $m^3/h$ (800 to 1,100 cfm; about 1,000 cfm currently) from a refuse mass of 2.7 Mtonnes (3 million tons). The two test cells now deliver a combined 109 $m^3/hr$ (64 cfm) to the project from 16,400 tonnes (18,000 tons) of refuse. Extrapolating that extraction rate to a total site refuse mass of 2.7 Mtonnes (3 million tons) yields an LFG extraction flow in excess of 17,000 $m^3/h$ (10,000 cfm). This extrapolated statistic will be carefully monitored and documented to determine persistence as a long-term phenomenon.

## 5. CONCLUSIONS

Field test cells demonstrate the ability to enhance LFG generation rates. The most important variables for attaining high LFG enhancement are high moisture content and a high temperature. Both were achieved in all cells at the Mountain View project and in the enhanced cell at Yolo. The control cell at Yolo has high temperature and enhanced LFG generation, but had not received any liquid addition as of March 1997. It remains to be seen whether the control cell can sustain its high LFG generation rate without future liquid additions.

Optimum management of the moisture/density relationships can lead to an increase in LFG yield of 150 percent. Perhaps an even more valuable result is that such management can shorten the decomposition time frame for the MSW to 5 to 10 years. The comparable term for decomposition of MSW that does not receive supplemental liquid is 25 to 50 years, or more. This feature could increase landfill refuse receipts by perhaps **20** percent, result in landfill post closure cost savings, and will certainly provide major encouragement to LFG energy projects.

The author believes that the ability to obtain the high initial temperature at both the Mountain View and Yolo landfills was due to the method of construction. The cells were constructed on a small base footprint surrounded by a clay berm, and intermediate cover consisted of 0.3 m (1 ft) of greenwaste overlying each 1.5 m (5 ft) refuse lift. The refuse attained an initial aerobic composting temperature of 55°C **(131°F)** or higher, retained that temperature during construction, and subsequently released heat slowly, except when managed enhancements were added. It appears that a naturally occurring high temperature can be developed using normal landfill construction procedures, without increasing the cost of operations. The high moisture and temperature results have been obtained in some operating landfills, unintentionally. Landfill operators are usually unaware that they have created such a condition and that it has potential value.

Field test cells such as Mountain View and Yolo were designed to demonstrate that the LFG enhancement goal is attainable. In addition, a significant number of landfills are demonstrating naturally occurring enhancement conditions. It is disappointing to note the limited commercial application of such encouraging LFG enhancement findings. This is particularly unfortunate because the landfills of the present and future have a high level of environmental security. It is hoped that this paper will encourage economical application of LFG enhancement programs at full-scale landfills.

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