EXPERT OPINION ON CONDITIONS AT BRIDGETON LANDFILL AND THE SUBSURFACE REACTION

by

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Appendices
1. PERSONAL STATEMENT

- I have prepared this report on behalf of Lathrop and Gage LLP and Bridgeton Landfill LLC.

- This report sets forth my professional opinions regarding conditions at the Bridgeton Landfill relevant to a subsurface reaction that has generated heat and odor. These opinions are expressed to a reasonable degree of scientific and engineering certainty.

- The documents and information I have considered in reaching my opinions are summarized in Sections 9 and 10.

- A list of cases in which I have given testimony in deposition or trial in the last four years is in Section 11.

- An up-to-date copy of my curriculum vitae is in Section 12.

- I have been compensated for my activities related to this matter at $295 per hour.

I declare under penalty of perjury that the information in this report is true and correct to a reasonable degree of scientific and engineering certainty.

Craig H. Benson, PhD, PE, NAE
30 October 2015

2. PROFESSIONAL BACKGROUND RELEVANT TO EXPERT OPINIONS

This report sets forth my professional opinions regarding operations at the Bridgeton Landfill in the context of a subsurface reaction event that was discovered around 1 January 2011 and has generated atypical heat and odor. My professional opinions focus on:

- Whether data from the gas and leachate collection systems provided insight that a subsurface reaction was likely to occur, and

- Whether oxygen intrusion through defects in the cover soils or through the subsurface periphery of the disposal unit caused reaction conditions that would result in elevated temperatures.

My opinions in this report are based on industry standards and are stated to a reasonable degree of scientific and engineering certainty.
My opinions are based on my education, including a PhD in engineering with a focus on landfills and waste containment systems. I have 30 years of experience in engineering research and practice related to municipal solid waste (MSW) landfills and solid waste containment systems. I am a Wisconsin Distinguished Professor of engineering at the University of Wisconsin-Madison and as Dean of the School of Engineering and Applied Science and Hamilton Endowed Chair in Civil and Environmental Engineering at the University of Virginia. I have publicly available scientific literature, documents on the websites operated by the State of Missouri Department of Natural Resources and Bridgeton Landfill LLC, and documents made available to me by Lathrop and Gage LLP and Bridgeton Landfill LLC.

My opinions reflect my experience working on landfills and waste containment systems for a diversity of waste streams at locations throughout the United States, Canada, South America, Europe, Africa, Japan, Australia, and New Zealand. This experience has provided me with a broad and detailed knowledge of operational and design issues for landfills. For example, one of my recent projects dealt with an independent assessment of the Wisconsin Organic Stability Rule, which required evaluation of landfill design and operations at MSW landfills throughout Wisconsin. Gas collection was a central theme at landfills evaluated in the assessment of the Wisconsin Organic Stability Rule. Most recently, I have appointed by the Environmental Research and Education Foundation as Principal Investigator of an expert team of engineers and scientists charged with understanding the mechanisms underlying landfills with unexpectedly high temperatures, developing strategies to prevent elevated temperatures, and evaluating methods to remediate landfills where elevated temperatures are present. As part of my practice, I have had the opportunity to serve in an expert engineering capacity on the four most prominent landfill sites in the US with elevated temperatures: Congress Development Company Landfill in Hillside, Illinois; Countywide Landfill in Stark County, Ohio; Middle Point Landfill in Murfreesboro, Tennessee; and Bridgeton Landfill in Bridgeton, Missouri (this project). My work on the Congress Development Company Landfill was part of the “Area 3 – Expanded Heat and Pressure Investigation,” which focused on identifying the source of heat as well as strategies to address the heat and related problems.

My expertise in waste containment systems, and my impact on the field, was cited when I was inducted into the United States National Academy of Engineering. Knowledge gained from my

1http://dnr.mo.gov/bridgeton/
2http://www.bridgetonlandfill.com
past research and practice was fundamental in reviewing, organizing, and interpreting the information associated with this case.

I was given free and unfettered access to review documents when forming my opinions. At no point was I restricted to specific documents, directed not to review documents, or otherwise precluded from reviewing particular documents. Consequently, this report reflects my views as a professional, and may not necessarily reflect the views of Lathrop and Gage LLP or Bridgeton Landfill LLC.

3. BRIDGETON LANDFILL

3.1 Description. The Bridgeton landfill in Bridgeton, Missouri was permitted to accept municipal solid waste (MSW) in 1985 and accepted waste until 2005. The landfill is located in a quarry formerly used as a source of limestone, and is comprised of two major areas, the North Quarry Area and the South Quarry Area (Fig. 1). A related site with debris containing radionuclides is also on the Bridgeton Landfill property, but is not within the scope of this report. The South Area is larger and has slightly greater maximum depth of waste ($\approx 320$ ft) than the North Area. This report focuses on the South Area.

The South and North Areas are unlined “inward gradient” disposal facilities. Vertical leachate extraction wells are used to withdraw leachate from the disposal area. The intent is to lower the potentiometric surface within the landfill below that in the surrounding geological environment, thereby drawing groundwater into the facility and preventing outward migration of contaminants. Leachate extracted from the leachate extraction wells undergoes primary treatment on-site and final treatment at a publically owned treatment works.

Installation and operation of the active gas system began in the 1990s, and the system has been augmented periodically since then. Vertical gas collection wells, conceptually similar to the well shown in Fig. 2, are employed to extract gas within the waste. Gas collected from the wells is flared. Gas temperature and composition are monitored at the wellheads, in leachate extraction wells, and at the flare.

An earthen final cover required by regulation was constructed over a 34.6-acre section of the landfill in 2006. This cover consisted of a 2-ft-thick barrier layer with a saturated hydraulic conductivity no more than $1\times10^{-5}$ cm/s overlain by a 1-ft-thick vegetated soil layer (Aquaterra 2006). A 4.5-acre section of the landfill (referred to colloquially as the amphitheater
Fig. 1. Areal view and cross-section A-A’ of Bridgeton Landfill.
Fig. 2. Schematic of vertical gas extraction well (a) and technician monitoring landfill gas at the wellhead (b).
area) was covered with a high-density polyethylene (HDPE) geomembrane in 2012-13. Additional exposed geomembrane cover was installed over the entire South Area in August 2013 and over a portion of the North Area in December 2014. The additional geomembrane cover employed a new EVOH geomembrane that is more resistant to transmission of odiferous compounds in landfill gas (Eun et al. 2015).

3.2 Closed Landfill Evaluation. Evaluating a closed landfill is fundamentally different from an operating landfill that is receiving waste. Because the landfill envelope is closed, conditions within the landfill are interpreted and evaluated using data collected from emission controls (gas collection system, leachate collection system), the physical condition of the exterior of the landfill, and the groundwater monitoring system. Managing a closed landfill, with or without permanent final cover, generally consists of collecting and treating landfill gas and leachate, maintaining surface water controls and erosion, monitoring physical stability, and monitoring groundwater quality. Conditions within the landfill are interpreted based on flow rates and chemical characteristics of the landfill gas and leachate streams, settlement of the landfill surface, and compliance with groundwater quality criteria.

3.3 Landfill Leachate. Leachate is water within a landfill that contains dissolved and suspended constituents derived from the waste. Some of these constituents are leached from the waste mass and others are generated via microbial decomposition processes. Major indicator parameters used to characterize leachate include biological oxygen demand (BOD), chemical oxygen demand (COD), pH, specific conductance or electrical conductivity, and total suspended solids.

BOD describes the amount of oxygen needed by aerobic biological organisms to degrade organic material present in water at standard temperature. COD is the oxygen equivalent of organic matter in water that is susceptible to oxidation by a strong chemical oxidant. The ratio BOD/COD is used as an indicator of decomposition. pH is a measure of acidity or alkalinity of leachate, and specific conductance is measure of the amount of dissolved charged matter in the leachate. Specific conductance is a measure of ionic strength of the water, or colloquially the total concentration of charged dissolved constituents. Suspended solids consist of the non-dissolved inorganic and organic solids suspended, but not dissolved, in leachate.

Changes in BOD, COD, pH, specific conductance, and/or total suspended soils in leachate reflect a change in the chemical characteristics of the waste. Tracking these parameters
provides an understanding of the state of decomposition of the MSW, biochemical changes occurring within the landfill that may affect behavior, and the type of treatment needed before the leachate can be discharged.

3.4 Landfill Gas. Landfill gas is generated as organic materials within the waste mass of a MSW landfill degrade in response to microbial activity. Landfill gas is a byproduct of decomposition. Biodegradation occurs in response to aerobic and anaerobic microbes depending on the availability of oxygen within the waste. In nearly all MSW landfills, however, oxygen within the waste is quickly consumed and exhausted by aerobic microbes before substantive decomposition occurs. Consequently, anaerobic microbes degrade nearly all of the organic matter in MSW landfills (Bareither et al. 2013).

Cellulose and hemi-cellulose are the predominant degradable organic materials in MSW. Anaerobic degradation of cellulose [(C\(_6\)H\(_{10}\)O\(_5\))\(_n\)] follows the following stoichiometry (Barlaz 2006):

\[
\left(\text{C}_6\text{H}_{10}\text{O}_5\right)_n + n\text{H}_2\text{O} \rightarrow 3n\text{CO}_2 + 3n\text{CH}_4
\]  

Equations 1 and 2 indicate that degradation of cellulose and hemi-cellulose in MSW results in a gas comprised of equal amounts of CO\(_2\) and CH\(_4\). Landfill gas also contains other non-methane organic compounds (NMOCs) derived from other processes such as volatilization of organic compounds within the waste, byproducts of sulfate reducing bacteria such as hydrogen sulfide (H\(_2\)S), siloxanes, etc. (Thomas and Barlaz 1998). For practical purposes, landfill gas can be considered to be roughly half CO\(_2\) and half CH\(_4\). In practice, each fraction will vary from 35-65% of the gas stream in a MSW landfill that is operating normally with methanogenic decomposition. Other “balance” gases will also present, with the sum of the gas fractions adding to 100% (LMOP 2015).
The rate of landfill production of methane gas (G) normally is predicted by the first-order rate expression:

\[ G = W L_0 k \exp(-kt) \]

where \( W \) is waste acceptance rate, \( L_0 \) is the methane generating potential per unit waste mass, \( k \) is the decay rate, and \( t \) is time (Benson et al. 2007, Barlaz et al. 2010). Computer models based on Eq. 3, such as the US Environmental Protection Agency’s LandGEM, are used by engineers in conjunction with realistic estimates for \( k \) and \( L_0 \) to predict the rate of gas generation when designing gas collection and treatment systems (Wang et al. 2013). Heat is also generated from the anaerobic microbial activity.

Data collected from gas wells are used to interpret conditions within the landfill. Wellhead temperatures and gas composition are monitored to ensure that conditions within the waste are suitable for methanogenic bacteria and that unsuitable reactions are not occurring. Landfills operating under methanogenic conditions typically will have landfill gas temperatures in the range of 85 to 140 °F (LMOP 2015). At temperatures much greater than this range, methanogenic bacteria cannot exist and the landfill gas will no longer follow the stoichiometry in Eqs. 1 and 2. For example, if oxygen is drawn into the waste by the gas collection system, aerobic biodegradation can be initiated, which generates higher temperatures and, in some cases, combustion will occur. Elevated temperatures and elevated oxygen content can be indicative of aerobic conditions, and carbon monoxide (CO) concentrations in excess of 1000 ppm, combined with smoke and light can be indicative of combustion (e.g., Thalhamer 2015). For this reason, most regulations require that gas wellhead temperatures be maintained below 131 °F, the oxygen content be less than 5%, and the CO in the landfill gas be less than 1000 ppm.

In the last several years, the landfill industry has recognized that conditions exist in some landfills that promote heat that results in temperatures far in excess of 131 °F without the presence of oxygen, aerobic microbial communities, unusual reactive wastes, and/or combustion. The reactions responsible for generating the heat and elevated temperature are unknown at this time, but field data indicate that there is a reaction initiation temperature beyond which the rate of the reaction increases. Energy associated with the heat generated by these reactions appears to promote spatial propagation of the reaction throughout a landfill. The Environmental Research and Education Foundation (EREF) has commissioned a team of
internationally recognized landfill experts to study and understand these reaction mechanisms so that problems with excessive heat can be avoided or remediated. The author of this report is a member of this expert team.

4. LEACHATE CHARACTERISTICS AT BRIDGETON LANDFILL

The leachate database for Bridgeton Landfill was analyzed to determine if trends in the leachate chemistry were indicative of a forthcoming change in behavior prior to 1 January 2011, when the subsurface reaction at Bridgeton was discovered. Common temporal trends used in landfill operations were evaluated. Data from Outfall 8, representing commingled leachate data before and after 1 January 2011, were used in the analysis.

BOD, COD, and BOD:COD are shown as a function of time in Fig. 3. The BOD and COD are relatively constant throughout 2010 and into 2011. The BOD:COD ratio is also relatively constant, and representative of waste at least 10 yr old (Benson et al. 2007, Barlaz et al. 2010). The pH is also relatively constant over the same period (Fig. 4), and generally within the range of 6-8 that is characteristic of leachate from decomposed refuse. The specific conductance and the total suspended solids are also relatively constant over this same period (Figs. 5 and 6).

In my professional opinion, a landfill technician or engineer reviewing these data for trends indicative of changing behavior would have no basis to foresee or expect the major subsurface reaction event that was discovered around 1 January 2011, or any other event. The absence of trends in the data suggests that the landfill is in a quasi state of equilibrium. In fact, significant changes in these parameters occurred approximately six months after the reaction was discovered, precluding the opportunity for foresight of a major pending catastrophe.

5. LANDFILL GAS CHARACTERISTICS AT BRIDGETON LANDFILL

5.1 Gas Temperature. Data in the Bridgeton Landfill gas database were analyzed to determine if trends in the gas temperature or composition were indicative of a forthcoming change in behavior prior to 1 January 2011, when the subsurface reaction at Bridgeton was discovered. All of the data used in the analysis were obtained from the database. Visual and statistical trend analyses were conducted on temperature data from each well to evaluate whether a landfill technician or engineer reviewing these data for trends indicative of changing behavior would have foreseen or expected the major subsurface reaction event that was discovered around
Fig. 3. BOD and COD (a) and BOD/COD ratio (b) of leachate as a function of time. Vertical lines mark acknowledged start of reaction and two years later, just before significant changes in the reaction occurred.
Fig. 4. pH of leachate as a function of time.
Fig. 5. Specific conductance of leachate as a function of time.
Fig. 6. Total suspended solids in leachate as a function of time.
1 January 2011. Statistical trend analysis was conducted regressing temperature on time and evaluating whether the slope of the regression analysis was statistically different from zero using a significance level of 0.05, as described in Benson et al. (1994). Trends were classified as increasing, decreasing, or none (no trend) for data collected prior to 2010 (historic perspective on well performance) and during 2010 (near term performance relative to subsurface reaction discovered around 1 January 2011). A summary of the analyses is in Table 1.

Typical trends in wellhead temperature are shown in Fig. 7. The upper graph is an example of no trend prior to 2010 or during 2010. The middle graph represents an increasing trend prior to 2010 corresponding to the normal climb of gas well temperature as the methanogenic microbial community evolves. The middle graph also shows no trend during 2010, indicating a steady condition. The bottom graph represents a decreasing trend prior to 2010 as the gas well cooled, followed by an upward trend as the methanogenic microbial community evolves.

Of the 59 wells in the South Area installed prior to 2010, 10 wells exhibited an increasing temperature trend prior to 2010. The other 49 wells demonstrated no trend or a decrease in temperature prior to 2010. Seven of the 10 wells with increasing temperature were undergoing a normal temperature climb as the microbial community evolved. Two exhibited a very gradual increase in temperature and remained well below 131 °F, and one well exhibited a very gradual increase in temperature, with temperature above 131 °F from the first measurement (near time of installation). That is, only one well (1.7% of wellfield) provided any potential indication of forthcoming problem. In my professional opinion, a landfill technician or engineer reviewing these data for trends indicative of changing behavior would not have expected a major subsurface reaction, or any other significant event, with such a small fraction of the wellfield exhibiting elevated temperature with an upward trend. In fact, even the one well that was elevated was not behaving in an unusual manner – the temperature had been climbing at a relatively slow and constant rate for years.

The analysis of data in 2010, just prior to the subsurface reaction, showed that 18 of 59 wells had increasing temperature. Of these wells, 10 were undergoing a normal climb in temperature (3 were installed in the third quarter 2009). The other five exhibited a very gradual trend of increasing temperature. That is, 8.5% of the well field was exhibiting a gradual increase in temperature. Moreover, five wells in the wellfield (12, 13, 19, 20, and 67) had exhibited temperatures close to or exceeding the 131 °F threshold for years with no significant ramifications (four with no trend).
Table 1. Evaluation of temperature trends in gas well heads at Bridgeton Landfill.

<table>
<thead>
<tr>
<th>Well No.</th>
<th>Temperature Trend Prior to 2010</th>
<th>Temperature Trend During 2010</th>
<th>Abrupt Rise</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>None</td>
<td>Decreasing</td>
<td>-</td>
<td>Slight decrease during 2010</td>
</tr>
<tr>
<td>11</td>
<td>Decreasing</td>
<td>None</td>
<td>3/12</td>
<td>&lt; 131 in 2007</td>
</tr>
<tr>
<td>12</td>
<td>None</td>
<td>None</td>
<td>9/11</td>
<td>&gt; 131 F entire record</td>
</tr>
<tr>
<td>13</td>
<td>Decreasing</td>
<td>Decreasing</td>
<td>1/11</td>
<td>&gt; 131 F from start of record</td>
</tr>
<tr>
<td>14</td>
<td>None</td>
<td>None</td>
<td>3/13</td>
<td>Slight increase 1/11, major change 1/14</td>
</tr>
<tr>
<td>15</td>
<td>None</td>
<td>Decreasing</td>
<td>1/14</td>
<td>&lt;&lt; 131 thru 2010</td>
</tr>
<tr>
<td>16</td>
<td>None</td>
<td>Increasing</td>
<td>1/11</td>
<td>Normal climb thru 2010</td>
</tr>
<tr>
<td>17</td>
<td>None</td>
<td>None</td>
<td>2/13</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>None</td>
<td>None</td>
<td>2/13</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>None</td>
<td>None</td>
<td>-</td>
<td>&gt; 131 F entire record, stable to mid-2012</td>
</tr>
<tr>
<td>20</td>
<td>None</td>
<td>None</td>
<td>9/15</td>
<td>Near 131 F to late 2012, then oscillates</td>
</tr>
<tr>
<td>21</td>
<td>Increasing</td>
<td>None</td>
<td>2/12</td>
<td>Normal climb thru 2010</td>
</tr>
<tr>
<td>22</td>
<td>None</td>
<td>None</td>
<td>6/13</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>None</td>
<td>None</td>
<td>2/14</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Decreasing</td>
<td>None</td>
<td>1/15</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>None</td>
<td>Increasing</td>
<td>6/13</td>
<td>Slight increase in 2010, &lt; 131 F</td>
</tr>
<tr>
<td>26</td>
<td>Decreasing</td>
<td>None</td>
<td>1/12</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Increasing</td>
<td>None</td>
<td>6/12</td>
<td>Normal climb thru 2010</td>
</tr>
<tr>
<td>28</td>
<td>None</td>
<td>None</td>
<td>1/15</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>None</td>
<td>Increasing</td>
<td>2/14</td>
<td>Normal climb thru 2010</td>
</tr>
<tr>
<td>30</td>
<td>None</td>
<td>None</td>
<td>1/11</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>None</td>
<td>None</td>
<td>9/11</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>None</td>
<td>Increasing</td>
<td>1/11</td>
<td>Slight rise through 2010, but &lt;&lt; 131 F</td>
</tr>
<tr>
<td>33</td>
<td>None</td>
<td>Increasing</td>
<td>2/12</td>
<td>Very slight increase in 2010, near 131 F</td>
</tr>
<tr>
<td>34</td>
<td>None</td>
<td>None</td>
<td>10/14</td>
<td></td>
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<tr>
<td>35</td>
<td>None</td>
<td>None</td>
<td>3/12</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>None</td>
<td>Increasing</td>
<td>2/12</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>Increasing</td>
<td>None</td>
<td>12/12</td>
<td>Normal climb thru 2010</td>
</tr>
<tr>
<td>38</td>
<td>None</td>
<td>None</td>
<td>3/13</td>
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</tr>
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<td>39</td>
<td>None</td>
<td>None</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>56</td>
<td>None</td>
<td>None</td>
<td>3/12</td>
<td></td>
</tr>
<tr>
<td>57</td>
<td>Increasing</td>
<td>None</td>
<td>9/11</td>
<td>Normal climb thru 2010</td>
</tr>
<tr>
<td>58</td>
<td>None</td>
<td>None</td>
<td>7/12</td>
<td></td>
</tr>
<tr>
<td>59</td>
<td>Increasing</td>
<td>Increasing</td>
<td>6/12</td>
<td>Normal climb thru 2010</td>
</tr>
<tr>
<td>60</td>
<td>Increasing</td>
<td>None</td>
<td>1/11</td>
<td>Normal climb thru 2009, &lt; 131 F</td>
</tr>
<tr>
<td>61</td>
<td>None</td>
<td>None</td>
<td>1/11</td>
<td></td>
</tr>
<tr>
<td>62</td>
<td>None</td>
<td>None</td>
<td>1/11</td>
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</tr>
</tbody>
</table>
### Table 1. Evaluation of temperature trends in gas well heads at Bridgeton Landfill (cont.).

<table>
<thead>
<tr>
<th>Well No.</th>
<th>Temperature Trend Prior to 2010</th>
<th>Temperature Trend During 2010</th>
<th>Abrupt Rise</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
<td>Decreasing</td>
<td>None</td>
<td>2/12</td>
<td>Recovered from cooling in 2010.</td>
</tr>
<tr>
<td>64</td>
<td>Increasing</td>
<td>Increasing</td>
<td>2/12</td>
<td>Very gradual trend, &lt; 131 F</td>
</tr>
<tr>
<td>65</td>
<td>Decreasing</td>
<td>Increasing</td>
<td>1/11</td>
<td>Normal climb thru 2010</td>
</tr>
<tr>
<td>66</td>
<td>None</td>
<td>None</td>
<td>1/11</td>
<td></td>
</tr>
<tr>
<td>67</td>
<td>Increasing</td>
<td>Increasing</td>
<td>1/11</td>
<td>&gt; 131 F entire record, steady rise</td>
</tr>
<tr>
<td>68</td>
<td>Increasing</td>
<td>None</td>
<td>2/13</td>
<td>Slight increase, &lt; 131 F until 3/13</td>
</tr>
<tr>
<td>69</td>
<td>None</td>
<td>None</td>
<td>7/13</td>
<td>&lt; 131 F until 6/12, normal climb 2010-11</td>
</tr>
<tr>
<td>70</td>
<td>Decreasing</td>
<td>Increasing</td>
<td>4/11</td>
<td>Normal climb before 1/2011</td>
</tr>
<tr>
<td>71</td>
<td>Decreasing</td>
<td>None</td>
<td>9/12</td>
<td></td>
</tr>
<tr>
<td>72</td>
<td>None</td>
<td>Increasing</td>
<td>11/12</td>
<td>Slight rise in 2010, &lt; 131 F</td>
</tr>
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<td>73</td>
<td>Increasing</td>
<td>None</td>
<td>7/13</td>
<td>Normal climb in 2008</td>
</tr>
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<td>75</td>
<td>Decreasing</td>
<td>Increasing</td>
<td>5/12</td>
<td>Normal climb to mid 2011</td>
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<td>None</td>
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<td>2/12</td>
<td></td>
</tr>
<tr>
<td>77</td>
<td>None</td>
<td>None</td>
<td>2/12</td>
<td></td>
</tr>
<tr>
<td>78</td>
<td>Decreasing</td>
<td>Increasing</td>
<td>4/13</td>
<td>Normal climb through 2011</td>
</tr>
<tr>
<td>79</td>
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<td>Increasing</td>
<td>9/12</td>
<td>Gradual climb through 2011</td>
</tr>
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<td>None</td>
<td>None</td>
<td>4/13</td>
<td></td>
</tr>
<tr>
<td>81</td>
<td>None</td>
<td>None</td>
<td>9/13</td>
<td></td>
</tr>
<tr>
<td>82</td>
<td>None</td>
<td>None</td>
<td>2/13</td>
<td></td>
</tr>
<tr>
<td>83</td>
<td>No Data</td>
<td>Increasing</td>
<td>4/13</td>
<td>New in late ’09, normal climb &amp; leveling</td>
</tr>
<tr>
<td>84</td>
<td>No Data</td>
<td>Increasing</td>
<td>10/13</td>
<td>New in late ’09, normal climb &amp; leveling</td>
</tr>
<tr>
<td>85</td>
<td>No Data</td>
<td>Increasing</td>
<td>10/14</td>
<td>New in late ’09, normal climb &amp; leveling</td>
</tr>
</tbody>
</table>
Fig. 7. Examples of different trends in gas wellhead temperature as a function of time.
In my professional opinion, a landfill technician or engineer reviewing these data for trends indicative of changing behavior would not have expected a major subsurface reaction, or any other major event, given the modest increases that were occurring over a relatively small fraction of the well field. However, careful observation of the well field would be warranted given the increase in fraction of wells with a trend of increasing temperature. The wealth of data in the Bridgeton Landfill gas database is indicative that landfill personnel were carefully observing the wellfield.

5.1 Gas Composition. Data in the Bridgeton Landfill gas database were analyzed to examine trends in the gas composition, namely CH₄, CO₂, O₂, and balance gases. For these data sets, the data were examined for two periods: (1) prior to 1 January 2011 and (2) after 1 January 2011. The data were identified as steady or trending, the latter corresponding to a concomitant decrease in the fraction of CH₄ and increase in the fraction of CO₂ and balance gases. The presence of oxygen in the landfill gas was also evaluated. A summary of the trend analyses is in Table 2.

Examples of the trends observed are shown in Fig. 8. The upper graph in Fig. 8 (Well 30) shows a well where the CH₄ and CO₂ fractions are steady (no trend), balanced, and within typical ranges up until the end of 2010. The balance gas was relatively low and steady, and there is virtually no incidence of oxygen in the well. Well 30 also had temperature near 131 °F for the entire duration, despite the absence of oxygen. Around 1 January 2011, the CH₄ and CO₂ fractions and the balance gas fraction change abruptly, with an increase in CO₂ and corresponding decrease in CH₄ fraction. The middle graph in Fig. 8 shows a gas well that is trending with CH₄ and the balance gases decreasing, CO₂ increasing, and virtually no incidence of O₂ in the gas. When viewed just prior to 1 January 2011, these trends would be considered an enormous success. The CH₄ and CO₂ fractions had become essentially equal, the balance gas had diminished, and O₂ was virtually non-existent. The lower graph in Fig. 8 exhibits a noisy well, with the CO₂ fraction relatively constant, the CH₄ and balance gas fractions oscillating, and only intermittent presence of O₂. Making inferences from these noisy trends is difficult. However, when viewed just prior to 1 January 2011, these trends would have indicated a well that was tuned to suitable conditions – CO₂ and CH₄ fractions were relatively equal, the balance gas was lower, and O₂ was absent.
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Balanced CH₄ &amp; CO₂ in typical ranges, diminishing balance gas</td>
<td>CH₄ diminishing, CO₂, increasing in 2011 followed by re-equilibration, increase in balance gas</td>
<td>Virtually none until 2014</td>
</tr>
<tr>
<td>11</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing, increase in balance gas in 2011</td>
<td>Virtually none until late 2013 and 2014</td>
</tr>
<tr>
<td>12</td>
<td>Balanced but trending, CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing, balance gas noisy later in 2011</td>
<td>Periodic occurrences, frequent in 2013.</td>
</tr>
<tr>
<td>13</td>
<td>Balanced but trending, CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing, increased balance gas</td>
<td>None until late 2013</td>
</tr>
<tr>
<td>14</td>
<td>Balanced CH₄ &amp; CO₂ in typical ranges, diminishing balance gas</td>
<td>CH₄ diminishing, CO₂ increasing, increased balance gas in 2011</td>
<td>None until late 2013</td>
</tr>
<tr>
<td>15</td>
<td>Noisy, balanced, trending CH₄ &amp; CO₂; high balance gas diminishing</td>
<td>CH₄ diminishing, CO₂ increasing, increased balance gas in 2011</td>
<td>Few early occurrences before 2009</td>
</tr>
<tr>
<td>16</td>
<td>Noisy, balanced CH₄ &amp; CO₂; high balance gas</td>
<td>CH₄ diminishing, CO₂ increasing, increased balance gas in 2011</td>
<td>Frequent in 2010. None afterwards</td>
</tr>
<tr>
<td>17</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing, increase in balance gas in 2012</td>
<td>Periodic occurrences before March 2010, late 2014 and 2015.</td>
</tr>
<tr>
<td>18</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, noisy balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in 2012, increase in balance gas</td>
<td>Periodic occurrences before March 2010, late 2014 and 2015.</td>
</tr>
<tr>
<td>19</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, noisy balance gas</td>
<td>CH₄ diminishing, CO₂ increasing, increase in balance gas in 2012</td>
<td>Infrequent occurrences in 2011 and after.</td>
</tr>
<tr>
<td>20</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, noisy balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in 2012, increase in balance gas</td>
<td>Frequent occurrences in 2013 and after</td>
</tr>
<tr>
<td>21</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, noisy balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in 2012, increase in balance gas</td>
<td>Frequent occurrences in 2012 and after</td>
</tr>
</tbody>
</table>
Table 2. Evaluation of composition trends in gas well heads at Bridgeton Landfill (cont.)

<table>
<thead>
<tr>
<th>Well No.</th>
<th>Gas Characteristics</th>
<th>Prior to 2011</th>
<th>During 2011</th>
<th>Oxygen Presence</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, noisy balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in 2012, increase in balance gas</td>
<td>Infrequent occurrences in 2014 and after</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, noisy balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in 2012, increase in balance gas</td>
<td>Virtually none</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, noisy balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in 2012, increase in balance gas</td>
<td>Infrequent occurrences in 2014 and after</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Noisy, balanced CH₄ &amp; CO₂ in typical ranges; high balance gas</td>
<td>CH₄ diminishing, CO₂ increasing, increased balance gas in 2011</td>
<td>Virtually none</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Noisy, balanced CH₄ &amp; CO₂ in typical ranges; high balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in 2012, increase in balance gas</td>
<td>Periodic before mid 2009, frequent 2014 and after</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Trending, balanced CH₄ &amp; CO₂ in typical ranges, diminishing balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in 2012, increase in balance gas</td>
<td>Periodic before mid 2009, frequent 2014 and after</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, noisy balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in 2012, increase in balance gas</td>
<td>Frequent occurrences in 2013 and after</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, noisy balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in 2011, increase in balance gas</td>
<td>Virtually none</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, noisy balance gas</td>
<td>CH₄ diminishing, CO₂ increasing late 2010, increase in balance gas</td>
<td>Virtually none</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, noisy balance gas</td>
<td>CH₄ diminishing, CO₂ increasing late 2010, increase in balance gas</td>
<td>Virtually none</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, noisy balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in 2011, increase in balance gas</td>
<td>Virtually none</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in 2011, increase in balance gas</td>
<td>Intermittent mid 2012 and after</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in 2011, increase in balance gas</td>
<td>Frequent occurrences in 2013 and after</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Trending &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing mid 2010, increase in balance gas</td>
<td>Intermittent in 2013</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Evaluation of composition trends in gas well heads at Bridgeton Landfill (cont.)

<table>
<thead>
<tr>
<th>Well No.</th>
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<th>Oxygen Presence</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>Trending &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2010, increase in balance gas</td>
<td>Intermittent in 2013</td>
</tr>
<tr>
<td>37</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in 2011, increase in balance gas</td>
<td>Infrequent in 2013 and after</td>
</tr>
<tr>
<td>38</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in 2011, increase in balance gas</td>
<td>Virtually none</td>
</tr>
<tr>
<td>39</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in mid 2011, increase in balance gas</td>
<td>Virtually none</td>
</tr>
<tr>
<td>56</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in 2011, increase in balance gas</td>
<td>Infrequent in 2014</td>
</tr>
<tr>
<td>57</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in 2011, increase in balance gas</td>
<td>Infrequent prior to 2010</td>
</tr>
<tr>
<td>58</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing in mid 2010, increase in balance gas</td>
<td>Infrequent in 2013 and after</td>
</tr>
<tr>
<td>59</td>
<td>Noisy, trending &amp; balanced CH₄, CO₂, balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2011, increase in balance gas</td>
<td>Infrequent before 2010</td>
</tr>
<tr>
<td>60</td>
<td>Trending &amp; balanced CH₄ &amp; CO₂ in typical ranges, increasing balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2011, increase in balance gas</td>
<td>Intermittent in 2010, 2013; frequent 2014</td>
</tr>
<tr>
<td>61</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2010, increase in balance gas</td>
<td>Frequent in 2014</td>
</tr>
<tr>
<td>62</td>
<td>Noisy, steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2010, noisy; balance gas noisy</td>
<td>Frequent in 2010, 2011, 2013 &amp; after</td>
</tr>
<tr>
<td>63</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2010, increase in balance gas</td>
<td>Intermittent 2008-2010, 2015</td>
</tr>
<tr>
<td>64</td>
<td>Trending &amp; balanced CH₄ &amp; CO₂ in typical ranges, increasing balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2011, increase in balance gas</td>
<td>Intermittent in 2010, 2013; frequent 2014</td>
</tr>
<tr>
<td>65</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2011, increase in balance gas</td>
<td>Intermittent 2007</td>
</tr>
<tr>
<td>66</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing mid 2010, increase in balance gas</td>
<td>Infrequent 2007-2009, 2013 &amp; after</td>
</tr>
</tbody>
</table>
Table 2. Evaluation of composition trends in gas well heads at Bridgeton Landfill (cont.)

<table>
<thead>
<tr>
<th>Well No.</th>
<th>Gas Characteristics</th>
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<th>Oxygen Presence</th>
</tr>
</thead>
<tbody>
<tr>
<td>67</td>
<td>Trending CH₄ &amp; CO₂ in typical ranges, increasing balance gas</td>
<td>CH₄ diminishing, CO₂ increasing as before, increase in balance gas</td>
<td>Infrequent 2010, frequent 2014</td>
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</tr>
<tr>
<td>68</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing late 2010, increase in balance gas</td>
<td>Virtually none</td>
<td></td>
</tr>
<tr>
<td>69</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2011, increase in balance gas</td>
<td>Virtually none</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>Noisy, steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2010, noisy; balance gas noisy</td>
<td>Frequent in 2010, 2011, 2013 &amp; after</td>
<td></td>
</tr>
<tr>
<td>71</td>
<td>Noisy, steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2011, noisy; balance gas noisy</td>
<td>Frequent in 2010, 2011,</td>
<td></td>
</tr>
<tr>
<td>72</td>
<td>Noisy, steady &amp; balanced CH₄ &amp; CO₂, noisy &amp; steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2011, noisy; balance gas noisy</td>
<td>Intermittent 2010, 2011; frequent 2014-15</td>
<td></td>
</tr>
<tr>
<td>73</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2012, increase in balance gas</td>
<td>Infrequent 2011, 2013</td>
<td></td>
</tr>
<tr>
<td>74</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2012, increase in balance gas</td>
<td>Frequent late 2013 &amp; after</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2012, increase in balance gas</td>
<td>Frequent 2013</td>
<td></td>
</tr>
<tr>
<td>76</td>
<td>Noisy, steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2012</td>
<td>Virtually none</td>
<td></td>
</tr>
<tr>
<td>77</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing late 2011,</td>
<td>Infrequent before 2010</td>
<td></td>
</tr>
<tr>
<td>78</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2012</td>
<td>Infrequent 2008, 2009</td>
<td></td>
</tr>
<tr>
<td>79</td>
<td>Noisy, steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2012, increase in balance gas</td>
<td>Frequent 2010, 2011, 2014 &amp; after</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>Steady &amp; balanced CH₄ &amp; CO₂ in typical ranges, steady balance gas</td>
<td>CH₄ diminishing, CO₂ increasing 2012, increase in balance gas</td>
<td>Virtually none</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 8. Examples of different trends in gas composition as a function of time.
In my professional opinion, a landfill technician or engineer reviewing these data sets for trends indicative of changing behavior would have no basis to expect a major subsurface reaction, or any other major event. In fact, a landfill technician or engineer would conclude that the wellfield was in trending to a optimal condition at the end of 2010. However, shortly thereafter, each of these wells exhibited radical departures from the historic trend that would never have been anticipated based on the preceding data or trend analysis. These abrupt changes in behavior could never have been anticipated based on historic data or experience in the wellfield. However, once these highly unusual and unexpected abrupt changes occurred, personnel at Bridgeton Landfill undertook actions to minimize their impact including tuning the well field, installation of state-of-the-art geomembrane cover, and construction of a new leachate treatment facility.

When considered in aggregate, 46 of the 59 wells exhibited no trend prior to 1 January 2011 and 4 wells were sufficiently noisy to preclude an assessment of trend. That is, no indication of a forthcoming problem was evident in 85% of the well field. Nine wells were trending, but only one of these wells (Well 67) had been trending long enough to observe a distinct change in behavior. Well 67 also had elevated temperature from its inception, with temperature exceeding 131 °F and exhibiting a slow and steady trend of increasing temperature with time despite the absence of O₂ in the gas. In my professional opinion, a landfill technician or engineer reviewing these data for trends indicative of changing behavior would have no reason to expect the catastrophic subsurface reaction that occurred subsequently.

6. SETTLEMENT AT BRIDGETON LANDFILL

Areal maps developed by Aquaterra (2012) using survey data from 2006 to 2012 were evaluated to determine if a major subsurface reaction would have been anticipated from the perspective of a landfill technician or engineer periodically inspecting the landfill surface. Major subsurface reactions that generate heat and high temperatures are known to induce large settlements, as has been observed at the Countywide Landfill, Congress Development Company Landfill, and Middle Point Landfill. Moreover, Bareither et al. (2012, 2013) show experimentally that the rate of compression of MSW increases dramatically as the temperature increases, even if the rate of biodegradation has not accelerated substantially.

Settlement data for the South Area for the period 10 October 2006 to 19 February 2009 are shown in Fig. 9. The areal map shows that settlements are greater in the interior of the South
Fig. 9. Settlement from 10 October 2006 to 19 February 2009 (from Aquaterra 2012).
Area than around the edges, which is expected because the waste is thicker in the interior. The quarry walls also provide restraint that will reduce settlement near the edges. However, there is no distinct settlement bowl or region where settlements are much larger than in other areas. Settlement data from 19 February 2009 to 26 January 2011 are shown in Fig. 10. This areal map looks very similar to the map in Fig. 9, with no distinct settled area indicative of a growing subsurface reaction.

The areal map in Fig. 11 corresponds to settlement from 1 December 2011 to 29 February 2012. In this map, a distinct settlement bowl has developed over the primary region where the reaction is occurring. The settlement bowl is even more distinct when viewed in the context of the settlement data from 26 January 2011 to 29 February 2012 (from Aquaterra 2012), as shown in Fig. 12.

In my professional opinion, a landfill technician or engineer evaluating settlement trends and periodically inspecting the landfill cover would never have expected the catastrophic subsurface reaction that was discovered after 1 January 2011. In fact, the settlement data collected prior to 1 January 2011 suggest that the landfill was in a relatively steady state condition prior to discovery of the subsurface reaction.

7. MECHANISMS CAUSING ELEVATED TEMPERATURES

Thalhamer (2015) and Sperling (2015) have concluded that the catastrophic subsurface reaction that occurred at Bridgeton Landfill should have been anticipated based on the landfill gas data collected at the site. They also conclude that the actions undertaken by the landfill operator exacerbated conditions responsible for the heat generation and elevated temperatures. Thalhamer (2015) implies that “over pulling” on the gas system by the landfill operator drew atmospheric O₂ into the landfill, either through cracks and erosion rills in the cover or through the quarry walls, and further opines that the O₂ induced oxidation of the MSW, resulting in “smoldering” combustion.

The data presented in this report contradict the opinions proffered by Thalhamer (2015) and Sperling (2015). For example, abrupt and dramatic changes in temperature and gas composition ultimately occurred in nearly all gas wells, but O₂ was effectively absent in the gas from 39 of the 59 wells. Moreover, in the wells that had elevated temperatures from the onset (12, 13, 19, 20, and 67), none had substantial O₂ in the gas early in the record. Oxygen was present in some of these wells in substantive amounts only towards the very end of the record. Thus, there is no information supporting that O₂ was drawn in from “over pull” or that O₂ contributed to an oxidation reaction that caused elevated temperature.
Fig. 10. Settlement form 19 February 2009 to 26 January 2011 (from Aquaterra 2012).
Fig. 11. Settlement form 1 December 2011 to 29 February 2012 (from Aquaterra 2012).
Fig. 12. Settlement form 26 January 2011 to 29 February 2012 (from Aquaterra 2012).
The evolution of the reaction also contradicts the opinion that gas flow through the quarry sidewall and into the landfill introduced O₂ that ultimately led to oxidation of the MSW, resulting in “smoldering” combustion. The areal map of the well field shown in Fig. 13 illustrates the temporal evolution of the subsurface reaction. Wells that had elevated temperature from the onset (2007 or earlier) are shown with RED circles. Wells where an abrupt change in temperature and gas composition occurred in 2011 are shown in YELLOW. Similarly, the abrupt changes occurring in 2012 are shown in BLUE, 2013 in GREEN, 2014 in ORANGE, and 2015 in PURPLE. As illustrated in Fig. 13, the reaction initially (2011) occurred primarily in the interior of the site (YELLOW circles), rather than the edges. If oxygen intrusion through the quarry walls had been a major factor, the reaction would have initiated around the edges and subsequently moved inward. In fact, the opposite occurred.

The temperature profiles measured within the waste also indicate that atmospheric O₂ drawn in through areas of the landfill with earthen cover containing cracks and erosion rills could not have been responsible for the reaction. Examples of typical temperature profiles within the waste are shown in Figs. 14 and 15. The highest temperatures, corresponding to the source of heat, typically are 40-100 ft below ground surface during the entire record. Above or below these depths, the temperature decreases, indicating that heat is flowing away from the central depth of the landfill. If oxygen intrusion from the cover surface had induced the reaction, then the highest temperatures would be near the surface, and the temperatures would gradually diminish with depth.

The temperature profiles shown in Fig. 15 also illustrate that some of the higher temperatures are at monitoring strings 14 and 32, which are in the interior of the quarry. This is consistent with the reaction being located internally rather than peripherally. Consequently, Thalhamer’s (2015) inference that “over-pulling” of the gas system occurred and drew O₂ through the quarry walls, promoting the reaction, is inconsistent with the data from the temperature profiles.

Thalhamer (2015) also concludes that the reaction is smoldering combustion, despite having made no measurements of light emission, which Thalhamer indicates is coincident with combustion. The data reported in Sperling (2015) and in the Expanded Heat Removal Pilot Study (4 August 2015) indicate that leachate levels in some of the areas of the landfill with the highest temperatures (i.e., where the reaction is underway) are 50-100 ft above the point of maximum temperature. That is, the primary reaction is occurring under saturated conditions. Therefore, the reaction is not “smoldering combustion” or a “landfill fire.”

8. SUMMARY OF OPINIONS

The following summarizes my professional opinions in this matter. These opinions are expressed to a reasonable degree of scientific and engineering certainty.
Fig. 13. Areal map of well field showing wells with elevated temperature in colored circles. RED > 131 F since installation. Others for year of abrupt rise as shown in legend.
Fig. 14. Temperature profile at temperature monitoring point TMP-16 from 31 August 2014 to 28 September 2015 (from Weekly Data Submittal, Week of September 27 – October 3, 2015, Bridgeton Landfill LLC).
Fig. 15. Temperature profiles in South Quarry area on 28 September 2015 (from Weekly Data Submittal, Week of September 27 – October 3, 2015, Bridgeton Landfill LLC).
• Trend analyses of the leachate data indicate that the catastrophic subsurface reaction that occurred at Bridgeton Landfill could not have been anticipated based on the trends in the data prior to the reaction. In my professional opinion, a trend analysis conducted prior to 1 January 2011 would have concluded that the landfill was operating in a near steady-state condition.

• Trend analyses of the landfill gas data in the South Area indicate that the catastrophic subsurface reaction that occurred at Bridgeton Landfill could not have been anticipated based on the trends in the gas data prior to the reaction. In my professional opinion, a trend analysis on the landfill gas conducted prior to 1 January 2011 would have concluded that the landfill was operating in a near steady-state condition.

• Review of the settlement data in the South Area provided no indication that a subsurface reaction was developing prior to 1 January 2011. The settlement data collected after this date do indicate clearly that the reaction was occurring internally, and not near the edges of the landfill.

• The temperature profiles indicate that the reaction is located internally, and at depth. Thus, ingress of oxygen from the quarry walls or through defects in the cover could not have been a cause of the reaction, or have exacerbated the reaction.

• Leachate levels in the South Quarry are well above the reaction zone, suggesting that the reaction is occurring in saturated waste and therefore cannot be smoldering combustion or fire.

A reasonable and competent engineer could not conclude from the leachate or gas data sets that a catastrophic subsurface reaction was imminent. As indicated in Section 3, the landfill industry has recognized that conditions exist in some landfills that promote heat that results in temperatures far in excess of 131 °F without the presence of oxygen, aerobic microbial communities, unusual reactive wastes, and/or combustion. The reactions responsible for generating this heat and elevated temperature are unknown at this time. More information on these reaction mechanisms is anticipated in the next several years as the expert team commissioned on this matter develops their scientific findings.
Bridgeton Landfill went to great lengths to manage the reaction and its impacts on the surroundings. For example, the gas system was extensively expanded and upgraded, a state-of-the-art leachate treatment system was added, and the entire South Area and a portion of the North Area were covered with a state-of-the-art EVOH geomembrane specifically engineered to minimize the flux of emissions of organic compounds, including highly odiferous gases, as well as in the influx of oxygen. These actions have been effective. The EVOH geomembrane has been highly effective in controlling odors associated with the geomembrane, the gas collection system has been collecting and treating landfill gas prior to discharge to the atmosphere, and the leachate treatment plant is producing leachate that can be readily accepted for final treatment by a publically owned treatment works.

9. ARCHIVAL DOCUMENTS CITED OR CONSIDERED IN THIS REPORT


10. CASE DOCUMENTS CITED IN THIS REPORT

Aquaterra (2012), Memorandum from M. Boussad to D. Vasbinder regarding Bridgeton Landfill Settlement, 15 March 2012.


Bridgeton Landfill Gas Database
Bridgeton Landfill Gas Buildout Database

Bridgeton Leachate Database


Bridgeton Temperature Probe Database

Bridgeton Landfill, Weekly Data Submittals, Missouri Department of Natural Resources Website.


Bridgeton Landfill, Bridgeton, St. Louis County, Missouri, August 2015.


Stark, T. (2015), Slope Stability Inspection 13 May 2014 – Bridgeton Landfill – Permit No. 0118912, Report to Missouri Department of Natural Resources (MDNR), 16 September 2014.


11. LIST OF CASES WITH TESTIMONY IN DEPOSITION OR TRIAL IN LAST FOUR YEARS

CHBM vs. State of NSW, Supreme Court of New South Wales, Australia.
    On behalf of plaintiff (CHBM Inc.)
    Attorney: Keith Redenbach, Norton Rose Australia (Sydney)

W. Berry and Ruth I. Berry vs. Lee County Landfill SC, LLC, Republic Services of South Carolina, LLC, and Republic Services, Inc.
    On behalf of defendant (Republic Services)
    Attorney: William Beck, Lathrop Gage

Terry Baker et al. vs. Tunnel Hill Reclamation LLC, Court of Common Pleas, Perry County, Ohio.
    On behalf of plaintiffs
    Attorney: Zakariah Johnson, PLLC, Jacksonville, FL
EDUCATION

BSCE, Lehigh University - 1985
MSE, University of Texas at Austin – 1987 (Civil Engineering, Geotechnical/Geoenvironmental)
PhD, University of Texas at Austin – 1989 (Civil Engineering, Geotechnical/Geoenvironmental)

REGISTRATION

Professional Engineer, State of Wisconsin, License No. 34108-006
Board Certified Environmental Engineer, American Society of Environ. Engrs. & Scientists

ACADEMIC LEADERSHIP APPOINTMENTS

Dean, School of Engineering and Applied Science, University of Virginia, Charlottesville, Virginia, July 2015 - present.
Director of Sustainability Research and Education and Co-Director of the Office of Sustainability, University of Wisconsin, Madison, Wisconsin, 2011-2015.
Chair, Civil & Environmental Engineering, University of Wisconsin, Madison, Wisconsin, 2011-2015.
Chair, Geological Engineering, University of Wisconsin, Madison, Wisconsin, 2007-2015.
Chair, Civil & Environmental Engineering, University of Washington, Seattle, WA, 2008-August 2009.
Director, Recycled Materials Resource Center, University of Wisconsin, Madison, Wisconsin, 2007-2011.
Director, Wisconsin Geotechnics Laboratory, University of Wisconsin, Madison, Wisconsin, 2000-2015.
Co-Director, Consortium for Fly Ash Use in Geotechnical Engineering, University of Wisconsin-Madison, Co-Director, 1999-2007.

FACULTY APPOINTMENTS

Janet Scott Hamilton and James Downman Hamilton Professor of Civil & Environmental Engineering, University of Virginia, July 2015-present.
Adjunct Professor, School of Civil, Environmental, and Mining Engineering, University of Western Australia, Crawley, WA, Australia, July 2015-present.
Affiliate Professor, Nelson Institute for Environmental Studies, University of Wisconsin, Madison, Wisconsin, 2010-2015.
Professor, University of Wisconsin, Madison, Wisconsin, 2000-2007 (joint appointment in Geological Engineering, Civil & Environmental Engineering).
Associate Professor, University of Wisconsin, Madison, Wisconsin, 1995-2000 (joint appointment in Geological Engineering, Civil & Environmental Engineering).
Assistant Professor, University of Wisconsin, Madison, Wisconsin, 1990-1995 (joint appointment in Geological Engineering, Civil & Environmental Engineering).

PROFESSIONAL AND COMMUNITY LEADERSHIP APPOINTMENTS

Board of Directors, Commonwealth Center for Advanced Manufacturing, Disputanta, Virginia, 2015-present.
Advisory Board, Global Waste Research Institute, California Polytechnic Institute at San Louis Obispo, (2010-present)
Geo Institute of ASCE, Board of Governors, Board Member 2007-2014, Treasurer 2010-11, Vice President 2011-12, President, 2012-13.
Park Commission, Town of Middleton, Wisconsin, Commissioner, 2010-12.
Research Council, Environmental Research and Education Foundation, 2011-present.

HONORS AND AWARDS

Professional
National Academy of Engineering, 2012
A. Ivan Johnson Outstanding Achievement Award, ASTM International, 2015
Fellow, ASTM International, 2011
Fellow, American Society of Civil Engineers, 2009
Academy of Distinguished Alumni, University of Texas at Austin, 2009
Diplomate, Geotechnical Engineering, Academy of Geo-Professionals, 2009

Research
Spencer J. Buchanan Lecturer, Texas A&M University, 2014
Best Paper Award, Waste Management Symposium 2014
G. Leonards Lecturer, Purdue University, 2013
Best Paper Honorable Mention (2nd Place), Geosynthetics International, 2013.
Ralph B. Peck Award, American Society of Civil Engineers, 2012
Croes Medal, American Society of Civil Engineers, 1998 and 2008
Alfred P. Noble Prize, American Society of Civil Engineers, 2008
Second Paper Award, Global Waste Management Symposium, 2008
Kellet Mid-Career Research Award, University of Wisconsin, 2005
Walter L. Huber Civil Engineering Research Award, ASCE, 2000
Casagrande Award, American Society of Civil Engineers, 1995
Middlebrooks Award, American Society of Civil Engineers, 1995, 2013
Collingwood Prize, American Society of Civil Engineers, 1994
Distinguished Young Faculty Award, U.S. Department of Energy, 1991
Presidential Young Investigator, National Science Foundation, 1991

Teaching
Polygon Outstanding Instructor Award, College of Engr., Univ. of Wisconsin, 1991, 93, 97
Outstanding Professor Award, ASCE Wisconsin Student Chapter, 1992
Top 100 Educators Award, Wisconsin Students Association, Univ. of Wisconsin, 1991

Professional Service
Honor Medal, Eurasian National University and Kazakhstan Geotechnical Society, 2013
Order of the Engineer, Geo Institute, 2011
Award of Merit, ASTM International, 2011
Richard S. Ladd Standards Development Award, Committee D18, ASTM International, 2002, 03, 04, 06, 08, 11
Special Service Award, Committee D18, ASTM International, 2007

Academics
Ford Foundation Fellowship, Univ. of Texas at Austin, 1989
John A. Focht Endowed Presidential Scholarship in Civil Engr., Univ. of Texas at Austin, 1988
Dawson Endowed Presidential Scholarship in Civil Engr., Univ. of Texas at Austin, 1986
Engineering Foundation Fellowship, University of Texas at Austin, 1985
John B. Carson Prize in Civil Engineering, Lehigh University, 1985
Phi Beta Kappa, Chi Epsilon, and Tau Beta Pi

CONGRESSIONAL TESTIMONY & DISCUSSION
Invited Discussion on Environmental Regulation and Sustainable Materials Management; Democratic Senators for Environmental Policy and Sustainability, 29-30 May 2012.

LEADERSHIP DEVELOPMENT
Academic Leadership Program, Committee on Institutional Cooperation, Big10 Universities and University of Chicago, 2010 – 2011. For more information →
Manager’s Boot Camp, Center for Executive Education, Haas School of Business, University of California-Berkeley
Negotiations and Influence, Center for Executive Education, Haas School of Business, University of California-Berkeley
Philanthropy Fundamentals: Developing and Stewarding Donors, UW Foundation
UNIVERSITY SERVICE

Academic Council, Dept. of Civil and Environmental Engineering (1994-99, Chair 1997-99)
Academic Planning Council, Nelson Institute for Environmental Studies (2012-present)
Ad Hoc Committee on Fossil Fuel Use and Climate Change (2013-2014)
Admissions Chair, Geotechnical Engineering Program (1990-2006)
Becker Award Committee, Civil and Environmental Engineering (Chair 2002-04)
Bollinger Academic Staff Award Committee (2010-11, Chair)
Byron Bird Award Committee, College of Engineering (1995)
Chancellor’s Campus Budget Model Committee (2013-2014)
Civil and Environmental Engineering Strategic Hiring Committee (2010-12, Chair 2010)
Classroom Space Utilization Committee, Co-Chair (2014)
Climate Change Solutions Committee (2013-present, Chair)
College of Engineering Search Committee for Executive Associate Dean (Chair, 2014)
College of Engineering Leadership Council (2013-present)
College of Engineering Promotion and Tenure Committee (2014-present)
College of Engineering Search Committee for Associate Dean for Advancement (2013)
College of Engineering Search Committee for Assistant Dean for Facilities (2013)
College of Engineering Academic Planning and Curriculum Committee (1996-99)
College of Engineering Curriculum Committee (1997-99, 2002-04)
College of Engineering Diversity Committee (2002-04)
Conflict of Interest Oversight Committee, University of Wisconsin (2000-02)
Governance Committee, Nelson Institute for Environmental Studies (2012-present).
Scholarship Committee, Dept. of Civil and Environmental Engineering (1998-2002)
Search Committee for Assoc. Vice Chancellor for Facilities Planning & Management (Chair, 2012)
Search Committees for Geological Engineering (Chair, 1997-98, 2003-04)
Undergraduate Committee, Geological Engineering (Chair, 2002-2008)
University of Wisconsin Information Technology Committee (2010-12)
University of Wisconsin Honors Committee (2010-2011)

PROFESSIONAL SERVICE & AFFILIATIONS

Steering Committee, Performance Assessment Community of Practice, Department of
External Advisory Board, Dept. of Geology and Geological Engineering, Colorado School of
  Mines (2015)
External Advisory Board, College of Engineering, Colorado School of Mines (2012)
External Advisory Board, Engineering School of Sustainable Infrastructure & Environment,
  University of Florida (2011)
American Association for the Advancement of Science
ASTM International
  D18 Executive Committee (2006-13, Vice Chair 2011-13)
  D18.14 – Sustainable Geotechnical Construction (founding member, 2008-present)
  D18.19 - Frozen Soil & Rock (1992-Present)
Geo-Institute of the American Society of Civil Engineers (Fellow ASCE)
Board of Governors (Treasurer 2010-11, V. President, 2011-12, President 2012-13)
Awards Committee (Chair, 1999-01)
Editor-in-Chief, JGGE, 2004-06, Editor JGGE, 1996-99
Geoenvironmental Engineering Committee (1990-Present, chair 1996-99)
Geo-Strata Magazine Task Force (1997-99)
TPC Subcommittee on Policies for Specialty Conferences (1997-99)
American Geophysical Union
British Geotechnical Association
Canadian Geotechnical Society
International Geosynthetics Society
National Ground Water Association
North American Geosynthetics Society
Soil Science Society of America

PATENTS
Pressure Plate Extractor, United States Patent No. 6,718,835.

PUBLICATIONS
Refereed Journal Articles: Environmental Containment Systems

Craig H. Benson, PhD, PE, NAE


Craig H. Benson, PhD, PE, NAE


Refereed Journal Articles: Sustainable Infrastructure


Camargo, F., Edil, T., and Benson, C. (2013), Strength and Stiffness of Recycled Pavement


**Refereed Journal Articles: Groundwater**


Refereed Journal Articles: Other Topics


Affecting the Friction Angle of Compacted Sands, J. Geotech. and Geoenvironmental Eng., 134(10), 1476-1489.


Discussions


Refereed Conference Papers

Abichou, T., Edil, T., Benson, C., and Tawfiq, K. (2004), Hydraulic Conductivity of Foundry Sands and Their Use as Hydraulic Barriers, Beneficial Reuse of Waste Materials in Geotechnical and


Craig H. Benson, PhD, PE, NAE

International Conference on Sustainable Construction Materials and Technologies, Università Politecnica delle Marche, Ancona, Italy.


Books


Chapters in Books


Non-Refereed Conference Papers


Brown, B., Bradshaw, S., Edil, T., and Benson, C. (2015), Leaching from Roadways Stabilized


Institute for International Cooperative Environmental Research, Florida State University, Tallahassee, FL, USA, 1-4.


Reviews, Editorials, and Magazine Articles


Benson, C. (2012), The Year Ahead, Geo-Strata, November/December, 8.


Reports


Bareither, C., Edil, T., and Benson, C. (2007), Determination of Shear Strength Values for Granular Backfill Materials Used by WisDOT, SPR No. 0092-05-08, Wisconsin Highway Research Program, Madison, WI.


Standards


**LIVE INTERVIEWS**

*Coal ash = environmental win (when you recycle it)*, with Dan Weissmann and Marketplace, National Public Radio, 28 April 2014.  

**SPONSORED RESEARCH**

Environmental Containment Systems

Behavior of Polymer-Modified Bentonites Contacted with Aggressive Leachates, Colloid Environmental Technologies Corporation, with W. Likos.  
Bench-Scale Comparison of EVOH and HDPE Geomembranes as Barriers to VOC and Methane Emissions, Kuraray America Inc.
Consortium for Risk Evaluation and Stakeholder Participation, US Department of Energy, with Vanderbilt University, Rutgers University, New York University, Oregon State University, University of Pittsburgh, Howard University, University of Arizona, Robert Wood Johnson Medical School.


Bentonite-Polymer Nanocomposites for Geoenvironmental Applications, National Science Foundation, with T. Edil and C. Shackelford.


Evaluating Long-Term Impacts on Final Covers - Exhumation of the ACAP Test Sections, National Science Foundation, US Environmental Protection Agency, Environmental Research and Education Foundation, with D. Fratta and W. Albright.


Predictive Tools for Sustainable Solid Waste Management Using Bioreactor Landfills, National Science Foundation, with M. Barlaz (Bioreactor Partnership).

The State of Municipal Solid Waste Bioreactor Landfills-II, US Environmental Protection Agency, with M. Barlaz.


Effect of Freeze Thaw on Compacted Soil Liners and Covers, University of Wisconsin Graduate School.

Fate and Transport of Chronic Waste Disease Prions in Municipal Solid Waste Landfills, US Environmental Protection Agency, with J. Pedersen and J. Aiken.


Bioreactor Landfills: State of the Practice, US Environmental Protection Agency, with D. Lane and M. Barlaz.

Field Performance of Alternative Covers, US Environmental Protection Agency.


Long-term Chemical Compatibility of Geosynthetic Clay Liners, National Science Foundation, with C. Shackelford.


Dry Barriers for Waste Containment, National Science Foundation, with S. Kung

Alternative Cover Assessment Program, United States Environmental Protection Agency, with W. Albright (Desert Research Institute) and Glendon Gee (Battelle PNNL).

Large-Scale Verification of a VOC Transport Model for Composite Liners, Groundwater Research Advisory Council, State of Wisconsin, with T. Edil.

Field Assessment of Geosynthetic Clay Liners in Final Covers, United States Environmental Protection Agency.

Unsaturated Hydraulic Properties of Alternative Cover Soils, Waste Management, Waste Connections, Blue stem Solid Waste Authority, and Marina Solid Waste Management District

Alternative Covers for Waste Containment in Southern California, San Bernardino County, CA.

Equivalency of Subtitle D and Alternative Earthen Covers, City of Glendale, Arizona.


Hydraulic Characterization of Mine Rock Backfill for the Flambeau Mine, Flambeau Mining Company, Ladysmith, WI

Hydraulic Characterization of Mine Rock Backfill for the Flambeau Mine: II-In Situ Verification, Flambeau Mining Company, Ladysmith, WI

Field Hydraulic Conductivity Assessment of the NCASI Test Plots, National Council of the Paper Industry for Air and Stream Improvement

Effect of Freeze-Thaw on the Hydraulic Conductivity of Compacted Papermill Sludge, the National Council of the Paper Industry for Air and Stream Improvement.


Laboratory and Field Evaluation of the Effects of Freeze-Thaw on Barrier Materials, United States Environmental Protection Agency.

Field-Evaluation of Geoinsulation-A Geosynthetic Insulation Material, Envotech Limited Partnership, with P. Bosscher


Rational Construction Quality Control Criteria for Compacted Soil Liners, University of Wisconsin Graduate School.

Final Cover Hydrologic Evaluation, Waste Management of North America, Inc.

Evaluation of Freezing and Thawing on the Hydraulic Conductivity of a Test Pad, Waste Management of Wisconsin, Inc.

Improved Design Methods for Landfill Final Covers, National Science Foundation.


Sustainability and Sustainable Infrastructure

Exchange Network for Expanded Polystyrene Bio-Shipping Containers, People, Prosperity, & Planet (P3) Program-Phase II, US Environmental Protection Agency
Exchange Network for Expanded Polystyrene Bio-Shipping Containers, People, Prosperity, & Planet (P3) Program-Phase I, US Environmental Protection Agency
Leaching From Roadways Constructed With Unencapsulated CCPs: Data Assessment & Synthesis, Electric Power Research Institute, with T. Edil.
Climate Change Mitigation and Adaptation in Dairy Production Systems of the Great Lakes Region, United States Department of Agriculture, National Institute of Food and Agriculture, with Matthew Ruark (PI) and others.
Recycled Materials Resource Center, Federal Highway Administration and United States Environmental Protection Agency, with K. Gardner
Environmental Benefits of Using Coal Combustion Products in Construction, Electric Power Research Institute, with T. Edil
Assessing Environmental Impacts Associated with Bases and Subgrades Stabilized with Coal Combustion Products, Center for Freight and Infrastructure Research and Education, US Department of Transportation, with T. Edil.
User Guidelines for Waste and By-Product Materials in Highway Pavements, US Environmental Protection Agency, with A. Graettinger and J. Jambeck
Gravel Equivalency of Fly Ash Stabilized Reclaimed Roads, Minnesota Local Roads Research Board, with T. Edil
In Situ Stabilization of Gravel Roads with CCPs, Combustion Byproducts Recycling Consortium, US Dept. of Energy, with T. Edil
Monitoring and Analysis of Leaching from Subbases Constructed with Industrial Byproducts, FHWA Recycled Materials Research Center, with T. Edil.
Ash Utilization in Low Volume Roads, Minnesota Department of Transportation, with T. Edil
Are High Carbon Fly Ashes Effective Stabilizers for Soft Organic Soils?, National Science Foundation, with T. Edil.
Use of Foundry Sands in Hot Mix Asphalt, University Industrial Relations, with H. Bahia

Field Demonstration of Beneficial Reuse of Foundry Byproducts in Highway Subgrade, Wisconsin Department of Transportation, with T. Edil.


Field Assessment of Barrier Layers Constructed with Foundry Sands, Solid Waste Research Council, State of Wisconsin, with T. Edil.

Use of Shredded Waste Tires in Highway Construction, United States Environmental Protection Agency, with T. Edil.


Use of Reclaimed Waste HDPE as Soil Reinforcement, Solid Waste Research Council, State of Wisconsin.

**Groundwater**

Sorption and Transport of Polycyclic Aromatic Hydrocarbons in Organoclays used for Permeable Adsorptive Barriers, CH2M Hill Inc. and Union Pacific Inc.

Environmental Impacts of Engineered Nanomaterials, Nanoscale Science and Engineering Center, National Science Foundation, with J. Pedersen and R. Hammers


Development of Large-Scale Application for Remediation of Chromium Ore Processing Residue, University Industrial Relations, University of Wisconsin, with T. Edil.


Uncertainty Based Design of Permeable Reactive Barriers, Wisconsin Ground Water Research Advisory Council, with G. Eykholt


Ultrasonic Probe to Evaluate the Integrity of Borehole Seals, Federal Highway Administration, with T. Edil.
Field Assessment of Monitoring Well Seal Integrity, Groundwater Research Advisory Council, State of Wisconsin, with T. Edil.
A Tool For Evaluating the Integrity of Monitoring Well Seals, Groundwater Research Advisory Council, State of Wisconsin, with T. Edil.

**Education**

Wisconsin-Puerto Rico Partnership for Research and Education in Materials [Wi(PR)EM], US National Science Foundation, with J. de Pablo, J. Pedersen, et al.
A Modular Geoenvironmental Curriculum, National Science Foundation, with other faculty from Wisconsin, Northwestern, Michigan, and Argonne National Laboratory.
Research Experience for Undergraduates Site, Geothermal and Energy Geotechnics, National Science Foundation, with J. Tinjum (PI), D. Fratta (co-PI), and S. Bradshaw.
Transforming CEE/GLE 330, Soil Mechanics, to Blended Learning, Division of Continuing Studies, University of Wisconsin-Madison.

**Other Topics**

Wisconsin Highway Research Program, Wisconsin Department of Transportation, with T. Edil.
Fate and Transport of Chronic Waste Disease Prions in Waste Water Treatment Plants, US Environmental Protection Agency
Stiffness and Stress State in Unsaturated Soils, Minnesota Department of Transportation, with T. Edil.
Thermal Conditions Below Highway Pavements During Winter, Wisconsin Department of Transportation, with T. Edil.
Design Protocols for Cellular Confinement with Geoweb, University Industrial Relations and Presto Products, Appleton, WI, with T. Edil.
Equivalency of Subgrade Improvement Methods, Wisconsin Department of Transportation, with T. Edil.
Reinforcement of Soft Subgrades with Geosynthetics, Wisconsin Department of Transportation, with T. Edil.
Evaluation of the DCP and SSG for Subgrade Evaluation, Wisconsin Department of Transportation, with T. Edil.
Shear Strength of Granular Backfill Materials, Wisconsin Department of Transportation, with T. Edil.
Correlating Index Properties and Engineering Behavior of Wisconsin Soils, Wisconsin Department of Transportation, with T. Edil.
Incorporating Alternative Subgrade Improvement Methods in Pavement Design, Wisconsin Department of Transportation, with T. Edil.

**STEM TEACHER ENGAGEMENT**

The following STEM teachers have been engaged in our research and educational programs through NSF’s Research Experience for Teachers (RET) program:

Hayden, Matthew, Earth Science Teacher, Glacier Creek Middle School, Middleton-Cross Plains School District, Middleton, Wisconsin.

GRADUATE STUDENTS SUPERVISED

PhD Students
Albright, W., Field Performance of Landfill Covers, 2005.
Chalermyanont, T., Reliability Analysis of Mechanically Stabilized Earth (MSE) Walls, 2002.
Chen, Nicholas, Chemical Interactions between Coal Combustion Products and Geosynthetic Clay Liners, expected 2015.
Nokkaew, K., Unsaturated Hydraulic Behavior of Recycled Base Course Materials, co-advised with J. Tinjum, January 2014
Scalia, J., Bentonite-Polymer Nanocomposites for Environmental Containment, 2012.

MS Students
Bradshaw, S., Effects of Stress, Hydration, and Ion Exchange on Geosynthetic Clay Liners, 2008.
Brown, B., Leaching of Trace Elements from Roadways Constructed with CCFs, expected 2015.
Dingrando, J., Beneficial Reuse of Foundry Sands in Controlled Low Strength Material, with T. Edil, 1999.
Elder, C., Modeling Mass Transfer During In Situ Air Sparging, 1996.
Gibson, S., Geoelectric Methods to Evaluate Borehole Seals, with T. Edil, 1999.
Marchesi, I., Simulating the Hydrology of Alternative Covers with SoilCover, 2002.
Meer, S., Effects of Ion Exchange and Desiccation on GCLs used in Final Covers, 2003.
Rochford, W., Effectiveness of Geomembrane and Soil-Bentonite Cut-Off Walls, 2002.
Vasko, S., Hydraulic Conductivity of Prehydrated Geosynthetic Clay Liners Permeated with Calcium Chloride Solutions, 1999.
Winkler, W., Thickness of Monolithic Covers in Arid and Semi-arid Climates, 1999.

KEYNOTE AND SPECIAL LECTURES

Are We Designing for Sustainability? Using Life Cycle Analysis to Assess Sustainability Accomplishment, Higley Endowed Lecture, Case Western Reserve University, April 2015.
Sustainable Closure of Waste Containment Systems Using Water Balance Covers: Lessons Learned from a Nationwide Field Experiment, Distinguished Lecture Series, University of Texas at Austin, November 2013.
Organoclays: Barrier Media for Managing Groundwater Flow and Transport At NAPL-Sites, University of Michigan, November 2013.
Solid Waste in the USA: Moving from Disposal to Sustainable Materials and Energy Management, University of California, Los Angeles, November 2013.


Physical and Chemical Processes Altering Geosynthetic Clay Liners In Situ, Distinguished Lecture Series, Department of Geology, Korea University, Seoul, Korea, October 2010.


Evaluating our Predictive Capabilities in Geoenvironmental Engineering, Distinguished Lecture Series, Dept. of Civil and Materials Engineering, University of Illinois-Chicago, April 2010.


Lessons Learned from North American Failures, Keynote Lecture, Fifth International Conference on Environmental Geotechnics, ISSMGE, Rio de Janeiro, Brazil, August 2002.
Liners and Covers for Waste Containment, Keynote Speaker, Fourth Kansai International Geotechnical Forum, Creation of a New Geo-Environment, Japanese Geotechnical Society, Kyoto, Japan, June 2000

EDITORSHIPS

Editor, ASCE Journal of Geotechnical and Geoenvironmental Engineering, 1996-99
Co-Editor, Waste Containment and Remediation, GSP No. 142, ASCE, A. Alshawabkeh et al., co-editors, 2005.
Editor, Risk-Based Corrective Action and Brownfields Restorations, GSP No. 82, ASCE, J. Meegoda, R. Gilbert, and S. Clemence, co-editors, 1998
Co-Editor, Environmental Geotechnics Section, Geotechnical News, 1994-96
APPENDIX A

GAS WELLHEAD TEMPERATURE RECORDS FOR GAS WELLS INSTALLED PRIOR TO 2010
GEW-014

Gas Well Head Temperature (°F)

GEW-015

Gas Well Head Temperature (°F)
GEW-018

Gas Well Head Temperature (°F)

1-1-06 1-1-08 1-1-10 1-1-12 1-1-14 1-1-16

GEW-019

Gas Well Head Temperature (°F)

1-1-07 1-1-08 1-1-09 1-1-10 1-1-11 1-1-12 1-1-13 1-1-14
GEW-036

Gas Well Head Temperature (°F)

1-1-07 1-1-08 1-1-09 1-1-10 1-1-11 1-1-12 1-1-13 1-1-14

GEW-037

Gas Well Head Temperature (°F)

1-1-07 1-1-08 1-1-09 1-1-10 1-1-11 1-1-12 1-1-13 1-1-14
GEW-038

Gas Well Head Temperature ($^\circ$F)

GEW-039

Gas Well Head Temperature ($^\circ$F)
Gas Well Head Temperature (°F)

GEW-080

GEW-081

131 °F
**GEW-084**

Gas Well Head Temperature (°F)

- 131 °F

**GEW-085**

Gas Well Head Temperature (°F)

- 131 °F
APPENDIX B

GAS COMPOSITION RECORDS FOR GAS WELLS INSTALLED PRIOR TO 2010
GEW-022

- CH4
- CO2
- O2
- Balance

Percentage of Total Composition

GEW-023

- CH4
- CO2
- O2
- Balance

Percentage of Total Composition
GEW-058

Percentage of Total Composition

GEW-059

Percentage of Total Composition
GEW-060

CH4
CO2
O2
Balance

GEW-061

CH4
CO2
O2
Balance

Percentage of Total Composition

1-1-06 1-1-08 1-1-10 1-1-12 1-1-14 1-1-16