Demonstration of Three Levels of In-Situ Heating for Remediation of a Former MGP Site

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ABSTRACT: TerraTherm used its In Situ Thermal Desorption (ISTD) technology at full scale to remediate a gasholder containing residual coal tar at a former manufactured gas plant (MGP) site in North Adams, Massachusetts. Prior to the site being heated, coal tar DNAPL had resisted recovery. After dewatering, TerraTherm applied ISTD in a step-wise fashion, without excavation. To our knowledge, this is the first site where a multi-level in-situ heating approach has been applied. We utilized three levels of heating (Levels 1, 2 and 3), achieving low (80°C), moderate (100°C) and higher (325°C) soil temperatures, respectively. During Level 1, >16,000 gal (60,000 l) of coal tar/emulsion was recovered, while during Levels 2 and 3, >166,000 lb (75,000 kg) expressed as naphthalene were extracted and treated in the vapor phase. ISTD resulted in the following reductions in soil concentrations (mg/kg): Level 2, benzene from 3400 to 0.95, naphthalene from 14000 to 70, and benzo(a)pyrene from 650 to 100; Level 3, benzene from 2068 to 0.35, naphthalene from 679 to 5.7, and benzo(a)pyrene from 20 to 0.33. No DNAPL remained within the gasholder, and all constituents were below the remedial goals. National Grid judged the turn-key cost ($850,000 for ISTD) to be less than the excavation alternative.

SITE BACKGROUND

TerraTherm, Inc. employed its ISTD process, also known as In-Situ Thermal Destruction at full scale to remediate a gasholder containing residual coal tar and related constituents (i.e., benzene; polycyclic aromatic hydrocarbons [PAHs] such as naphthalene and benzo(a)pyrene; and petroleum hydrocarbons) at a former MGP site in North Adams, a city in northwestern Massachusetts. From about 1860 to 1952, coal carbonization and later, carbureted water gas manufacturing were conducted at the site. The facility included gasholders, storage tanks, switch houses, purifier boxes, retorts and other gas manufacturing equipment. Massachusetts Electric Co., which assumed ownership of the entire site in 1972, later became a subsidiary of National Grid.

Although leaks are not known to have occurred from this gasholder, the potential for releases of coal tar to the adjacent Hoosic River was a significant concern. During decommissioning, the superstructure of the 62-ft (18.9-m) diameter cylindrical gasholder had been removed and its 18-ft (5.5-m) deep underground portion backfilled with a mixture of silt, sand, gravel, cobbles and debris (bricks, concrete fragments, wood, metal scrap, ash and clinker). Most of the pore spaces of the 2,013 cy (1,539 m^3) subsurface volume of the gasholder were initially filled with water. Residual coal tar was evident within the soil but coal tar dense non-aqueous phase liquid (DNAPL) had been recovered only to a limited extent during bailing of wells under ambient temperatures.

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Water was encountered within the brick-walled gasholder during remedial investigations at a depth of approximately 1 m below ground surface (bgs), i.e., at the height of the top of the brick wall, but outside the gasholder it was > 2 m beneath its concrete bottom. Based on soil investigations within the gasholder, residual coal tar was present from 6.5 to 18 ft (2 to 5.6 m) bgs, and the bottom 4 ft (1.2 m) of the soil fill material was saturated with coal tar DNAPL.

Contaminants and Remedial Goals. Pretreatment concentrations of contaminants of concern (COCs) were as high as 14,000 mg/kg for naphthalene; 650 mg/kg for benzo(a)pyrene [B(a)P]; 650 mg/kg for benzo(a)anthracene [B(a)A]; 6,200 mg/kg for benzene; and 230,000 mg/kg for petroleum hydrocarbons (PHCs). National Grid's remediation objectives for the gasholder were to achieve a Permanent Solution in accordance with the Massachusetts Contingency Plan (MCP) (310 CMR 40). Their Licensed Site Professional, Brown and Caldwell conducted a human health risk assessment pursuant to the MCP and selected the following treatment goals: (a) within the midsection of the gasholder, 6 to 15 ft (1.8 to 4.6 m) deep, which fell within their construction worker exposure scenario, the goal was elimination of DNAPL and reduction of concentrations of volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs) and PHCs below MCP "Upper Concentration Limits" (UCLs) so that residual risk to human health and groundwater (GW) is minimized; and (b) within the bottom of the gasholder 15 to 18 ft (4.6 to 5.5 m) deep, which they deemed to be below the depth of potential exposure to construction workers, the goal was elimination of DNAPL so that it would no longer pose a threat of future release to groundwater. After evaluating a range of alternatives, they selected the TerraTherm ISTD technology to treat the gasholder and achieve the remedial goals.

INTRODUCTION TO ISTD AND TAILORED HEATING

ISTD is a patented technology that combines the application of thermal conductive heating (TCH) and vacuum for remediation of soil/waste materials, particularly source areas, contaminated with a wide range of organic compounds. Heat is injected into the soil from a network of vertical electrically powered heating elements suspended inside steel pipes ("heater-only wells"). Because the temperature of the heating elements is easily controlled, much like an electric oven, the operator can adjust the set points of the heaters as desired to maintain any temperature between ambient and ~1600°F (870°C). This allows flexibility in tailoring the heating process to the remediation requirements. At full duty cycle, the typical heating element delivers 1.15 kW/m (0.35 kW/ft) over its entire length. Heat is transferred to the soil from the heater wells primarily by thermal conduction, and secondarily by convection. Baker and Heron (2004) described the various items that make up the heating budget at a site, and how to estimate them.

Mechanisms of ISTD Treatment. As the site is heated, several mechanisms contribute to ISTD's ability to achieve the remedial standards for both VOCs and SVOCs, as follows: (1) Evaporation into the subsurface air stream – for example, the vapor pressure of naphthalene increases 4000-fold from ambient temperature to its boiling point at 424°F (218°C); (2) Steam Distillation – as the treatment zone is heated to the boiling point of water, each milliliter of soil moisture eventually produces over a liter of steam.

Organic vapors tend to partition into the produced steam, and be swept along with it toward extraction wells; (3) Boiling – by the time the soil temperature is raised above the boiling point of the CoC, it cannot physically remain in the soil except as a gas; (4) Decomposition reactions – the kinetics of various chemical reactions such as hydrolysis, oxidation and pyrolysis (chemical decomposition in the absence of oxygen) increase markedly with temperature. As the vaporized water and contaminants are drawn toward the vacuum extraction wells ("heater-vacuum wells"), they encounter very hot soil (e.g., at 1000°F [500°C] adjacent to the thermal wells), within which the vapors have a relatively long residence time. Most of the CoCs will decompose within that zone, leaving the balance to be treated in the aboveground air quality control (AQC) system.

Prior to the initiation of this project, the combination of these ISTD mechanisms had already been proven to be highly effective in treating a variety of VOCs and SVOCs (Stegemeier and Vinegar 2001). This experience led to TerraTherm's development of a three-level tailored heating approach to the treatment of MGP wastes, which we described in an earlier paper (Baker et al. 2004). Briefly, our generalized approach proposed three Levels of Heating (Table 1). The following points are also offered:

TABLE 1. Levels of ISTD heating for MGP sites.

Level of Heating and Contaminant Type	Target Treatment Temperature	Thermal Well Spacing	Goal of Treatment
1. Gentle Heating (Coal Tar)	< 212°F (< 100°C)	> 20 ft (> 6 m)	• Remove Mobile NAPL
2. Moderate Heating for VOC Removal (Benzene, Naphthalene)	212°F (100°C)	10-20 ft (3-6 m)	• Remove Mobile NAPL • Minimize Risk to GW and Indoor Air
3. Elevated Heating for SVOC Removal (Higher Boiling PAHs)	>> 212°F (>> 100°C)	6-12 ft (2-4 m)	• Remove Mobile NAPL • Minimize Risk to GW and Indoor Air • Achieve Stringent Cleanup Goals

1. Level 1 can be used to accomplish thermally-enhanced coal tar recovery. Other potential applications include thermal enhancement of recovery of other types of viscous NAPL, thermally-enhanced soil vapor extraction, thermally-enhanced bioremediation, and thermally-catalyzed persulfate oxidation.
2. Level 2 can effectively remove VOCs, (e.g. benzene, naphthalene), which being the most mobile of the MGP constituents, often drive the risk. Moderate heating was also judged capable, based on laboratory tests (Bhupendra et al. 2002) of solidifying and stabilizing the remaining, higher boiling coal tar residuals.
3. Level 3 heating to higher ISTD temperatures, e.g., 617°F (325°C) for PAHs, is used when thorough removal of SVOCs need to be achieved (equivalent degree of cleanup as excavation).

We envisioned that one or more levels might be used in a given project, depending on its goals. For example, some projects might begin with Level 1 and proceed directly to either Level 2 or 3. This paper describes the first field demonstration of this tailored heating approach, a single ISTD project that demonstrated all three levels of heating.

METHODS

During the remedial design, TerraTherm submitted a sample of the coal tar from the gasholder for laboratory analyses of viscosity at the Center for Petroleum and Geosystems Engineering, Univ. of Texas at Austin. The tests indicated that modest heating from ambient temperature to 170°F (77°C) was accompanied by a twenty-fold decrease in viscosity. It was concluded that raising the soil temperatures to such a degree would greatly increase the fluidity and recoverability of the tar. These and other aspects of the remedial design, including simulation modeling were discussed in an earlier paper (Baker et al. 2004).

Beginning in November 2003, TerraTherm installed 25 thermal wells at 12-ft spacing in three concentric rings within the gasholder, with the middle ring consisting of six heater-vacuum wells. The heating elements extended from 4 to 18 ft (1.2 to 5.5 m) bgs (Figure 1, vertical lines inside heater wells), and were designed to deliver 0.300 kW/ft (0.984 kW/m) over their entire length, except for the lowermost 2 ft (0.6 m), which was boosted to deliver 0.350 kW/ft (1.148 kW/m). Simple electrical distribution gear powered the thermal wells and treatment equipment. Silicon Controlled Rectifiers and Watlow controllers modulated the amount of power to each thermal well circuit to achieve the desired temperature setting. A total of 46 thermocouples were situated at 16 locations and four depths to afford us the ability to track the progress of heating throughout the Target Treatment Zone (TTZ). Three gas pressure monitoring points enabled monitoring of the application of vacuum below the concrete surface cover, which served as an insulating vapor barrier. We installed two screened recovery wells for dewatering and coal tar recovery. Extracted water passed through an oil-water separator, liquid-phase granular activated carbon (GAC) and a frac tank prior to discharge. Extracted coal tar/emulsion was collected for off-site disposal. Extracted vapor passed through a heated manifold, blowers and a 133 scfm (3.8 m^3/min) thermal oxidizer (with backup GAC vessel available) prior to discharge. In addition, a Programmable Logic Controller continuously monitored key process functions, and an emergency backup generator was

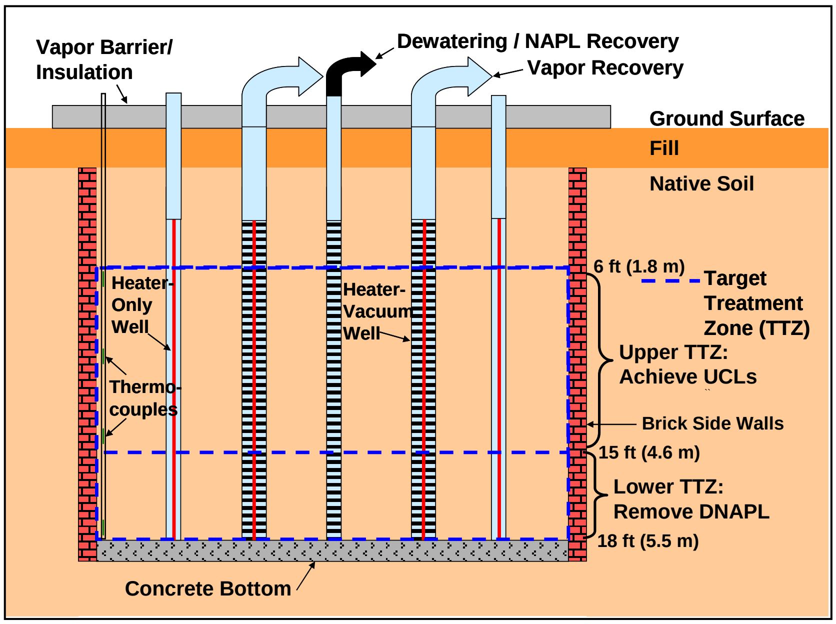

FIGURE 1. Cross-Section of former MGP Gasholder (after Baker et al. 2006).

also tied into the system to provide electricity to operate the treatment and control equipment in the event of a power outage.

RESULTS AND DISCUSSION

TerraTherm carried out the remediation in phases. From February through March of 2004, we dewatered the gasholder, removing >110,000 gal (>416,000 l) of water and treating it prior to discharge. Then we commenced the heating phase. Initially we set the heaters to operate at low temperatures, during which we removed >16,000 gal (>60,000 l) of recoverable tar/emulsion from the gasholder via the liquid extraction wells (Figure 2). After about three months of Level 1 heating, thermally enhanced coal tar recovery had diminished. We then ramped up the heaters to the full operating wattage in early July 2004, and over the next nine months heated the soil throughout the mid-section of the gasholder to a target temperature of 617°F (325°C) (Figure 3). Soil in close proximity to the heater wells became even hotter, hastening reaction kinetics for in-situ SVOC destruction by oxidation and pyrolysis. Within the lower portion of the gasholder, a more modest level of heating to approximately the boiling point of water, 212°F (100°C) was sufficient to thoroughly remove the DNAPL and VOCs, specifically benzene and naphthalene.

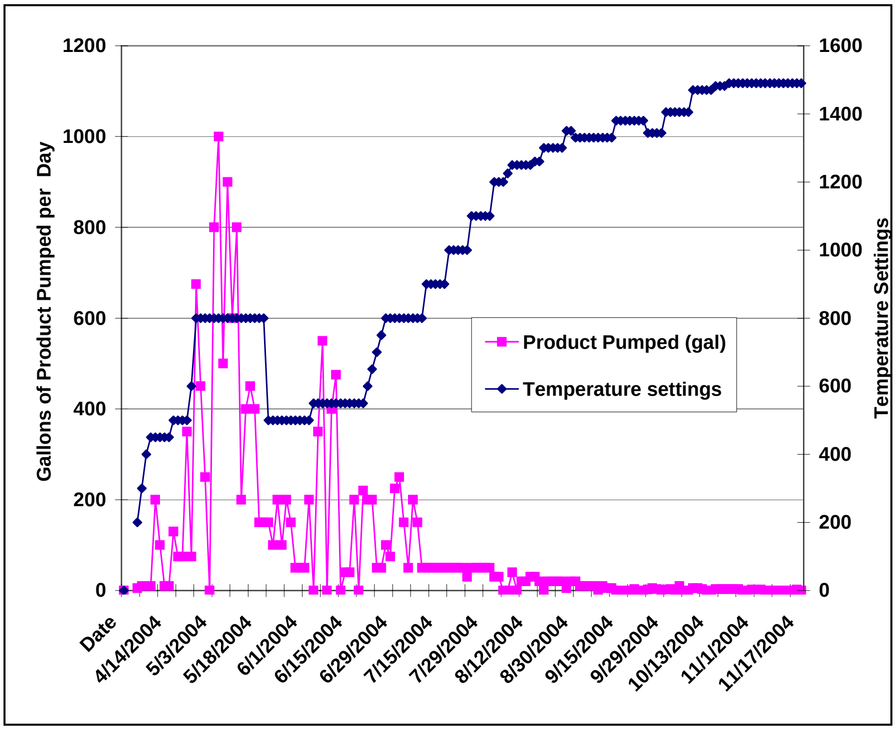

FIGURE 2. Product recovered as a function of temperature settings (°F) of thermal wells. The first three months comprised the Level 1 phase, after which the temperatures were ramped up to accomplish Level 2/3 heating.

Mass Removal. We extracted a total of 165,000 lb (75,000 kg) vapor expressed as naphthalene, treating it in the aboveground thermal oxidizer. Most of the contaminant vapor was removed from 11/04-2/05. Note that adding this 165,000 lb (75,000 kg) of contaminant mass extracted as vapor to the ~135,000 lb (61,000 kg) recovered as product, the total contaminant mass removed was at least 300,000 lb (136,000 kg). This is an underestimate, since the additional mass destroyed in situ is difficult to quantify.

We consistently met the required 95% Destruction and Removal Efficiency (DRE), never dropping below 98% and nearly always close to 100%, with non-detectable stack emissions (<0.1 ppmv). Overall the project consumed 701,000 kWh of electricity.

In March 2005, Brown and Caldwell conducted confirmatory sampling following a pre-established plan, under which they collected a total of 28 soil samples from randomly-selected locations and depths throughout the gasholder. Within its mid-section, where the remedial goals were to achieve UCLs, elevated (Level 3) heating resulted in the following representative reductions in soil concentrations (mg/kg): benzene from 2,068 to 0.35; naphthalene from 679 to 5.7; and B(a)P from 20 to 0.33 (Table 2).

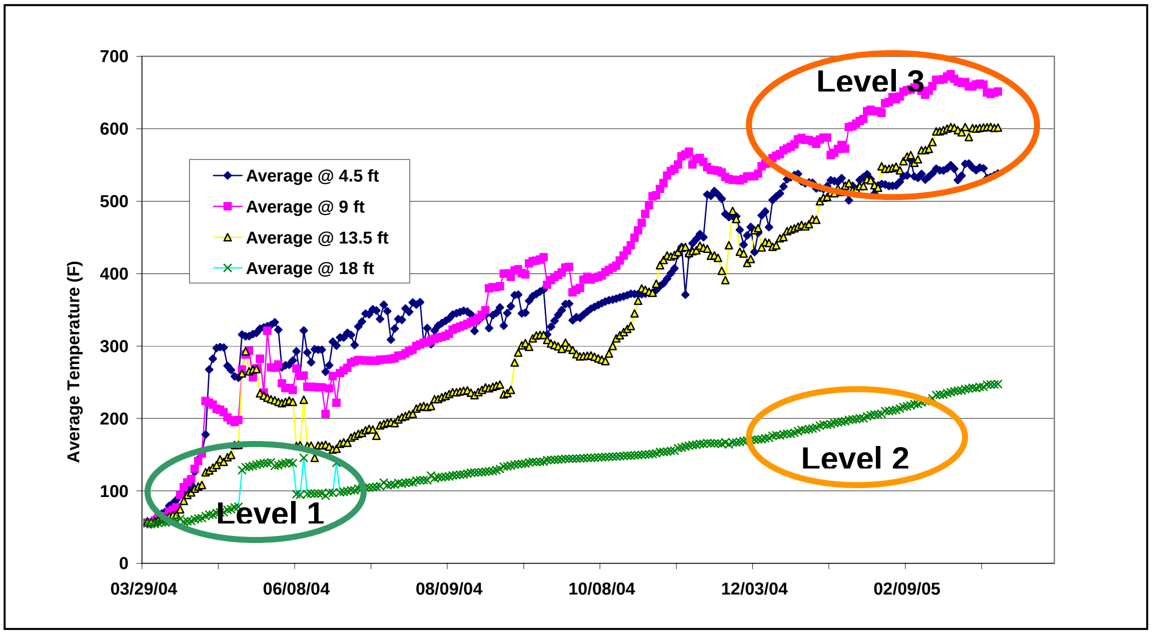

FIGURE 3. Average temperature (°F) by depth, and level of heating achieved.

TABLE 2. Average pre- and post-treatment soil concentrations within the 6-14 ft (1.8-4.2 m) sampling interval, corresponding to the Level 3 heating zone. Note that all post-treatment concentrations within this zone were below the UCLs (Baker et al. 2006).

Constituent	Pre-Treatment mg/kg	Post-Treatment mg/kg	Reduction %
Benzene	2068	0.35	99.98
Anthracene	19	0.48	97.47
Benzo(a)anthracene	20	0.51	97.45
Benzo(a)pyrene	20	0.33	98.35
Chrysene	20	0.71	96.45
Fluoranthene	43	1.02	97.63
Naphthalene	679	5.70	99.16
Phenanthrene	107	3.82	96.43
Pyrene	65	1.12	98.28
C11-C22 Aromatics, unadj.	4000	43.15	98.92

Within the lower portion of the gasholder, more moderate (Level 2) heating resulted in the removal of all DNAPL as was required, with the residual sampled material having the appearance of a dry, brittle black solid. Reductions in benzene within that zone were from 3,400 to 0.95, and in naphthalene from 14,000 to 70 mg/kg (Table 3). These results were consistent with laboratory results reported by Bhupendra and co-workers (2002), which indicated that driving off the VOCs would result in the solidification and stabilization of the remaining, higher molecular weight coal tar residuals as an asphalt-like material. All COCs within the gasholder were significantly below the remedial goals.

TABLE 3. Maximum pretreatment and average post-treatment soil concentrations within the 14-18 ft (4.2-5.5 m) sampling interval, corresponding to the Level 2 heating zone. All DNAPL was eliminated, as was required.

Constituent	Pre-Treatment mg/kg	Post-Treatment mg/kg	Reduction %
Benzene	3,400	0.95	99.97
Anthracene	650	101	84.46
Benzo(a)anthracene	650	166	74.46
Benzo(a)pyrene	650	100	84.62
Chrysene	650	152	76.62
Fluoranthene	650	199	69.38
Naphthalene	14,000	70	99.50
Phenanthrene	3,400	313	90.79
Pyrene	650	303	53.38
C11-C22 Aromatics, unadj.	143,000	4,540	96.83

TerraTherm decommissioned the ISTD wellfield and demobilized from the site in June 2005.

CONCLUSIONS

The first demonstration of a tailored heating approach to the application of ISTD for MGP wastes enabled the attainment of all remedial goals at a turnkey cost ($850,000 for ISTD, $55,000 for electricity, plus $86,000 for tar disposal), which National Grid judges to be less than excavation. TerraTherm carried out the project under a guaranteed performance contract.

The tailored heating approach presented here can be designed to meet the needs of a wide range of MGP projects. At some sites, use of Level 1 heating alone will be sufficient to enable thermally-enhanced recovery of mobile coal tar DNAPL and prevent its seepage into nearby water bodies. At other sites, use of Level 2 heating by itself will remove mobile VOCs such as benzene and naphthalene from the MGP waste, eliminating the risk drivers and enabling the in-situ stabilization of the heavier coal tar residuals. When this approach is not acceptable due to the need to achieve more stringent cleanup levels, Level 3 heating will be the best choice, given its ability to attain post-treatment concentrations throughout the treatment zone that are at or even below detection limits, making it equivalent to complete source removal, without excavation. We envision that a combination of two or more levels of heating may be applicable to many sites, as was demonstrated in this project. Regardless of the approach selected, ISTD is rapid, certain and thorough, without the drawbacks and cost growth typically associated with excavation.

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