United States Environmental Protection Agency | National Risk Management Research Laboratory Cincinnati, OH 45268
Research and Development | EPA/600/SR-96/031 March 1996

EPA

Project Summary

UST Corrective Action Technologies: Engineering Design of Free Product Recovery Systems

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The objective of the report summarized here is to develop and evaluate the applicability of improved technologies for assessing subsurface liquid fuel spills and for evaluating effects of well placement and pumping rates on separate phase plume control and on free product recovery. Procedures are described for estimating hydrocarbon spill volume from soil core data and monitoring well data. The first method involves vertical integration of soil concentration measurements to yield oil volume or species mass-per-unit area within the measurement zone. This method is especially well suited to determine the amount of residual product in the unsaturated zone. The second method uses a physically based model for vertically hydrostatic three-phase fluid distributions that converts well product thickness to soil product thickness, followed by areal integration to estimate the volume of free product floating on the water table. A procedure is presented to evaluate the effects of water pumping on the oil flow gradients to evaluate if plume spreading will be hydraulically controlled for a selected system. Procedures are also described to estimate the volume of recoverable product as influenced by well placement and operation. Practical examples and case studies are presented to illustrate the methodology and to demonstrate how various factors interact to affect the free product recovery system. The applicability of trenches and vacuum-enhanced product recovery to hydrocarbon spills is also discussed.

This Project Summary was developed by EPA's National Risk Management Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The characterization and remediation of petroleum-contaminated groundwater is currently one of the most challenging problems. Hydrocarbon fluids that are immiscible with water are referred to as nonaqueous phase liquids (NAPLs). In general, most hydrocarbon compounds are less dense than water and are termed light nonaqueous phase liquids (LNAPLs). When released in the subsurface, LNAPLs remain as distinct fluids and flow separately from the water phase. The downward migration of LNAPLs in the vadose zone is generally rapid and, depending upon the complexity of the heterogeneities in the soil, may form an intricate network of pathways. Once in the vicinity of the capillary fringe, LNAPLs will spread horizontally with limited penetration below the water table due to buoyancy. Contact with groundwater and with infiltrating soil pore water causes chemical constituents to dissolve from the LNAPLs into the groundwater and to contaminate the aquifer. Further, volatile constituents may partition into and move in the soil vapor. Through this complex array of physical and chemical processes, the hydrocarbon continually changes. The characterization, containment, and remediation of hydrocarbons pose unique and difficult problems because of the various processes that may occur at a given site.

The first step in assessing a hydrocarbon spill generally involves delineating the vertical and horizontal extent of soil and groundwater contamination. Characterization may include visual observations of soil borings, in situ vapor readings, laboratory analysis of soil concentrations, measurements of fluid levels and dissolved and vapor concentrations in monitoring wells or probes, and surface or subsurface geophysical methods.

Measurements of soil concentrations (e.g., total petroleum hydrocarbons or individual species) provide the most reliable quantitative information on the actual volume or mass of hydrocarbon in the subsurface. Since laboratory analyses of the soil samples are costly and are not practically amenable in monitoring temporal changes, estimating spill volume from fluid level measurements in monitoring wells is more practical. Unfortunately, estimation of hydrocarbon volume from well fluid level data is less straightforward than estimation from soil concentration data. A general lack of understanding in this area, compounded by promulgation of methods of doubtful validity and poor accuracy, has resulted in widespread misunderstanding.

A theoretically based method for estimating oil-specific volume from well product thickness was developed based on the assumption of vertical equilibrium pressure distributions near the water table, which can be inferred from well fluid levels. From the fluid pressure distributions and a general model for three-phase capillary pressure relations, vertical oil saturation distributions are computed and integrated to yield oil-specific volume (hydrocarbon volume per unit soil area).

In addition to "free" product that is sufficiently mobile to enter a monitoring (or recovery) well, a significant portion of the total spill volume may occur as "residual product," confined as hydraulically isolated blobs or thin films of oil that are effectively prevented from moving by capillary forces. Changes in water table elevations will generally result in increased residual volumes over time. These fluctuations may result from natural recharge variations, drawdown, or injection as well as from air-oil and oil-water fluid interface elevation changes resulting from plume spreading or recovery operations. The key to maximizing product recovery from spill sites involves minimizing the volume of residual product.

Product recovery systems are often based solely on containment considerations. That is, trenches and/or wells are located to prevent further plume migration. Although such an approach may be effective in a limited sense, it disregards an evaluation of efficiency because plume containment can be achieved through the use of many different well/trench configurations and operating conditions. Depending on the regulatory requirements, risk characterization, and hence the cleanup objectives, "efficiency" may have different meanings: total volume of product recovered, ratio of product recovered per gallon of water pumped, time to reach asymptotic recovery, capital and operating costs, etc. Once specific objectives have been defined, various design strategies may be evaluated to obtain the desired "efficiency."

Recent advances in numerical models for multi phase flow along with increases in microcomputer speed and capability have made it possible to perform sophisticated analyses to assess the effects of various design options and natural events on spill migration and recovery system performance. Although such analyses require significant computational effort and personnel commitment, which can limit their applicability to large or high-risk sites, their use is essential to fully evaluate the potential complexities of hydrocarbon assessment and remediation.

Purpose

The purpose of the full report is to present a set of accurate yet computationally simple protocols for spill site assessment and remedial design for hydrocarbon spills. The methods are particularly suited to small spills, for which more sophisticated analyses may not be warranted, and as a preliminary modeling tool for larger spills. This report discusses the physical processes that control hydrocarbon retention, movement, and recovery. It describes algorithms for estimating free and residual hydrocarbon volumes from monitoring well and soil boring data as well as for evaluating plume migration and containment, and for evaluating product recovery volume and time as affected by well and/or trench placement and operation. The methodologies are simple and, although somewhat laborious for hand calculations, require minimal computational effort for desktop computers.

Document Contents

The document summarized consists of five sections that provide a fundamental understanding of free product behavior in the subsurface and of spill assessment methodologies that can be used to design product recovery systems. Section 1 provides an introduction and background on previous methodologies that have been used for estimating free and residual hydrocarbon thickness and for designing recovery systems.

Section 2 provides the fundamental concepts of hydrocarbon movement and retention in the subsurface and the methods for estimating fluid and soil properties. The concepts presented include: two- and three-phase (water, air, and NAPL) fluid flow; capillary retention relations (i.e., capillary pressure-saturation functions); vertical equilibrium fluid distributions (i.e., fluid "table" elevations); residual oil in saturated and unsaturated zones; oil relative permeability and transmissivity; and estimation of fluid and soil properties.

Section 3 presents a methodology for hydrocarbon spill assessment. The methodology includes: interpreting soil contaminant data (TPH or BTEX) to estimate the hydrocarbon volume and volume of contaminated soil; estimating free oil volume from monitoring well data; and estimating dissolved and free-phase transport. Example calculations illustrate the use of the methodology.

Section 4 builds on the concepts presented in the previous sections and presents a methodology for the design of product recovery systems. Discussions concern the criteria for system design, the effects of well placement and operation, evaluation of plume capture and travel time analysis, and estimation of recoverable product. Considerations are also given on the use of trenches and vacuum-enhanced free product recovery systems. Example problems illustrate the methodology presented in this section.

Section 5 applies the methodology presented in this report for assessment and remediation of a hydrocarbon spill site in a case study. As part of this case study, a screening level model that employs this methodology was used to calculate the mobile hydrocarbon volume, contaminated soil volume, recoverable and residual hydrocarbon volumes to estimate the flow field configuration, time of recovery, optimal recovery rates, and system efficiency. The methodology described in this report has been implemented in the program SpillCAD.

The full report was submitted in fulfillment of Contract No. 68-C2 0108 by IT Corporation and its subcontractor Environmental Systems & Technologies, Inc. under the sponsorship of the U.S. Environmental Protection Agency.

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The complete report, entitled "UST Corrective Action Technologies: Engineering Design of Free Product Recovery Systems," (Order No. PB96-153556; Cost: $25.00, subject to change) will be available only from:
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