ABSTRACT: Cover temperatures were measured at four MSW landfills located in different climatic regions in North America: Michigan, New Mexico, Alaska, and British Columbia. Temperature measurements were made on a weekly basis throughout the depth of the cover profiles extending from the surface into the top layers of the underlying wastes. Bias was produced in the surface temperature data due to the combined effects of the time of day that weekly surface measurements were taken and the high diurnal variations at the surface. Analytical methods were used to obtain representative surface temperature functions for the covers from experimental data. Mean cover surface temperatures were estimated by extrapolating near-surface temperatures using exponential functions and by interpolating between air and below-surface cover temperatures using weighting factors. Surface temperature amplitudes were estimated by extrapolating near-surface amplitudes using conventional earth temperature theory. Analysis of data indicated that mean cover surface temperatures and cover temperature amplitudes can also be obtained directly from temperature measurements at 150 to 300 mm depth, when such data are available. Surface parameters obtained in this study can be used at other sites with similar climatic conditions for thermal analysis of cover systems.

INTRODUCTION

Temperatures influence the engineering properties of geomaterials. Temperature extremes and thermal cycles affect the integrity and durability of earthen and geosynthetic components of waste containment barrier systems as well as the properties of wastes (Lamothe and Edgers 1993, Rowe 2005). Determination and prediction of thermal conditions within landfill systems are required to evaluate the performance of landfill facilities. Several investigators reported methods for modeling heat transfer in landfill systems. These investigators generally used simplistic surface boundary conditions, e.g., a constant temperature (El Fadel et al. 1996, Yoshida et al. 1997). The use of more sophisticated (cyclic) boundary models would allow for representative modeling of near-surface temperatures, near-surface thermal gradients, and frost depths.

The mechanisms for heat transfer at the ground/air interface are complicated and determination of representative ground surface temperatures is highly involved. Heat
transfer at the surface occurs due to radiation, conduction, and convection. Surface temperatures depend on ground cover, highly localized climatic conditions, and the resulting heat flux (Pikul 1991). At the surface, the effects of convection and radiation are significant. Dramatic and rapid changes in ground surface temperature are common. Determination of soil surface temperatures requires measurement of parameters for reflected and incident short wave radiation, aerodynamic resistance, friction velocity, distribution of wind speed with distance above ground surface, relative humidity, and accumulated net radiation since the last rain, in addition to measurement of temperatures (Pikul 1991). The presence of heat generation due to decomposition of underlying wastes (Yesiller et al. 2005) further complicates determination of landfill surface temperatures.

Alternatively, ground surface temperatures can be estimated using conventional earth temperature theory (Carslaw and Jaeger 1959). The theory is generally well established with provisions for coverage of seasonal ground surface temperature cycles; amplitude decrement and phase lag with depth; frost depths; and layered systems. Analytical solutions are available for thermal analysis under seasonally cyclic ground surface temperature conditions (ORNL 1981).

The authors have measured temperatures in cover systems for 2 to 3 years at four municipal solid waste landfills located in North America: Michigan, New Mexico, Alaska, and British Columbia (Yesiller et al. 2008). Temperature measurements were made on a weekly basis throughout the depth of the cover system profiles extending from the surface into the top layers of the underlying wastes. Large daily temperature cycles at the surface combined with the time of day that the weekly surface temperature measurements were taken produced bias in the surface temperature data. In addition, parameters such as wind speed, relative humidity, etc. described above were not included in determination of surface temperatures in the study program. An example of measured cover temperature profile extending from the surface into the waste mass is presented in Fig. 1. A well-defined exponential envelope was observed below the surface. However, the surface temperatures deviate significantly from the envelope and are biased towards high temperatures.

![Fig. 1. Example of Measured Cover Temperatures with Depth](image)
Use of a biased surface temperature function similar to the example in Fig. 1 for heat transfer modeling would result in errors in prediction of below surface thermal conditions (e.g., temperatures, gradients, frost depths). This investigation was conducted to obtain representative surface temperatures and thermal boundary conditions for covers using analytical approaches and experimental data. Data from a total of 13 arrays from the four sites were used. Landfill cover mean surface temperatures \( T_{ms} \) and cover surface temperature amplitudes \( A_s \) were determined. Recommendations are provided for estimating cover surface temperature parameters for other sites.

**LANDFILL SURFACE TEMPERATURES**

### Mean Surface Temperature

Mean cover surface temperatures were estimated by extrapolating below surface temperatures to the surface at the study sites. The below surface mean temperatures were extended to the surface using exponential extrapolations (Eq. 1). An example of near surface data with closely spaced temperature sensors and the exponential curve fit is presented in Fig. 2. The exponential curve fits are unable to provide representative mean surface temperatures for cases with less than 3 temperature measurement locations below the surface since 3 inputs are required for a unique solution. In addition, the exponential curve fitting method resulted in non-representative mean surface temperatures at one array in Alaska, where an unrealistically low mean surface temperature was extrapolated.

\[
T_{ms} = T_{mz} + b \left( 1 - e^{-cz} \right)
\]  

(1)

where \( T_{mz} \) is the mean temperature (°C) at depth \( z \), \( T_{ms} \) is the mean surface temperature at 0 m depth (°C), \( z \) is depth below surface (m), \( e \) is the base of natural logarithms, and \( b \) (°C) and \( c \) (m\(^{-1}\)) are curve fitting parameters.
Temperature data from sites that contained closely-spaced near-surface sensors were investigated to identify whether data from a single very shallow sensor could be used to directly estimate mean surface temperatures. Comparisons were made between $T_{ms}$ obtained using the exponential extrapolations and mean temperatures obtained at 150, 300, and 450 mm depths. Mean temperatures from 150 and 300 mm depths were within 0.7°C of $T_{ms}$, whereas differences more than 1°C were present between $T_{ms}$ and data from 450 mm depth. In all cases, the estimates for mean surface temperature from individual at-depth data were higher than the $T_{ms}$ obtained from exponential extrapolation.

Further analysis was conducted for cases where near-surface (within 300 mm of surface) data were not directly available or data were only available at one or two below-surface depths. The mean surface temperature was assumed to be between mean air temperature and mean temperature at shallow depths. The mean surface temperatures were determined by using a weighted average of air and below-surface cover temperatures. The weighting factors for this calculation were determined using data from closely-spaced near-surface temperature sensors at the Michigan and British Columbia sites. $T_{ms}$ values for these installations were obtained from the exponential extrapolations. The weighting factors were back-calculated using the mean surface temperature, mean air temperature, and measured mean temperatures at depth (Eq. 2).

$$T_{ms} = \frac{T_{m-air} + T_{ms} W_z}{1 + W_z} \tag{2}$$

where $T_{ms}$ = mean surface temperature (°C), $T_{m-air}$ = mean air temperature (°C), $T_{mz}$ = mean temperature (°C) at depth $z$, and $W_z$ = depth-specific weighting factor. The weighting factors determined in the study are presented in Fig. 3. The magnitude of weighting factors decreased with depth as the relative effect of below surface temperatures on $T_{ms}$ decreased with depth. The weighting factors determined using data from Michigan and British Columbia were applied to the sites in New Mexico and Alaska with limited number of below-surface temperature measurements (Oettle 2008). Mean cover surface temperatures at these sites were estimated using the weighting factors.

Fig. 3. Variation of Weighting Factors with Depth
Surface Temperature Amplitude

Surface temperature amplitudes were determined by extrapolating at depth amplitudes to the surface using conventional earth temperature theory (ORNL 1981).

\[ A_z = A_s e^{-az} \]

where \( A_z \) = amplitude of temperature wave (°C) at depth \( z \) (m), \( A_s \) = amplitude of ground surface temperature wave (°C), \( a \) = constant that accounts for envelope curvature (i.e., thermal diffusivity). Amplitudes for depths at which sinusoidal seasonal temperature fluctuations were discernable were used for this analysis (for this study, depths to approximately 4 m).

Temperature data from sites that contained closely-spaced near-surface sensors were investigated to identify whether data from very shallow sensors could be used to directly estimate surface amplitudes. Comparisons were made between \( A_s \) obtained using the exponential extrapolations and amplitudes obtained at 150, 300, and 450 mm depths. Amplitudes from 150 and 300 mm depths were within 1.0°C of \( A_s \), whereas differences more than 1°C were present between \( A_s \) and data from 450 mm depth. In all cases, the estimates for surface amplitude from at-depth data were lower than the \( A_s \) obtained from conventional earth temperature theory.

Surface Temperature Functions

The mean surface temperatures and surface temperature amplitudes determined in this study are presented in Table 1 for each site. Mean annual earth temperature (at great depth) and mean air temperature are provided for reference. These representative surface parameters can be used for thermal analyses including numerical modeling at sites with similar climatic conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Michigan</th>
<th>New Mexico</th>
<th>Alaska</th>
<th>British Columbia</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{ms} )</td>
<td>11.8</td>
<td>19.8</td>
<td>6.9</td>
<td>13.0</td>
</tr>
<tr>
<td>( A_s )</td>
<td>12.0</td>
<td>12.0</td>
<td>14.3</td>
<td>11.6</td>
</tr>
<tr>
<td>( T_{m-earth} )</td>
<td>11.7</td>
<td>20.0</td>
<td>6.0</td>
<td>11.5</td>
</tr>
<tr>
<td>( T_{m-air} )</td>
<td>9.8</td>
<td>18.2</td>
<td>2.3</td>
<td>9.9</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

Based on the analysis of temperatures in cover systems at landfills located in Michigan, New Mexico, Alaska, and British Columbia, the following conclusions are drawn:

- Direct measurements of cover surface temperatures using periodic monitoring events do not produce representative cover surface temperature functions due to the bias that results from the combined effects of the time of day that periodic surface measurements are taken and the high diurnal variations at the surface. Multi-parameter measurements (e.g., wind speed, solar radiation) are not practical for typical landfill analysis. Therefore, analytical approaches are required to estimate cover surface temperature functions.
- Mean cover surface temperatures can be estimated by extrapolating near-surface temperatures using an exponential function.
- Mean cover surface temperatures can be estimated by interpolating between air temperatures and near-surface temperatures using weighting factors developed in this study. The weighting factors for appropriate corresponding depths can be used to determine $T_{ms}$ when limited below surface data are available.
- Surface temperature amplitude can be estimated by extrapolating near-surface amplitudes using conventional earth temperature theory.
- Mean cover surface temperatures and cover temperature amplitudes can be obtained from direct measurements at 150 to 300 mm depths.
- The surface parameters determined in this study should be representative for sites with similar climatic conditions.

**ACKNOWLEDGEMENT**

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