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Thermal Treatment of Hydrocarbon-Impacted Soils: A Review of Technology Innovation for Sustainable Remediation

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ABSTRACT

Thermal treatment technologies hold an important niche in the remediation of hydrocarbon-contaminated soils and sediments due to their ability to quickly and reliably meet cleanup standards. However, sustained high temperature can be energy intensive and can damage soil properties. Despite the broad applicability and prevalence of thermal remediation, little work has been done to improve the environmental compatibility and sustainability of these technologies. We review several common thermal treatment technologies for hydrocarbon-contaminated soils, assess their potential environmental impacts, and propose frameworks for sustainable and low-impact deployment based on a holistic consideration of energy and water requirements, ecosystem ecology, and soil science. There is no universally appropriate thermal treatment technology. Rather, the appropriate choice depends on the contamination scenario (including the type of hydrocarbons present) and on site-specific considerations such as soil properties, water availability, and the heat sensitivity of contaminated soils. Overall, the convergence of treatment process engineering with soil science, ecosystem ecology, and plant biology research is essential to fill critical knowledge gaps and improve both the removal efficiency and sustainability of thermal technologies.

1. Introduction

Soil contamination by petroleum and other heavy hydrocarbons is a major global environmental problem. For example, over 100 000 barrels of oil are spilled on average every year in the US, contaminating soils with a range of petroleum hydrocarbons, from crude oils and sludge to refined fuels such as gasoline [1,2]. While a cornucopia of remediation technologies exist, technologies that can quickly treat soils contaminated with a wide range of petroleum hydrocarbons are especially desirable. For example, *in situ* bioremediation of sites impacted by petroleum release can take years, particularly when recalcitrant species such as high molecular weight hydrocarbons are present [3–6]. In contrast, thermal technologies can remediate sites quickly and efficiently (hours to months), often removing over 99% of a wide range of hydrocarbon fractions [7–13]. The latter processes result in high removal efficiencies of both total hydrocarbon mass and total petroleum hydrocarbon (TPH) concentrations, which is a more common regulatory metric.

Quite frequently, the selection of remediation method is driven by considerations that require expeditious completion (e.g., compliance issues, impending property transactions, and impacts on third-party property). Thus, thermal technologies fill an important niche in petroleum hydrocarbon remediation.

Despite these advantages, the high treatment temperatures required by most thermal technologies can pose several downsides.

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First, heating contaminated soils to high temperatures is energy intensive and, thus, a relatively costly endeavor. Secondly, soil minerals and organic matter (OM) decompose and may be totally destroyed at high temperatures, potentially limiting the ability to restore soils and ecosystems to their original state [8,14,15]. While it is clear that thermal remediation technologies effectively remove contamination, the impacts of high temperatures on ecosystems (i.e., plant growth and soil organisms) and re-greening efforts are relatively unexplored. Furthermore, there is a growing need to establish a framework for optimizing thermal remediation with sustainable objectives such as energy and water conservation and ecosystem preservation. The development of a holistic approach toward thermal remediation is imperative in order to ensure that environmental cleanup efforts do not incur unnecessary environmental damage, but rather align with global efforts to enable a more sustainable future [12].

This paper reviews thermal treatment technologies for remediating soil contamination by petroleum hydrocarbon release, and summarizes both the current state of knowledge and potential unintended impacts on ecosystem health. We consider the relative importance of different removal mechanisms for different types of hydrocarbons and operating temperatures, as well as the associated energy and water requirements to discern opportunities to enhance process sustainability in tandem with hydrocarbon-removal efficiency.

2. Thermal technologies

2.1. Thermal desorption

Thermal desorption (TD) involves the application of heat to contaminated soils with the intention of volatilizing/desorbing hydrocarbons, which are then carried away by a sweep gas or vacuum and eventually destroyed via incineration or carbon adsorption [16–18]. TD can be divided into low-temperature thermal desorption (LTTD, 100–300 °C) and high-temperature thermal desorption (HTTD, 300–550 °C).

In concept, TD consists of hydrocarbon desorption alone, but in reality, TD systems often achieve hydrocarbon removal through multiple mechanisms, including oxidation/incineration and pyrolytic reactions (thermal cracking, etc.) [16,18]. The dominance of these mechanisms depends on temperature and oxygen distribution [16]. Heavy hydrocarbons in areas containing low oxygen may be pyrolyzed (thermal cracking, etc.) at corresponding temperatures, whereas hydrocarbons in high-temperature, oxygen-containing regions may be incinerated.

2.1.1. *Ex situ* TD

During these processes, soil is excavated and heated in TD units such as thermal screws or rotary drums (Fig. 1). Desorbed hydrocarbons are carried away from the main reactor chamber by a sweep gas and incinerated or adsorbed onto activated carbon for final disposal and air pollution control. Fuel and heat recovery may be possible if soil moisture is low and hydrocarbon British thermal unit (BTU) content is high. Treated soils must then be re-moisturized to control dust.

In TD processes utilizing dryers (or kilns) with rotary drums and direct heating, contaminated soils are heated with an open-flame burner that typically requires excess oxygen [19]. In counter-current operation, the heater is located at the end where solids exit the TD unit and combustion gases flow against the direction of the solids. Solids entering the rotary drums first come into contact with gases that may have little or no oxygen. Desorption and/or pyrolysis of contaminant hydrocarbons may take place as the soils are heated in this anoxic or hypoxic zone. As the solids approach the exit, however, they enter an oxygen-rich zone where the remaining hydrocarbons and any char produced during pyrolysis are combusted and destroyed.

2.1.2. *In situ* TD

TD is achieved *in situ* through the application of dual heater/vacuum wells to desorb and remove contaminants via vapor extraction (Fig. 2). Thermal conduction heaters are effective for uniformly heating the entire contamination zone. Because thermal conductivity varies very little between soil types, heating is minimally affected by heterogeneity in soil structure or contaminant dispersal [18]. However, because soils have relatively low heat capacity, initial heating of the contaminated zone may require long periods of energy input before desorption will occur [7]. Moving radially from the heater/vacuum wells, radiative heat transfer dominates initially. However, thermal conduction (heat transfer via direct contact of soil particles) is the dominant form of heat transfer overall [7]. These wells may be either horizontal or vertical to suit the depth of contamination [18]. Shallow soil contamination (less than three feet deep) may be treated by thermal blankets or horizontal wells. Once extracted, hydrocarbon-laden air can be incinerated, reused, or adsorbed on activated carbon [20].

In practice, heating and removal mechanisms for *in situ* methods vary spatially depending on proximity to heat/vacuum wells [7,18]. Although precautions are sometimes taken to maintain anoxic conditions and prevent combustion, practices in the field vary widely and the lack of standardization often fails to ensure consistent gas flow conditions [13,21]. Furthermore, to ensure sufficient temperatures throughout the contaminant zone, soils

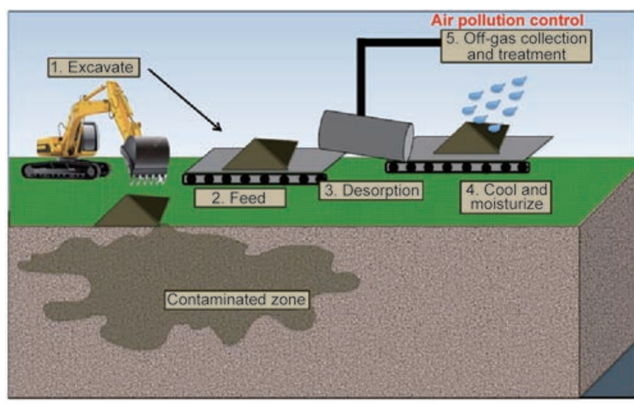

Fig. 1. *Ex situ* TD includes the excavation of contaminated soils, which are heat-treated in a desorption unit (gas flow conditions may vary). Off-gases are collected for reuse or disposal.

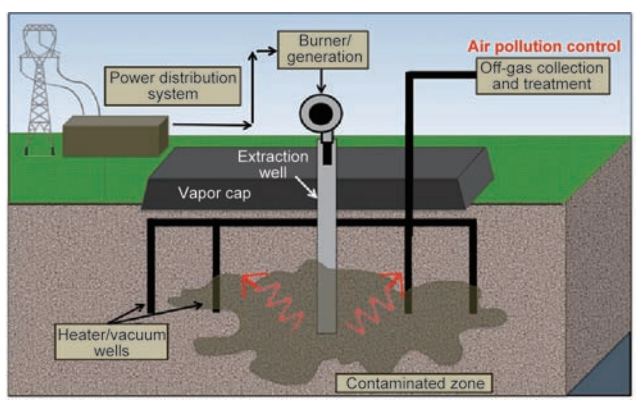

Fig. 2. *In situ* TD utilizes dual heater/vacuum wells to heat soils and remove contaminants. Off-gases are collected for reuse or disposal.