ANALYSIS OF TEMPERATURES AT A MUNICIPAL SOLID WASTE LANDFILL

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SUMMARY: A study is conducted to determine the thermal regime within and around a municipal solid waste landfill located in midwestern U.S.A. Spatial distributions of temperatures have been determined over time since 1999 within the waste mass, liner and cover systems, and surrounding subgrade. Seasonal variations, placement of waste, age of waste, depth and location of waste, and available moisture have significant effects on temperatures. Temperatures of wastes at shallow depths, bottom liner systems prior to waste placement, and final cover systems conform to seasonal temperature variations. Steady elevated temperatures are reached with respect to air and ground temperatures at central locations and at depth in the waste mass. Increasing trends are observed for temperatures in wastes and bottom liner systems in cells containing newly placed wastes. It is estimated that waste temperatures increased due to effects of leachate recirculation at portions of the facility. Subgrade temperatures at the perimeter of the landfill have not yet been significantly affected by the presence of the facility.

1. INTRODUCTION

Temperature affects the physical, chemical, biological, and mechanical properties and behavior of wastes and liner materials in landfills. Hartz et al. (1982) identified optimum temperature ranges for decomposition and degradation of wastes. Settlements and various compositional and stress parameters for a waste mass are affected by temperature (Edil et al., 1990; Fassett et al., 1994). Settlements increase with increasing temperatures indicating a potential decrease in shear strength. Temperature affects the structure and engineering behavior of clays (Campanella and Mitchell, 1968). Temperature effects can occur in the form of cracking due to both freeze-thaw cycles (Othman et al., 1994) and desiccation (Daniel, 1987) in addition to potential changes in shear strength, settlement, and hydraulic conductivity of liner soils. Doll (1997) demonstrated potential desiccation and cracking of bottom clay liners due to heat generated in overlying waste mass using numerical analysis. High temperatures increase degradation and aging and low temperatures decrease flexibility of geosynthetic liner materials (Rigo and Cazzuffi 1991). Diffusive transport through liner materials increases with increasing temperatures (Rowe 1998). Even though temperature has significant effects on various landfill components, limited information exists on temperatures within wastes, liner systems, and surrounding subsurface.

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Elevated temperatures (up to 70ºC) in comparison to local air and ground temperatures have been reported for wastes, leachate, and landfill gas (Rowe 1998). In general, detailed spatial distributions or comprehensive long term trends are not available.

This study is conducted to determine long term temperature trends in various components of a landfill on a field scale. Effects of environmental, compositional, and operational factors on temperatures have been investigated at the facility. Onset and duration of temperature variations with respect to local air and ground temperatures have been studied.

2. FIELD SITE AND INSTRUMENTATION

The study has been conducted at a municipal solid waste landfill located in midwestern U.S.A. Waste has been placed at the site since the late 1960's originally in uncontrolled trenches. A modern regulated landfill with liner systems and leachate and gas collection and removal systems has been constructed at the site since 1983. The landfill is located in an area containing silty clay soils to typical depths of 20 m underlain with hardpan (stiff layer consisting of cemented sand and fine gravel) with bedrock present at a depth of approximately 23 m. A confined aquifer is located at the hardpan/bedrock elevations. Excavations for the construction of individual cells extend to depths of approximately 11 to 14 m below original ground surface.

The site is located in an area that has a humid continental temperate climate. The annual normal average high temperature is 14.5 °C and the annual normal average low temperature is 3.9 °C based on climatological data from a nearby weather station. The annual normal precipitation at the site is 828 mm. The annual normal snowfall for the site is 1046 mm.

The annual normal average high and low temperature for the study period are 15.1 °C and 5.5 °C, respectively. The coldest months on record since the beginning of the study have been December or January with an average temperature for these months at –3.3 °C. The warmest months on record since the beginning of the study have been July or August. The average temperature for the warmest months for this period is 23.5 °C. The average annual precipitation at the site is 886 mm for the study period. The driest and wettest months on record varied year to year in this period. The average precipitation for the driest and wettest months for this period are 26.9 mm and 148.1 mm, respectively. The average annual snowfall for the study period is 1016 mm. The seasonal ground surface temperatures measured at the site typically vary between -1 °C and 30 °C. The mean annual earth temperature measured at depth at the site is 11.7 °C.

The total area of the facility is 81 ha and the permitted area for waste placement is 65 ha. The facility has a design capacity of 26,240,000 m^3 of volume for waste disposal. Currently, waste is placed over approximately 77% of the permitted area and occupies approximately 40% of the design volume. The current average height of waste column is 40.5 m. The unit weight of waste placed at the site in recent years is estimated to be 10.0 kN/m^3, which is determined as the quotient of total weight of waste received (determined from measurements of weights of incoming waste loads) to total volume occupied by waste (determined using ground and aerial surveys). The current rate of waste acceptance at the site is approximately 34,375 kN/day.

The landfill is divided into eleven cells (Cells A-K). Bottom liner systems have been constructed for eight of the cells, with construction for the remaining cells planned in the near future. Active waste placement typically occurs in one cell at a time. Final waste elevations have been reached along the perimeter slopes of three of the cells and final cover systems have been placed over these areas. Interim covers have been placed over all inactive regions of the landfill. Temperature sensors have been placed in six cells (A, B, D, I, J, and L) at the facility.

Cell L (area 10.5 ha) has a liner system that consists of two layers (3000-mm-thick native clay and 300-mm-thick sand), with no geosynthetic component. The leachate collection and removal

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system in the cell is relatively simple. Waste was placed in the cell between 1984 and 1987 and then again between 1993 and 1994. The bottom liner system for Cell J (area 3.2 ha), Cell I (area 3.5 ha), and Cell D (area 5.2 ha) consists of (from top to bottom): 450-mm-thick protective sand layer, geotextile/geonet composite, 1.5-mm-thick geomembrane, geosynthetic clay liner, and compacted clay in regions containing sands. The bottom liner system in Cell B (area 3.7 ha) is similar, with the exception that the geosynthetic clay liner is replaced by a 910-mm-thick compacted clay liner. Cell B was constructed in 1994 and filled with waste from 1994 to 1999. Cell J was constructed in 1998 and filled with waste from 1999 to 2001. Cell I was constructed in 1999 and filled with waste from 2000 to 2002. Cell D, which is the currently active cell at the landfill, was constructed in 2001 and has been filled with waste since December 2002. Cell A (area 3.6 ha) was constructed in 1994 and filled with waste from approximately 1994 to 1996. Final cover systems were constructed over perimeter slopes of Cells J and A in June and August 2002, respectively. The cover system consists of (from top to bottom): 150-mm-thick vegetative topsoil layer, 600-mm-thick protective soil layer, geotextile/geonet composite, 1-mm-thick geomembrane, and 450-mm-thick compacted clay. The approximately 30-year-old wastes that were deposited in the uncontrolled trenches at the site were excavated and placed in central locations in Cells J and I as well as at to a lower extent at some locations in Cells A and B.

Instrumentation has been installed at the site in existing cells and in new cells that have been constructed since the beginning of the study. Temperature data have been obtained using thermocouple sensor arrays. An array consists of a series of wires beginning at a monitoring box and terminating at various points along a linear path within the facility. Type K thermocouple wires consisting of Nickel alloys (Ni-Cr/Ni-Mn-Al) are used for the installations. Type K thermocouples were selected for their resistance to chemical environments. The total number of individual temperature sensors is approximately 200 and the number of arrays is 17. Individual arrays range from 10 to 200 m in length and the total length of the arrays installed at the site is approximately 1600 m. Sensor arrays are installed vertically and horizontally to investigate temperature profiles through various cross sections at the site (Figure 1). Variations in temperatures with depth are investigated using the vertical sensor arrays. Variations in temperatures at a given depth and in a given landfill component are investigated using the horizontal sensor arrays. The existing data collection locations are: immediately below bottom liner system (Type 1); within bottom liner system in the protective sand layer (Type 2); within the waste mass (newly placed and older wastes, Types 3 and 4, respectively); within temporary and final cover systems (Types 5 and 6, respectively); and in native soil adjacent to active cells (Type 7). Details of the installations in the six cells at the site are presented in Table 1.

3. RESULTS AND DISCUSSION

Temperature data collection at the site started on March 6, 1999 and has continued on a weekly basis since then. Variations of temperatures with time for bottom liner systems, waste masses, and cover systems are presented in Figures 2-6. In addition to the temperatures measured in a particular landfill component, air temperatures are also presented on each plot. Actual air temperatures are provided for figures with relatively small number of data points (Figures 2 and 6) whereas sinusoidal representations of actual air temperatures are presented for figures with large number of data points to improve clarity in the figures (e.g. Figure 3). Dates for waste placement are indicated on the figures for new cells (e.g. Figure 3). Distances associated with sensors (with reference to the monitoring boxes) are provided on the figures. Temperature measurements in soils at the perimeter of the site indicate that the subgrade in the vicinity of the facility has not yet been significantly affected by the presence of the facility.

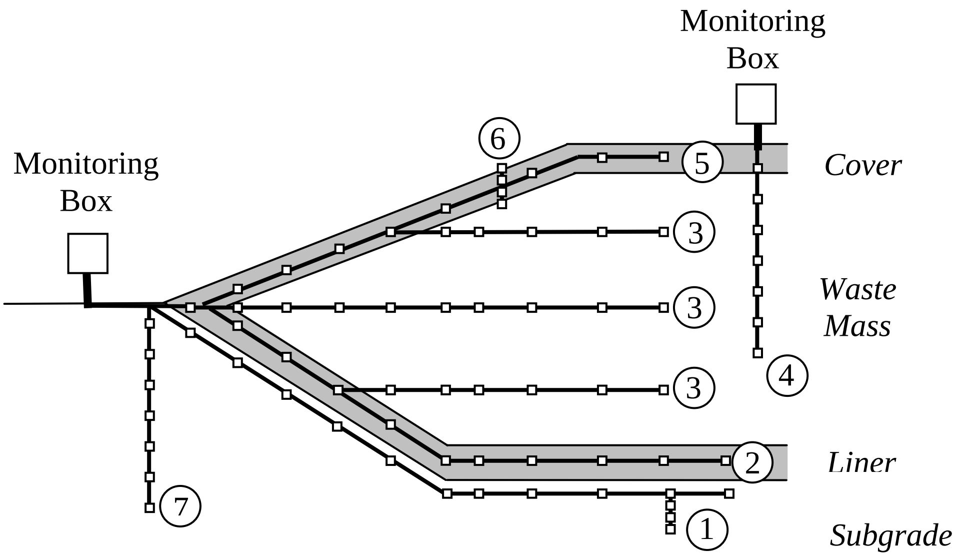

Figure 1. Types of sensor arrays.

Temperature trends below (BL) and within (L) the bottom liner system for Cell D are presented in Figure 2. Data from two locations near the edge of the cell (15 m) and near the center of the cell (186 m) are presented in Figure 2a. Temperatures for a vertical profile below the liner system are provided for a location approximately 95 m away from the edge of the cell in Figure 2b. The liner system was in place for approximately 15 months prior to the start of waste placement in the cell. It is observed that the magnitude and variation of below and above liner temperatures are generally similar to seasonal air temperatures with liner temperatures being typically slightly higher (3 to 5 °C on average) than air temperatures in winter months prior to waste placement in the cell (Figure 2a). The average of the thermal gradients across the liner system is 9.7 °C/m (absolute value) with a typical range of -23.3 (upward heat flow) to +13.3 °C/m (downward heat flow). The majority of the gradient data indicated upward heat flow from below liner to within liner sensors prior to waste placement. The data indicate a phase lag of

Table 1 - Summary of temperature sensors at the landfill

Installation	Type	Date of Installation	Temperature Sensors	Length of Array (m)	Comments
Cell J Liner	2	3/6/1999	10	183	New cell
Cell B Waste 1	4	8/7/1999	17	17	Old waste
Cell J Clay North	7	8/23/1999	4	5	Subgrade
Cell J Clay South	7	8/23/1999	12	12	Subgrade
Cell L Waste	4	8/23/1999	11	20	Old waste
Cell J/L Interface	2	9/30/1999	9	166	New waste
Cell I Liner	2	11/5/1999	21	169	New cell
Cell I Waste Mass	3	3/25/2000	9	163	New waste
Cell B Waste 2	4	1/16/2001	12	28	Old waste
Cell J Midheight	5	5/23/2001	8	213	Interim cover
Cell D Below Liner	1	9/8/2001	12	186	New cell
Cell D Liner	2	12/18/2001	8	186	New cell
Cell J Waste 1	4	5/29/2002	10	27	New Waste
Cell J Waste 2	4	5/30/2002	13	28	New Waste
Cell J Cover Profile	6	12/16/2002	12	11	Final cover
Cell A Cover Profile	6	12/16/2002	14	13	Final cover
Cell D Low Waste	3	3/29/2003	9	185	New Waste

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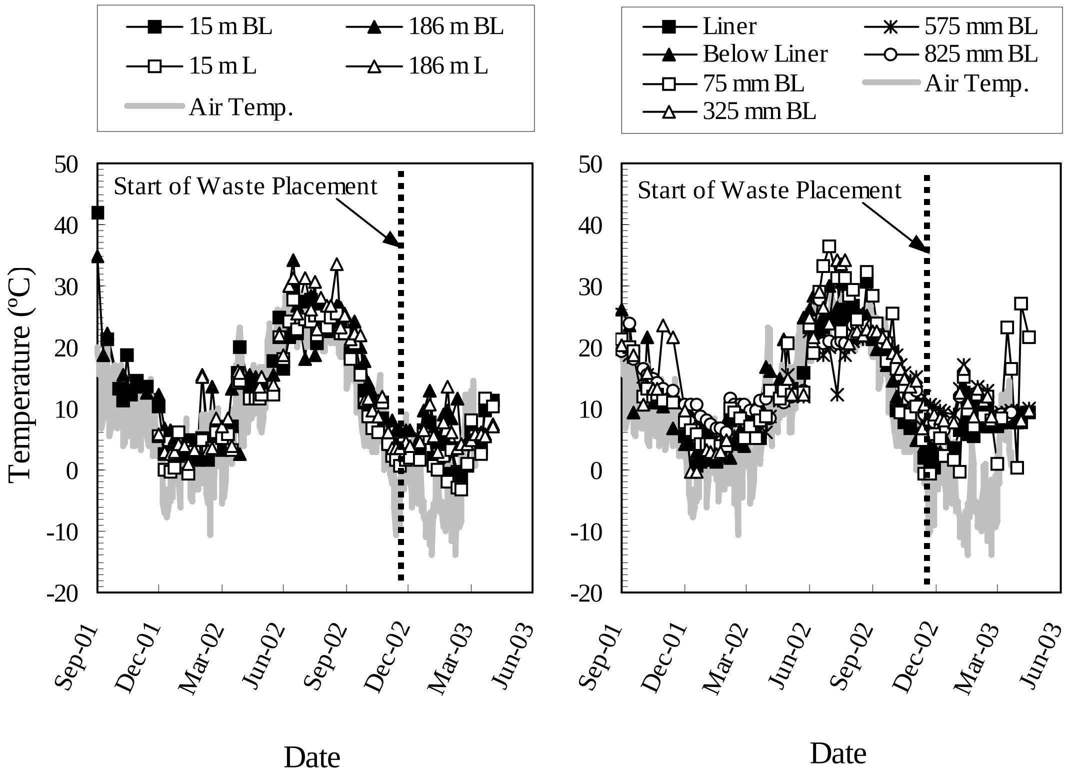

(a) (b)

Figure 2. Bottom liner temperatures in Cell D.

approximately 35 days and an amplitude decrement of approximately 6 to 9 °C across the sensor array (Liner to 825 mm BL) prior to waste placement (Figure 2b). Temperatures in the liner started increasing due to the placement of the first lift of waste (approximately 4.5 m depth).

Temperatures in the bottom liner systems of Cells J and I are presented in Figure 3 for locations from the edge to near the center of the cells. Waste placement in these cells started shortly after construction of the liner systems. It is observed that the temperatures near the edge of the cells are undergoing fluctuations similar to seasonal air temperature fluctuations, whereas the temperatures near the center are relatively steady demonstrating increasing trends. Temperatures have reached 30 °C at liner locations near the center of Cell J under approximately 4-year-old waste, corresponding to 44 m of average waste height. Temperatures have reached 21 °C at liner locations near the center of Cell I under approximately 3-year-old waste, corresponding to 31 m of average waste height. Waste is placed in constant height lifts that cover the entire base area of a cell at the site. Such a lift generally has an accumulated constant thickness of 4.5 m and is placed over a duration of approximately 40 days. Seasonal temperature fluctuations in the liner systems are dampened significantly due to the placement of the first constant waste height of 4.5 m over the liner system, except at the edge of a cell.

Data from sensors placed horizontally in the relatively newly placed waste mass in Cell I are presented in Figure 4. The sensor array is underlain by 9.3 m of waste and overlain by 5 m (near the edge of the cell) to 27 m of waste (near the center of the cell). The temperatures near the edge of the cell are similar to seasonal air temperatures, whereas the temperatures near the center are relatively steady demonstrating increasing trends (temperatures reached in excess of 40 °C). The age of the wastes in the vicinity of 5 to 41 m sensors is approximately 3 years old. It is believed that sensors from 72 m to 163 m are near the vicinity of the old waste relocated in the cell. Initial temperatures at these sensors are relatively high (in excess of 30 °C) even though the installation was made in March. The temperatures at 72 m and 102 m sensors decrease initially

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as they are potentially affected by the nearby new waste, whereas the temperatures at 133 m and 163 m sensors continue to increase under the effects of the old waste as well as potentially due to the high waste depth over these sensors. The temperatures at these sensors are overall approximately 10 °C higher than the remaining sensors.

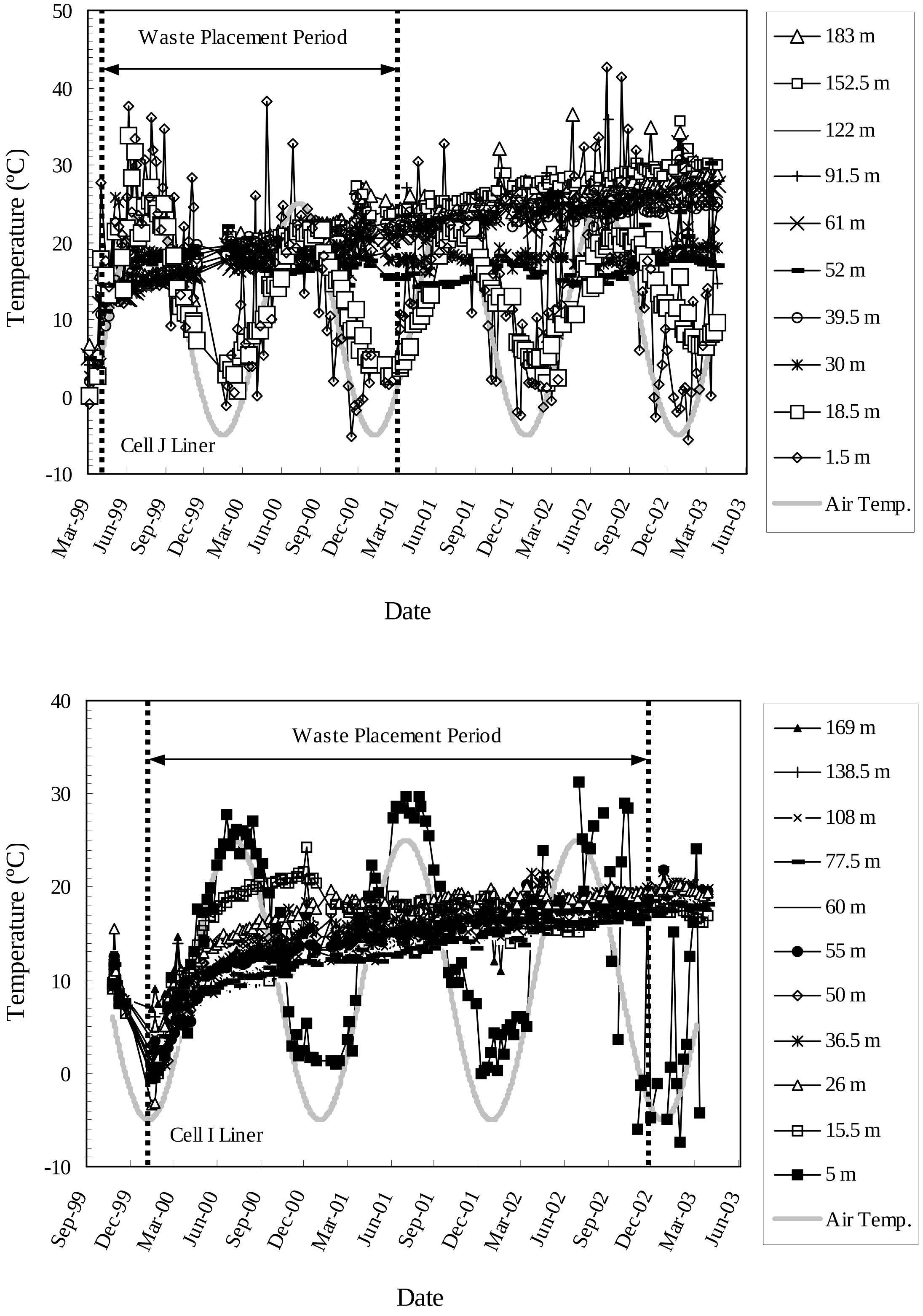

Figure 3. Bottom liner temperatures in Cells J and I.

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The seasonal variations in temperatures decreased significantly within approximately 12 to 21 m from the edge of a cell under corresponding maximum waste heights of 7 to 16 m (Figures 3 and 4). The rate of temperature increase in the liner systems subsequent to waste placement is 2.6 °C/a (obtained using linear regression of data in Figure 3). The rate of temperature increase in the waste mass is 4.0 °C/a (obtained using linear regression of data in Figure 4).

Temperature trends obtained for waste mass with depth using vertical installations (Type 4) are presented in Figure 5. It is observed that seasonal variations affect the temperatures of wastes at shallow depths (up to 8 m depth) to varying degrees. Steady elevated temperatures are measured at greater depths in the waste mass. Temperatures range from 35 to 50 °C for 9-year-old waste (Cell L); from 35 to 56 °C for 6 to 7 year-old waste (Cell B); and from 33 to 60 °C for 2 to 3-year-old waste (Cell J). The average thermal gradient between 8 and 17 m depth (regions not significantly affected by seasonal variations) in Cell B is 2.9 °C/m. The average thermal gradient between 3 and 20 m depth in Cell L is 1.5 °C/m. The average thermal gradient between 12 and 28 m depth in Cell J is 0.4 °C/m. The medium age wastes (Cell B) are demonstrating the highest gradients, which may indicate significant biological activity in the waste. In addition, it is observed that the rate of temperature increase is low in Cells B and L (negligible rates) that contain older wastes compared to the increase rate in Cell J (average rate is 16.1 °C/a) that contains relatively new wastes. The presence of the old waste in Cell J may have resulted in the rapid increase of the temperatures in the waste mass.

Active leachate recirculation was used at the site between 1994 and 2002 in all cells except for Cell L. Leachate recirculation rates up to 120 m^3/day were reported for a single cell. Even though acute effects of leachate recirculation are not observed in the data, the temperatures within the waste masses in Cells B and J are generally 5 to 10 °C higher than the temperatures within the waste mass in Cell L. Rainfall is the main source of leachate generation in the waste mass. Overall, effects of normal seasonal precipitation or the effects of major rain events (or dry periods) were not readily identified in the data. Such effects may be identified using comparisons to data from landfills located in additional climatic regions.

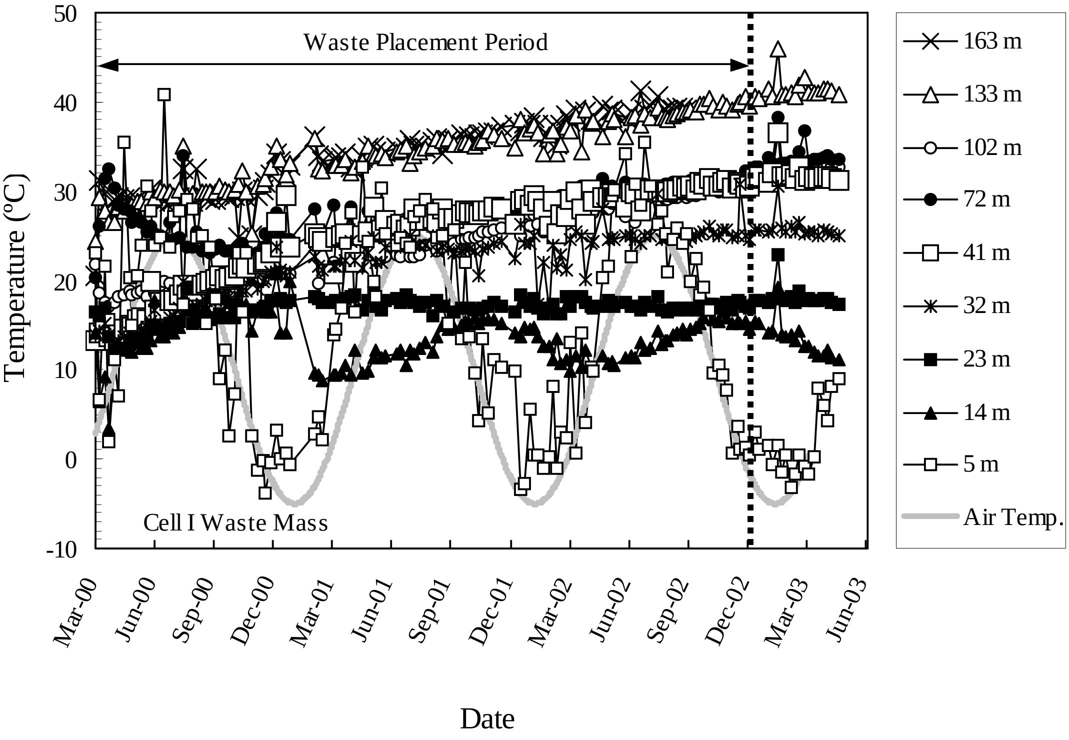

Figure 4. Waste mass temperatures in Cell I.

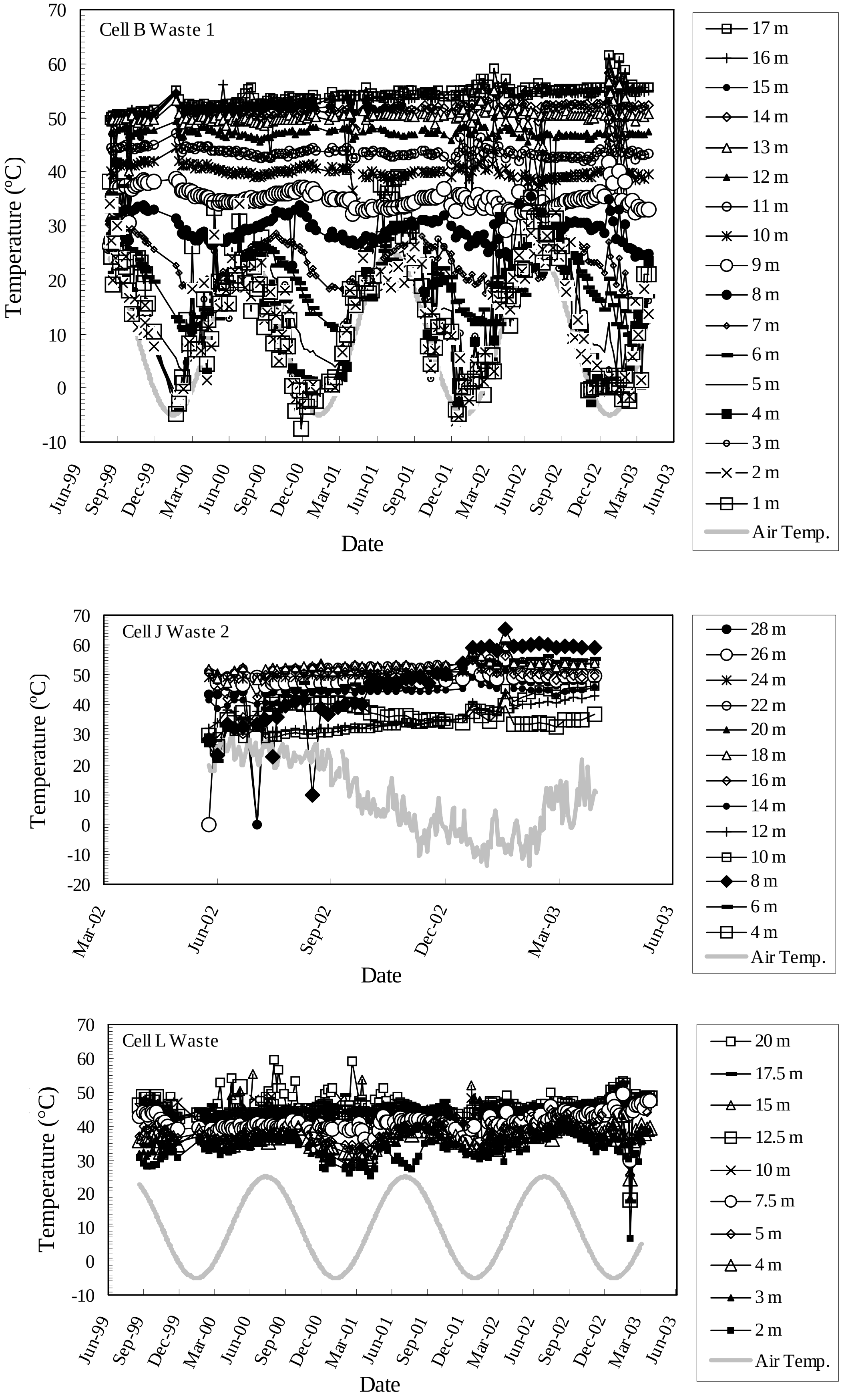

Figure 5. Variation of temperatures with depth in waste.

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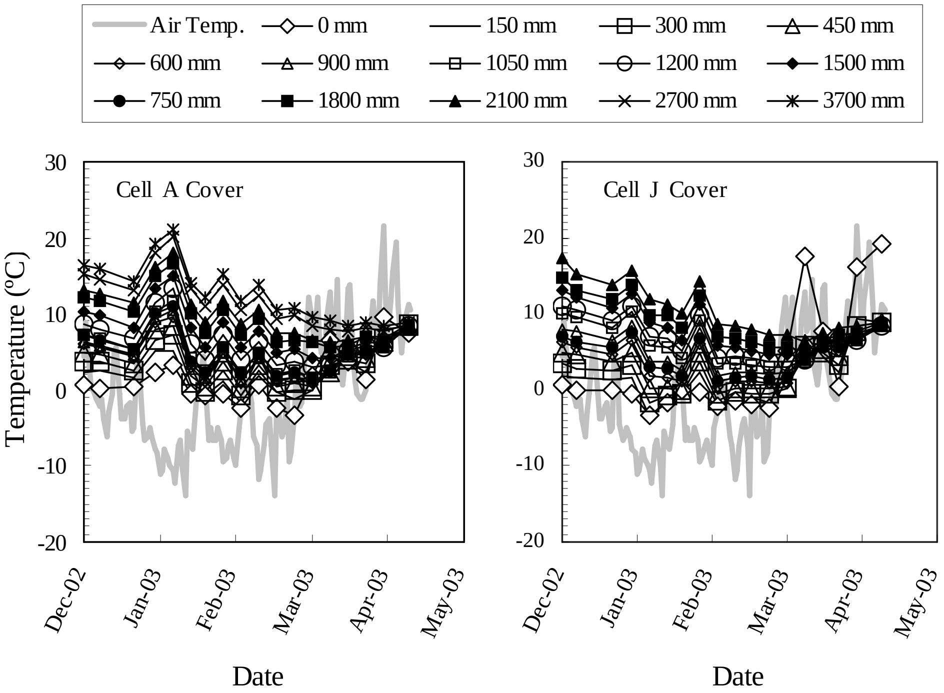

Figure 6. Vertical temperature profiles within and near cover systems in Cells A and J.

While not reported in this paper, landfill gas data is also obtained in all of the cells instrumented for temperature measurements. These data indicate that oxygen levels decrease and carbon dioxide and methane levels increase within 2 to 9 months of waste placement near the sensor locations in liner systems. Anaerobic conditions are also observed for the waste masses in Cells B, I, J, and L. Therefore, the elevated temperatures obtained at the site are predominantly associated with anaerobic conditions near the sensor locations with relatively low increases occurring in the temperatures in the liner systems over the short periods prior to onset of anaerobic conditions.

Temperature trends for cover liner systems are presented in Figure 6. Data is obtained for vertical profiles through the cover system and the underlying waste in Cells A and J. These installations have been in place for 5 months. Seasonal variation is evident in the temperature profiles. For the period monitored (winter months), the ground surface (0 mm) is the coldest location of the profile. Temperatures consistently increase with depth below the ground surface. Maximum temperature differences up to 15 °C are observed for the winter months between the top (0 mm) and the bottom of the liner system (1200 mm). The temperature difference between the ground surface and deeper locations is decreasing as the warmer seasonal temperatures commence. A phase lag of temperature variation is present with depth.

4. CONCLUSIONS

The conclusions provided below are drawn based on long term monitoring of temperatures within various components of a municipal solid waste landfill:

- Temperatures within and below an exposed bottom liner system are generally similar to seasonal air temperatures with slightly higher (3-5 °C) values in winter. A 450-mm-thick protective sand layer does not prevent seasonal air temperature fluctuations in the liner system. Temperatures in cover systems are also generally similar to seasonal air temperatures with up to 10 °C higher values immediately below the cover system in winter.

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- Waste temperatures at locations near the edge of cells (up to 20 m away from the edge) and at shallow depths (up to 8 m depth) undergo fluctuations similar to seasonal air temperature fluctuations, whereas the temperatures at central locations and at great depth are relatively steady. Seasonal temperature fluctuations dampen significantly due to the placement of the first constant waste height of 4.5 m over the measurement locations.
- Temperatures in excess of 30 °C and 60 °C have been measured in liner systems and waste masses, respectively. The rate of temperature increase in the liner systems is 2.6 °C/a subsequent to waste placement and the rate of temperature increase in the waste mass is 4.0 °C/a for newly placed wastes. The rate of temperature increase is higher for new wastes compared to old wastes.

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