

Closure Checklist & Closure Citation Guidelines

Nevada Division of Environmental Protection
Bureau of Corrective Action
Petroleum in Soils Closure Checklists
June 2014

Statement of Purpose

“The purpose of this document and the attached checklists is to clearly define all options and requirements for closure under Nevada’s Corrective Action regulations for sites that have soil contamination resulting from releases of petroleum. It has been drafted to assist property owners, environmental consultants, and NDEP case officers in making informed decisions about petroleum cleanups, to promote consistency in closure decisions, and to make petroleum cleanups efficient and protective.”

Introduction

In 2009, the Nevada Division of Environmental Protection, Bureau of Corrective Actions (NDEP) amended its site cleanup regulations at NAC 445A.226 to 445A.22755 and removed its longstanding numeric soil action level for total petroleum hydrocarbons (TPH). The soil action level for TPH of 100 mg/kg was originally established as part of the leaking underground storage tank program and was later included for all sites under corrective action. No other hazardous substances were given specific, numeric action levels in regulation. Hazardous substances other than petroleum relied on risk-based decision making to address these substances on a site- and chemical-specific basis. The removal of the numeric standard in 2009 was intended to place petroleum in the same risk-based decision making framework as all other hazardous substances.

Having a single action level for TPH did not accurately reflect the wide range of petroleum products that may require site cleanup, and the use of the action level as a default cleanup standard often led to costly cleanups that did not consider site risks. As defined in statute, “petroleum” refers to a range of petroleum mixtures and formulations which are liquid at standard temperature and pressure and includes crude oil, diesel, heating oil, gasoline, mineral oil, or any other formulation. Each formulation may behave differently when released to the environment based on their composition, mobility, volatility, and persistence. Each formulation also consists of constituents with different toxicities and exposure risks. The 100 mg/kg action level was established to ensure protectiveness for the petroleum formulations that presented the greatest risk to human health. This resulted in releases of less mobile and less toxic formulations being held to a restrictive standard.

Not only is the use of a single action level hindered by the range of formulations that falls under the regulatory definition of “petroleum” but also by the fact that each formulation of petroleum is itself a mixture of many constituent hydrocarbon molecules. The 100 mg/kg petroleum action level in regulation was based on analysis of Total Petroleum Hydrocarbons (TPH). This approach does not differentiate between individual petroleum constituents. Analysis of total petroleum hydrocarbons may not provide an accurate reflection of site risks because it does not differentiate between the constituents that serve as risk-drivers based on the toxicity and mobility of constituents with known health effects.

The NDEP decided to deemphasize the 100 mg/kg TPH in soil action level at corrective action sites by eliminating that numeric value from the regulations; however, the NDEP has not eliminated it as a pathway to closure for sites with petroleum contamination. Rather, the use of a single numeric action level has been placed alongside a number of equally valid pathways to closure that can be considered by owners or operators of property where a petroleum release has occurred. All closure options discussed in this document are fully supported by the corrective action regulations at Nevada Administrative Code 445A.226 to 445A.22755. This document is intended to identify and describe all options for closure so that an owner or operator may select an approach that best meets their available resources, timeframes, and intentions.

At this time, this document only addresses corrective actions involving petroleum. Corrective actions involving other hazardous substances follow the same regulations and many of the same considerations, but this document is specific to petroleum and to the issues related to petroleum hydrocarbons. Some assumptions about the mobility and biodegradation of petroleum may not be applicable to other hazardous substances. While the general precepts about corrective action and site closure under Nevada regulations have wide applicability and can be used as a guide for all soil cleanups, specific determinations for petroleum cleanups should not be applied to other cleanups without chemical-specific consideration by property owners, consultants, and NDEP case officers.

Additionally, this document is intended for use at sites with soil contamination only. The NDEP will not provide closure of a site until all contaminated media have been adequately addressed; however, the soil-specific focus of this document may not be applicable at sites with both soil and groundwater contamination.

Document Overview

The substance of this document is the checklists, tables, and technical papers located in the appendices. These are tools to help NDEP case officers make consistent, defensible closure determinations for petroleum releases. They are also intended to communicate requirements for soil closure to property owners and environmental consultants. The next few sections of this document describe some of the decision-making for determining the appropriate closure method and provide justification for the general requirements applicable to all sites.

The Four Closure Options

For any Corrective Action project it is critical to identify an endpoint or goal that can guide site cleanup decisions. To assist owners and operators the NDEP has identified four endpoints in its corrective action regulations for sites with soil contaminated by petroleum. Each of the four closure options relies on a few different regulatory citation and has different requirements for demonstration, but all options are available and equally valid for use at all sites.

This section is intended to introduce the four closure options and to provide general comparisons between them. The comparisons are intended to assist property owners and operators make a determination about their preferred approach to site cleanup since each closure option may have its own benefits or drawbacks. The NDEP does not dictate which closure option is appropriate for sites but determines whether requirements have been satisfied. The four closure options are

- 1) **Clean Closure:** all confirmation samples (using analytical EPA Method 8015 modified) at the site are below 100 mg/kg for TPH. This is the reportable concentration that has been set for TPH by the NDEP as generally posing an acceptable level of risk for all exposure scenarios.
- 2) **Analyte-Specific Closure:** all confirmation samples show that petroleum hydrocarbon constituents are below default screening levels established by the NDEP to be protective of direct contact exposure and leaching to groundwater. Constituents to be screened are selected based on their toxicity (both cancer and non-cancer hazards) and presence in petroleum formulations.
- 3) **A-thru-K Closure:** concentrations of petroleum hydrocarbons and petroleum constituents above screening levels may be left in place based on a site-specific analysis of the A-thru-K factors listed in the corrective action regulations to show that known residual concentrations are still protective even if they are above action levels.
- 4) **ASTM RBCA Closure:** all concentrations of petroleum hydrocarbons and constituents are below Site Specific Target Levels established through a Tier II or Tier III analysis conducted consistent with the ASTM Risk-Based Corrective Action method E1739-95 or equivalent.

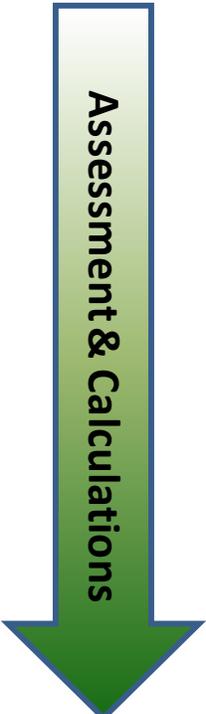
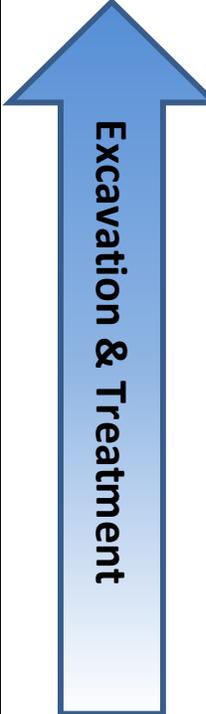
The ordering of the closure options is not intended to convey agency preference. Rather, the closure options are presented as a continuum, from options that rely more on cleanup and removal of soil to options that rely more on modeling or calculation of site risks.

There are many factors that weigh into an owner or operator's decision about the best pathway to closure. Among the many considerations are costs for assessment and cleanup; project turnaround time; long-term liability and continuing obligations; future site uses; technical knowledge and sophistication required to achieve closure; level of regulatory involvement and the likelihood of findings of deficiencies by case officers; and property ownership issues. Each closure option represents a balance of these factors: some closure options may have a lower cleanup cost that comes at the expense of longer project times or greater continuing obligations, while others may favor swift resolution of issues through excavation with little or no requirement for regulatory review of protectiveness determinations.

The most fundamental balancing factor amongst the closure options is the level of effort for assessment versus cleanup necessary to achieve regulatory concurrence. Generally, sites that achieve closure through excavation or treatment will require fewer resources for assessment and vice versa. Excavation and/or treatment of contaminated soils can represent a significant portion of project costs; however, the costs of assessment, calculations, and modeling should not be discounted. Making a defensible argument that residual petroleum contamination can remain in place above action levels involve variable costs depending on the size of the project, regulatory scrutiny, land use assumptions, and site conditions. In most instances, at small sites the costs of excavation and disposal will generally be lower than the cost to make a defensible argument to leave the contamination in place. As the volume and depth of contamination increases, the cost of excavation, disposal and/or treatment will begin to exceed the costs of leaving it in place.

There may be other factors besides cost which influence an owner or operator's decision about an appropriate closure approach. Closure approaches that rely on excavation and disposal are generally quicker than other approaches. If a site cleanup is under a time deadline because of property transfer or construction, then additional costs for excavation and disposal of soils may be less important than the time it takes to obtain a no further action determination from the NDEP. An owner's long-term liability or continuing obligations to maintain the protectiveness of leaving residual contamination in place may

be another consideration that is prioritized above cleanup cost. Because determinations to leave residual contamination in place usually involve assumptions about land use and nearby populations, these closures might be reevaluated in the future if assumptions change, or they may need to rely on the protection of an environmental covenant; this can represent an unacceptable continuing obligation or liability for a property owner, who may elect to avoid these obligations or liabilities by undertaking additional cleanup. Also, individuals who are undertaking corrective action on property that they do not own may be constrained by the desires of the property owner for a specific level of cleanup.

| General relationship between closure types and the level of effort for both assessment and cleanup to achieve closure | | |
|---|--|--|
|  |  | 1) Clean Closure: cleanup proceeds until confirmation samples show that TPH is below 100 mg/kg. Cleanup costs are higher because less residual contamination is left behind, but the assessment and analytical costs are lower for TPH analyses and there is less likelihood of regulatory determinations requiring additional information for closure. |
| | | 2) Analyte-Specific Closure: cleanup proceeds until confirmation samples show that constituents are below action levels even while residual TPH contamination remains. Assessment costs are higher because the laboratory analyses are more costly, residential vs. industrial exposures must be addressed, and accurate volatile results must be obtained. |
| | | 3) A thru K Closure: residual petroleum contamination above action levels may be left in place through a site-specific demonstration of protectiveness. Protectiveness must be demonstrated through site characterization and defensible arguments of fate and transport. Assumptions may need to be controlled by land use restrictions. |
| | | 4) ASTM RBCA Closure: site-specific target levels are developed for a site through risk-based calculations of fate, transport, and toxicity. The process is fully laid out in ASTM standards but requires site-specific inputs for calculations. Assumptions may need to be controlled by land use restriction. |

It should be noted that once an owner or operator selects a closure option and a corrective action approach, he or she is not irreversibly tied to that closure option or approach, since corrective action sites might evolve as more information is collected. For instance, a property owner who decides that clean closure is the appropriate goal may make a different decision later in the project if significantly more contamination is discovered or if excavation becomes difficult because of utilities or overlying structures. Corrective Action Plans will need to be amended to incorporate revised approaches, but the NDEP will not hold a property owner or operator to a specific cleanup as long as another viable approach to closure is presented.

General Provisions for All Closures

Each of the closure options has different requirements that must be demonstrated to allow the NDEP to provide a “No Further Action” letter to a property owner or operator; however, there are some requirements that are common to all closure decisions made by the NDEP. These requirements have

been identified as general provisions that apply to all soil corrective action cases regardless of which closure option is being pursued:

General Provision #1 – Ongoing Releases Addressed

All continuing inputs of petroleum contamination to the soil being addressed by corrective action shall be identified and eliminated prior to closure. This includes ongoing releases from underground storage tanks and associated piping; discharges from drains and washouts; leaks from barrels or aboveground tanks; and etc. This provision does not, in itself, create an obligation for an owner or operator to address any other potential sources of petroleum that may result in future releases or to address any sources not directly related to the contamination being addressed by corrective action.

General Provision #2 – Abatement

Closure decisions are made on residual concentrations that remain in soil after actions are taken to respond to the release of petroleum. None of the closure options are intended to relieve an owner or operator from the obligation to take abatement actions in response to releases of petroleum, such as the removal of released product and the excavation of grossly impacted soil. In instances where historic contamination is discovered, there may no longer be any product or grossly impacted soil present, and this provision for abatement may not apply.

General Provision #3 – Complete Characterization

Closure shall be provided only with a full understanding of contaminant delineation. This includes knowledge of the depth and lateral extent of soil contamination as well as a general understanding of the location and volume of the areas with the highest remaining concentrations of petroleum (and petroleum constituents, as appropriate). Closure will also be dependent on a full understanding of exposure pathways relevant to the site including pathways and rates of migration for contaminants and awareness of any potential receptors.

General Provision #4 – Aesthetics

While site closure is granted by the NDEP based on health-based standards and/or determinations in accordance with Nevada statutes and regulations, the consideration of aesthetic factors will assist in ensuring closure decisions are not reopened. Any visible staining or odoriferous soil left at or near the surface, even if the release was closed using health-based standards, may result in future notification by the public, adjacent property owners, or future operators to the NDEP as an apparent release, which could result in the reopening of a case. The NDEP recommends a minimum of one (1) foot of clean material be present, where feasible, over any underlying residual contamination that remains in-place at closure to address potential aesthetic concerns. The NDEP may also recommend additional actions to address aesthetic concerns.

General Provision #5 – Imported Fill Is Consistent With Closure Conditions

Any fill material that is imported to the site as a component of corrective action to fill excavations, restore grades, or cap residual contamination must meet closure criteria for the site, which

may be required to be demonstrated at NDEP's discretion. Property owners/operators and CEMs are also cautioned that use of fill containing hazardous substances above reporting limits established in NAC 445A.347 can be considered a separate reportable release for the site.

Using the Closure Checklists

Closure checklists (Appendix A) have been developed to summarize and condense the general provisions and closure-specific requirements for cases with petroleum contamination in soil. The general closure provisions, applicable for all cases, need to be satisfied to allow the case officer to advance towards closure. If any of these general closure provisions is not satisfied for a given site, the case officer is instructed to work with an owner or operator to resolve the deficiency prior to providing closure. For the closure-specific checklists, only one of the separate checklists must be completed. If an owner or operator cannot satisfy the requirements of a particular checklist, one of the other closure options may be applicable.

Appendix B contains tables developed by the NDEP that provide greater detail for specific closure types as referenced in the checklists in Appendix A.

Appendix C contains a technical paper published by the American Petroleum Institute that is referenced in several of the closure-specific checklists.

**Nevada Division of Environmental Protection
Bureau of Corrective Action
Petroleum in Soils Closure Checklists**

**Appendix A
Checklists**

Nevada Division of Environmental Protection
Petroleum in Soils Closure Checklists
General Closure Provisions

Facility Name: _____ Case Officer: _____

Facility ID: _____ Date: _____

In order to achieve closure for a site where petroleum has been released to the soil or where petroleum has been discovered in soils as a result of subsurface investigation, a facility owner/operator must be able to demonstrate that these five general closure conditions have been satisfied.

A case officer should use his or her best professional judgment to determine whether information provided by the facility owner/operator is sufficient to make a determination and to check off the "Satisfied" box.

A set of general guidelines to help a case officer make a decision is included for each provision. A case officer may fill out the "Notes:" section to provide a brief justification for the determination, if warranted.

General Closure Provision#1—Ongoing Releases Satisfied Not Satisfied

Requirement: *All continuing inputs of contamination to the soil (directly related to the corrective action case) have been identified and controlled to prevent redeposition of contaminants after closure.*

Some things to look for when determining that the "Ongoing Releases" provision is Satisfied

- The release was a one-time, accidental event such as mobile source releases, gas station overfills, and etc. that does not represent a potential on-going source.

- If leak is from an active regulated UST, all compliance issues related to release prevention and leak detection have been resolved or are being actively overseen by the appropriate UST compliance group.

- If the release occurred at a facility with a water pollution control permit or a RCRA waste generation permit, the facility owner or operator has resolved all permit compliance issues arising from the release.

- If the release was from a fixed source container that is not regulated by another program (i.e., aboveground storage tanks), the facility owner or operator has taken steps to prevent future releases.

- If the release source is not known, the facility owner or operator has provided adequate documentation to demonstrate that there are no on-going sources to the contamination.

Notes: _____

Recommended next steps: _____

General Closure Provision #2—Abatement

Satisfied

Not Satisfied

Requirement: *Appropriate abatement actions were taken in response to the release to prevent further degradation, and closure decisions are being made on residual soil contamination only.*

Some things to look for when determining that the “Abatement” provision is Satisfied

- If the case was the result of a release to the ground, the owner or operator conducted abatement and/or cleanup prior to applying action levels or pursuing a risk-based closure.
- The case was the result of discovery of subsurface contamination, and the owner or operator pursues a risk-based closure after reducing the volume or concentration of contaminants remaining in place.
- If the NDEP used EMAR or other sources of funding to address an imminent and substantial hazard at the site or another government agency expended funds to address hazards that are recoverable through regulation, cost recovery has been resolved with the owner or operator.

Notes: _____

Recommended next steps: _____

General Closure Provision #3—Characterization

Satisfied

Not Satisfied

Requirement: *Site decisions were made with an understanding of contaminant makeup, location, concentrations, and exposure pathways.*

Some things to look for when determining that the “Characterization” provision is Satisfied

- Vertical delineation of soil contamination has been determined with either non-detect samples at depths below the contamination, a data set showing clear decreasing trends of contaminants at depth (approaching action levels or other acceptable concentrations under a risk-based closure), or samples from the soil column all the way to the top of the water table.
- Lateral delineation of soil contamination has been determined by surface sampling, sidewall sampling, or other exploratory sampling (drilling, boreholes, and etc.).
- For sites with multiple release sources or commingled soil contamination, vertical and lateral delineation has been achieved for all sources or areas of contamination.
- Density of confirmation samples is adequate to make an informed decision (e.g. equal to or greater than the regulatory minimum established for a UST excavation or an equivalent density for larger excavations).

Notes: _____

Recommended next steps: _____

General Closure Provision #4—Aesthetics

Satisfied

Not Satisfied

Requirement: *The release has been addressed such that site conditions will not likely result in the re-reporting of residual contamination by occupants, neighbors, or future owners based on visual or other aesthetic conditions.*

Some things to look for when determining that the “Aesthetics” provision is Satisfied

- Surface staining associated with remaining contaminants is not present in an area exceeding 4’ by 4’ after corrective action.
- Soils with contaminants near saturation are not present within 2 feet of ground surface after corrective action, as this would likely cause surface staining in the future as a result of capillary action.
- Odors from volatile constituents are not noticeable and persistent in adjacent structures after corrective actions.
- Excavations have been filled in, and the site is free of depressions that would promote ponding.
- Solid waste indirectly related to the release (such as vehicle wreckage at mobile source cases, solid wastes co-disposed with hazardous substances at illegal dumps, etc.) have been removed or addressed to end perception of release and to not promote future illegal disposal.

Notes: _____

Recommended next steps: _____

General Closure Provision #5—Imported Fill

Satisfied

Not Satisfied

Requirement: *Any material imported to the site as a component of corrective action to fill excavations, restore grades, or cap residual contaminants has either been demonstrated to be consistent with closure criteria or is not likely to be inconsistent with closure criteria.*

Some things to look for when determining that the “Imported Fill” provision is Satisfied

- Source of imported fill is discussed in the closure request and reasonably rules out the presence of hazardous substances, regulated substances, or hazardous waste.
- Sampling results are provided to reasonably rule out the presence of hazardous substances, regulated substances, or hazardous waste at concentrations inconsistent with site closure.

Notes: _____

Recommended next steps: _____

Nevada Division of Environmental Protection
Petroleum in Soils Closure Checklists
“Clean Closure” Checklist

Facility Name: _____ Case Officer: _____

Facility ID: _____ Date: _____

Clean Closure: all confirmation samples (using analytical EPA Method 8015 modified) at the site are below 100 mg/kg for TPH. This is the reportable concentration that has been set for TPH by the NDEP as generally posing an acceptable level of risk for all exposure scenarios.

| Clean Closure Checklist | |
|---|---|
| All Requirements In Grey Must Be Met | |
| _____ | Proper field sample collection procedures used |
| Confirmation samples are taken as discrete samples and are collected and preserved using appropriate procedures to minimize loss of volatile constituents prior to analysis. | |
| _____ | Proper laboratory analytical method used |
| All confirmation samples are analyzed using EPA Method 8015 Modified for Petroleum Hydrocarbons | |
| _____ | Proper laboratory sample preparation procedure used |
| The laboratory preparation procedure is appropriate for the type of petroleum product released: Gasoline—Purge and Trap Diesel and other mid-range products—Purge and Trap + Solvent Extraction Oil and other high-range products—Solvent Extraction Unknown—Purge and Trap + Solvent Extraction | |
| _____ | Appropriate detection limit achieved |
| The reported detection limit from the laboratory is less than 100 mg/kg for total petroleum hydrocarbons for all confirmation samples. | |
| _____ | Action level for clean closure met in all confirmation samples |
| All confirmation samples are below 100 mg/kg for Total Petroleum Hydrocarbons. | |
| _____ | Destruction certificates or disposal certificates provided for all excavated soil |
| All soil above 100 mg/kg TPH that was excavated as a result of corrective action or abatement actions and that has been taken off-site for treatment or disposal has been accounted for with disposal or destruction certificates. If soil has been treated on-site and remains on-site in accordance with an approved corrective action plan, this requirement may be marked N/A and considered satisfied. | |

Nevada Division of Environmental Protection
Petroleum in Soils Closure Checklists
“Analyte-Specific Closure” Checklist

Facility Name: _____ Case Officer: _____
 Facility ID: _____ Date: _____

Analyte-Specific Closure: all confirmation samples show that petroleum hydrocarbon constituents are below default screening levels established by the NDEP to be protective of direct contact exposure and leaching to groundwater. Constituents to be screened are selected based on their toxicity (both cancer and non-cancer hazards) and presence in petroleum formulations.

| Analyte-Specific Closure Checklist All Requirements In Grey Must Be Met | |
|---|---|
| ___ | Proper field sample collection procedures used |
| Confirmation samples are taken as discrete samples and are collected and preserved using appropriate procedures to minimize loss of volatile constituents prior to analysis. | |
| ___ | All contaminants of potential concern have been analyzed |
| Confirmation samples contain analytical results for all contaminants of potential concern associated with the petroleum product released. The contaminants of potential concern are identified on Table 1 of Appendix B. If the petroleum product has not been identified, all constituents on the Table should be analyzed. | |
| ___ | Proper laboratory analytical methods used |
| All confirmation samples are analyzed using the appropriate laboratory method identified on Table 1 of Appendix B, and the laboratory has employed an appropriate sample preparation for the analytical method. | |
| ___ | Appropriate detection limit achieved |
| The reported detection limit from the laboratory is below the screening level for all constituents. (This may require the use of Selected Ion Monitoring for polynuclear aromatic hydrocarbons for sites where they are a contaminant of potential concern.) | |
| ___ | Action levels for Analyte-Specific Closure have been met |
| All concentrations are below the action levels for analyte-specific closure in all confirmation samples. | |
| ___ | Residual TPH concentrations are not indicative of NAPL migration |
| All concentrations of TPH are below the levels indicative of NAPL migration for the soil type at the site as published by the American Petroleum Institute in Appendix C | |
| ___ | Land use assumptions are supported and protective |
| If the higher action levels for industrial or commercial exposure scenarios are used at the site, information presented by the facility owner or operator should demonstrate that future land use will remain industrial/commercial or is controlled through an environmental covenant. | |
| ___ | Environmental Covenant discussed when residual petroleum contamination exceeds 100 yds³ |
| If greater than 100 yds ³ of petroleum impacted soil is to remain on the site, an environmental covenant should be considered and discussed with a supervisor to determine whether future management of petroleum contaminated soils needs to be controlled. | |
| ___ | Destruction certificates or disposal certificates provided for all excavated soil |
| All soil above 100 mg/kg TPH that was excavated as a result of corrective action or abatement actions and that has been taken off-site for treatment or disposal has been accounted for with disposal or destruction certificates. If soil has been treated on-site and remains on-site in accordance with an approved corrective action plan, this requirement may be marked N/A and considered satisfied. | |

Nevada Division of Environmental Protection
Petroleum in Soils Closure Checklists
“A thru K Closure” Checklist

Facility Name: _____ Case Officer: _____

Facility ID: _____ Date: _____

A-thru-K Closure: concentrations of petroleum hydrocarbons and petroleum constituents above screening levels may be left in place based on a site-specific analysis of the A-thru-K factors listed in the corrective action regulations to show that known residual concentrations are still protective even if they are above default action levels.

| A thru K Closure Checklist | |
|---|---|
| All Requirements In Grey Must Be Met | |
| _____ | “A Thru K” closure request presented in an acceptable format |
| The “A Thru K” presents a coherent, defensible argument for closing the site with contamination above action levels, and it includes all supporting data, figures, and calculations relied on in the argument. | |
| _____ | Data quality is sufficient to make defensible determinations about protectiveness |
| The “A thru K” analysis is based on data of sufficient quality as determined either by adherence to an approved quality assurance project plan or to generally accepted standard operating procedures for data collection and analysis. | |
| _____ | All constituents of concern have been identified and properly addressed |
| The “A thru K” closure request addresses all constituents of concern at the site. Constituents of potential concern include all the constituents associated with the petroleum product that has been released; constituents of concern include all the constituents of potential concern that exceed health-based standards (Table 1 of Appendix B). | |
| _____ | All exposure pathways have been examined and properly addressed |
| The “A thru K” closure request examines all exposure pathways and determine whether they are incomplete, potentially complete, or complete at the site. | |
| _____ | The direct contact exposure pathway is demonstrated to be incomplete |
| Contamination in the top 6 feet at a site must be below analyte-specific action levels (Table 1 of Appendix B) or demonstrated to be inaccessible both to excavation/treatment and to direct contact by receptors. | |
| _____ | Petroleum saturated soils have been remediated or removed to a reasonable extent |
| The facility owner or operator must make reasonable efforts to treat or remove soils that are indicative of NAPL formation or migration (API, Appendix C) as a step to minimize further degradation of subsurface soils or potential impacts to groundwater. The reasonableness of efforts may consider the vicinity of structures, depths of contamination, or remoteness of the location. If petroleum concentrations above screening levels for NAPL migration remain at the site, vadose zone modeling or calculations must demonstrate that groundwater impacts will not occur or will be sufficiently controlled. | |
| _____ | Environmental Covenant discussed when residual petroleum contamination exceeds 100 yds³ |
| If greater than 100 yds ³ of petroleum impacted soil is to remain on the site, an environmental covenant should be considered and discussed with a supervisor to determine whether future management of petroleum contaminated soils needs to be controlled through a covenant. The covenant may also stipulate specific land use practices, engineering controls, and periodic review and reporting to NDEP to affirm maintenance of the engineering and institutional controls. | |

Nevada Division of Environmental Protection
Petroleum in Soils Closure Checklists
“ASTM RBCA Closure” Checklist

Facility Name: _____ Case Officer: _____

Facility ID: _____ Date: _____

ASTM RBCA Closure: all concentrations of petroleum hydrocarbons and constituents are below Site Specific Target Levels established through a Tier II or Tier III analysis conducted consistent with the ASTM Risk-Based Corrective Action method E1739-95 or equivalent.

| ASTM RBCA Closure Checklist | |
|--|---|
| All Requirements In Grey Must Be Met | |
| _____ | ASTM RBCA conducted in accordance with Method E1739-95 |
| The facility owner/operator and their consultant have submitted sufficient information to the NDEP and in a format that allows the NDEP to determine whether the Method was followed appropriately. | |
| _____ | Data quality is sufficient to make defensible determinations about protectiveness |
| The analyses in the ASTM RBCA are based on data of sufficient quality as determined either by adherence to an approved quality assurance project plan or to generally accepted standard operating procedures for data collection and analysis. | |
| _____ | All constituents of concern have been properly addressed in the RBCA analysis |
| Procedures in the ASTM RBCA method are followed for the identification of contaminants of concern. Site Specific Target Levels are developed for all contaminants of concern. | |
| _____ | All exposure pathways have been examined and properly addressed |
| Procedures in the ASTM RBCA method are followed for the identification of completed exposure pathways and the Site Specific Target Levels are established based on the most conservative exposure pathway calculation for the site. | |
| _____ | Confirmation sampling shows constituents of concern to be below Site Specific Target Levels |
| Samples show that residual contamination is below Site Specific Target Levels developed for the site. The density and quality of samples is sufficient to demonstrate achievement of Site Specific Target Levels. | |
| _____ | Residual TPH contamination addressed either directly or indirectly in the ASTM RBCA |
| Residual TPH contamination is shown to be unlikely to further degrade subsurface soils or groundwater through either the development of SSTLs for TPH or through the excavation and treatment of soils above screening levels for NAPL migration published by the API in their June 2000 “Soil and Groundwater Research Bulletin” (Appendix C). | |
| _____ | Environmental Covenant discussed when residual petroleum contamination exceeds 100 yds³ |
| If greater than 100 yds ³ of petroleum impacted soil is to remain on the site, an environmental covenant should be considered and discussed with a supervisor to determine whether future management of petroleum contaminated soils needs to be controlled through a covenant. The covenant may also stipulate specific land use practices, engineering controls, and periodic review and reporting to NDEP to affirm maintenance of the engineering and institutional controls. | |

**Nevada Division of Environmental Protection
Bureau of Corrective Action
Petroleum in Soils Closure Checklists**

**Appendix B
Tables**

NDEP Petroleum In Soils Closure

Table 1: "Analyte-Specific Closure" Levels^a

| Analyte Name | Preparation/ Analytical Method ^b | Gasoline | Diesel | Heating oil | Jet Fuel | Residential ^c (mg/kg) | Industrial ^d (mg/kg) |
|-----------------------------|--|----------------|--------|-------------|----------------|-------------------------------------|------------------------------------|
| Acenaphthene | 3540 ^e /8270C or D | | | X | | 3500 | 45000 |
| Anthracene | 3540/8270C or D | | X | X | | 17000 | -- ^f |
| Benzene | 5035/8260B | X | X | X | 4 ^g | 1.2 | 5.1 |
| Benzo(a)anthracene | 3540/8270C or D ^h | | X | X | | 0.15 | 2.9 |
| Benzo(a)pyrene | 3540/8270C or D ^h | - ⁱ | X | X | | 0.015 | 0.29 |
| Benzo(b)fluoranthene | 3540/8270C or D ^h | | X | X | | 0.15 | 2.9 |
| Benzo(k)fluoranthene | 3540/8270C or D ^h | | X | X | | 1.5 | 29 |
| Chrysene | 3540/8270C or D | | X | X | | 15 | 290 |
| Dibenz(a,h)anthracene | 3540/8270C or D ^h | | X | X | | 0.015 | 0.29 |
| Ethylbenzene | 5035/8260B | X | X | X | 4 | 5.8 | 25 |
| Fluoranthene | 3540/8270C or D | | X | X | | 2300 | 30000 |
| Fluorene | 3540/8270C or D | | X | X | | 2300 | 30000 |
| Ideno(1,2,3-c,d)pyrene | 3540/8270C or D ^h | | X | X | | 0.15 | 2.9 |
| Methyl t-butyl ether (MTBE) | 5035/8260B | X | | | | 47 | 210 |
| 1-Methylnaphthalene | 3540/8270C or D | | X | X | X | 17 | 73 |
| 2-Methylnaphthalene | 3540/8270C or D | | X | X | X | 230 | 3000 |
| Naphthalene | 5035/8260B or 3540/8270C or D | X | X | X | X | 3.8 | 17 |
| Pyrene | 3540/8270C or D | | X | X | | 1700 | 23000 |
| Styrene | 5035/8260B | | X | | | 6000 | 35000 |
| Toluene | 5035/8260B | X | X | X | 4 | 4900 | 47000 |
| 1,2,4-Trimethylbenzene | 5035/8260B or 3540/8270C or D | - ⁱ | X | | X | 58 | 240 |
| 1,3,5-Trimethylbenzene | 5035/8260B or 3540/8270C or D | - ⁱ | X | | 4 | 780 | 12000 |
| Xylene (mixture) | 5035/8260B | X | X | | X | 580 | 2500 |

Notes:

- a—The use of this table is subject to the general and specific provisions listed in the Petroleum in in Soils Closure Checklists.
- b—The EPA Methods listed for each constituent are accepted for use by the Division. Other laboratory methods may be acceptable to the Division but must be pre-approved prior to use.
- c—Residential screening levels for all constituents are based on numbers developed by the US EPA as the "Regional Screening Levels for Chemical Contaminants at Superfund Sites" for a default residential exposure scenario.
- d—Industrial screening levels for all constituents are based on numbers developed by the US EPA as the "Regional Screening Levels for Chemical Contaminants at Superfund Sites" for a default exposure scenario. Industrial screening levels can be allowed at industrial and commercial sites where a case officer is comfortable that the reasonable expectation of future land use is industrial or commercial; if there is any doubt about future land use or surrounding land use, an environmental covenant should be considered in order to control the land-use assumption or additional corrective action should be undertaken to meet residential screening levels.
- e—EPA Method 3550 for ultrasonic extraction is also an acceptable method with any 8270C or D analysis in this table. When using method 3550 it is necessary to determine whether the low-concentration procedure or moderate/high-concentration procedure is appropriate. The low-concentration procedure is appropriate if anticipated concentrations are below 20 mg/kg.
- f—Screening level is above soil saturation value and is therefore not applicable in an industrial scenario.
- g—A differentiation is made between JP-4 and other formulations of jet fuel. Where a constituent is marked "4", that constituent should only be sampled if the source of contamination is suspected to be JP-4. An "X" indicates that the constituent should be sampled for any formulation of jet fuel.
- h—An optional procedure in EPA Method 8270 for lower detection limits on polynuclear aromatic hydrocarbons (PAH) is Selected Ion Monitoring (SIM). In order to achieve detection limits below residential screening levels and some industrial screening levels, the NDEP is currently recommending the use of SIM on confirmation samples for PAHs.
- i—The NDEP is currently evaluating the prevalence of this constituent in gasoline formulations and its usefulness in determining exposure risks at gasoline release sites. At this time, the NDEP is **not** requiring the analysis of this constituent for confirmation at gasoline-only sites.

NDEP Petroleum in Soils Closure

Table 2: Types of information that may be appropriate for an A thru K Closure

| <p>Simple Sites</p> <p>Small volume of residual soils Low concentrations Incomplete exposure pathways Qualitative analysis</p> | |  | <p>Complex Sites</p> <p>Large volume of residual soils High concentrations Complete exposure pathways Quantitative analysis</p> | |
|--|--|---|---|--|
| (a) The depth of any groundwater | | | | |
| <p>A narrative of contaminant locations in relation to the top-most water table from site-specific investigations or reasonably accurate, published sources</p> <p>An understanding of all productive saturated zones underlying the site</p> <p>First-order fate and transport calculations</p> <p>Site comparisons of contaminant migration to groundwater from similar sites in the vicinity</p> | | | <p>Multi-phase vadose zone modeling of contaminant transport to the top-most water table</p> <p>Identification of all nearby sources of hydraulic head such as areas of heavy irrigation, infiltration basins, leaking utilities, etc</p> <p>Analysis of historic water table fluctuations</p> | |
| (b) The distance to irrigation wells or wells for drinking water | | | | |
| <p>Inventory of all wells within a ¼-mile, ½-mile, and 1-mile radius</p> <p>Narrative of general groundwater consumption in the vicinity of the site, i.e. prevalence of irrigation, domestic use, and municipal supply</p> <p>General depths of drinking water and irrigation extraction from area groundwater</p> | | | <p>Construction details of wells in the vicinity of the site</p> <p>Saturated zone modeling of potential groundwater contaminant transport with established wells as target points</p> <p>Environmental covenant on groundwater use to preclude future well installations</p> | |
| (c) The type of soil that is contaminated | | | | |
| <p>A discussion of soil type and its relation to migration of contaminants to groundwater or exposure of residual contaminants due to erosion or runoff</p> <p>Site lithology and the presence or absence of aquitards</p> <p>Quality of imported fill</p> | | | <p>Derivation or collection of soil properties for vadose zone modeling including effective porosity, bulk density, soil organic carbon, and water content</p> <p>Biological activity of the soil and biodegradation of residual contaminants</p> <p>Environmental covenant which precludes export of site soils for use as fill in other locations</p> | |
| (d) The annual precipitation | | | | |
| <p>A narrative of precipitation and storm events typical for the site and its relation to vadose zone migration and surface runoff</p> <p>Infiltration calculations</p> <p>Presence of site features that may act equivalently to engineered controls or caps to prevent run-off or infiltration, such as paved surfaces</p> <p>Identification of any major sources of additional hydraulic head in the vicinity of the site</p> | | | <p>Use of site-specific precipitation regime in vadose zone modeling</p> <p>Drainage analysis for a 24-hour 25-year storm event</p> <p>Engineered controls for prevention of run-off or infiltration</p> <p>Use of designed and maintained evapo-transpirative covers</p> | |

| (e) The type of waste or substance that was released | |
|---|---|
| <p>For petroleum releases, the specific petroleum product involved in the release should be known or deduced based on site sampling</p> <p>The age of the release and the amount of weathering of petroleum contamination should be determined</p> <p>While the NDEP is already aware of the mobility, toxicity, and amenability to treatment of most petroleum products, it should be shown how these factors were considered as part of a determination to leave contamination in-place</p> | <p>TPH fractional analysis for use to model total petroleum hydrocarbon behavior in the subsurface</p> <p>Leach tests of site samples as an input to vadose and saturated zone modeling</p> |
| (f) The extent of the contamination | |
| <p>As a general condition of closure, all sites should have an understanding of the lateral and vertical extent of remaining contaminants</p> <p>Simple mass calculations for remaining contaminants, contaminants removed through corrective action, and contaminants released to the environment, if known</p> <p>Identification and extent of any contaminants at concentrations that indicate potential soil saturation</p> | <p>Stratigraphic analysis of subsurface concentrations for a conceptual model of historic fate and transport of petroleum constituents in the soil</p> <p>Modeling of potential LNAPL formation and movement in the vadose zone</p> <p>Mass flux potential to groundwater</p> |
| (g) The present and potential use for the land | |
| <p>An operational site history including present use and recently past uses</p> <p>A discussion of property uses in the vicinity of the site</p> <p>Property zoning</p> <p>Identification or location of overlying or adjacent Redevelopment Zones</p> | <p>Deed restrictions</p> <p>Environmental covenant containing specific land use restrictions</p> <p>Durable engineering controls intended to prevent future exposures regardless of land use</p> |
| (h) The preferred routes of migration | |
| <p>A complete Conceptual Site Model including migration pathways and receptors</p> <p>Vapor intrusion screening</p> | <p>Identification of preferential paths for migration for any and all pathways, such as utility corridors, vaults, unsealed well bores, discontinuities in aquatards, sand lenses, etc.</p> <p>Detailed vapor intrusion studies and risk assessment</p> |
| (i) The location of structures or impediments | |
| <p>If petroleum constituents above health-based action levels are left in-place in the top six feet of soil, a fully detailed rationale should be given as to why the location of structures or impediments prevents corrective action</p> <p>An updated, correctly scaled and labeled site map showing locations of residual contamination in relation to all surface structures and subsurface utilities, to the extent known</p> | <p>Structural analysis to support termination of excavation of contaminants at depth, including both the integrity of surrounding structure foundations and excavation shoring requirements</p> |

| | |
|---|--|
| (j) The potential for a hazard related to fire, vapor or an explosion | |
| A professional judgment as to whether the volume and concentrations of residual contamination would be able to produce flammable vapors Identification of all adjacent subsurface, enclosed spaces, particularly any utility vaults or any other space with potential ignition sources | PID readings from any adjacent subsurface vaults, basements, crawlspaces, or sub-basements Installation of vapor barrier, ventilation or recovery systems |
| (k) Any other information specifically related to the site which the director determines is appropriate | |
| Recalcitrance of site contaminants to past corrective actions | Data Quality Assessment in accordance with federal guidelines |

**Nevada Division of Environmental Protection
Bureau of Corrective Action
Petroleum in Soils Closure Checklists**

Appendix C

American Petroleum Institute

“Soil & Groundwater Research Bulletin” June 2000

Non-Aqueous Phase Liquid (NAPL) Mobility Limits in Soil

SOIL & GROUNDWATER RESEARCH BULLETIN

*A summary of research
results from the American
Petroleum Institute & GRI.*

June 2000

No. 9

NON-AQUEOUS PHASE LIQUID (NAPL) MOBILITY LIMITS IN SOIL

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ABSTRACT

Conservative screening concentrations for non-aqueous phase liquids (NAPL) that could be considered immobile in unsaturated zone soils are presented. Total concentrations measured at a crude oil or petroleum product release site (using total petroleum hydrocarbon [TPH] or a similar analysis method) can be compared to the screening concentrations to determine the potential for NAPL to migrate in soil. The screening values are based on an analysis of published data for a range of soil texture classifications and a range of NAPL density from 0.7 to 1.5 g/cm³.

The paper includes summary tables and histograms of residual NAPL void fraction, S_r , as a function of soil type. These provide a basis for selecting conservative values used in calculating screening concentrations for immobile NAPL. For example, in medium to coarse sands, with $S_r = 0.06$ cm³-oil/cm³-void, one would expect that NAPL would be immobile in 90% of samples with equivalent NAPL concentration levels for this soil type.

Measured concentrations of immobile NAPL reported in the literature vary considerably with soil type, chemical composition, and the measurement method. The proposed screening levels are conservative (lower range) estimates within the range of measured residual NAPL concentration values. Higher values could be applicable in many cases, both in unsaturated and saturated soil conditions.

This paper addresses immobile bulk NAPL in soils at concentrations up to the threshold of mobility. This document does not address the movement and flow of NAPL, the dissolution of NAPL chemical into soil pore water solution, nor NAPL volatilization into soil pore air. Transport by these mechanisms may be estimated using other published and accepted methods.

INTRODUCTION

Organic chemicals released to soil may migrate as vapors in soil gas, as dissolved constituents in soil pore water, or as a bulk phase liquid which is immiscible in water. Assessment of potential migration pathways for chemical releases into the environment are discussed in several related documents (USEPA 1996, 1991; ASTM E1739, PS104-98). These migration pathways are important in a general risk-based site

assessment. This paper is confined to discussion of the mobility of non-aqueous phase liquids, either as pure chemicals or as chemical mixtures.

Many organic chemicals, including hydrocarbons, are nearly immiscible in water. Release of a non-aqueous phase liquid (NAPL) to near-surface unsaturated soil can result in downward gravity-driven migration of the NAPL towards the water table. At the water table, light nonaqueous phase liquids (LNAPL), including petroleum, which are less dense than water, will mound and spread horizontally. LNAPL may also move with the groundwater gradient. Dense nonaqueous phase liquids (DNAPL) will migrate downward, mound, and spread horizontally, until a path of least resistance further downward into the saturated region is found. This could be when the accumulation is great enough to exceed the capillary entry pressure into the saturated zone, or when the DNAPL mound reaches a region of high vertical permeability, or when it reaches a fracture.

The volume of mobile NAPL depletes as immobile residual chemical is left behind through the soil column in which the NAPL is descending. NAPL migration may be limited by this depletion, or by physical barriers, such as low permeability layers. Our intent in this paper is to determine conservative NAPL concentrations in unsaturated soil, below which the NAPL will be immobile. By "conservative" we mean under-predicting the concentration at which mobility would actually occur.

PRESENCE OF A NAPL IN SOIL

For a pure chemical, NAPL will not be present at concentrations below the soil saturation limit (USEPA, 1996; ASTM E1739, PS104-98), defined as:

$$C_{\text{sat,soil},i} = S_i \cdot \left(\frac{\theta_w + K_{oc,i} \cdot f_{oc} \cdot \rho_s + H_i \cdot \theta_a}{\rho_s} \right) \quad [1]$$

with

- $C_{\text{sat,soil},i}$ soil saturation limit for chemical i (mg/kg)
- S_i pure chemical aqueous solubility limit for chemical i (mg/L)
- θ_w soil water content (cm³-water/cm³-soil)

| | |
|------------|--|
| $K_{oc,i}$ | organic carbon/water partition coefficient for chemical i (L-water/kg-oc) |
| f_{oc} | mass fraction of organic carbon in soil (g-oc/g-soil) |
| ρ_s | dry soil bulk density (g/cm ³) |
| H_i | Henry's law coefficient for chemical i (cm ³ -water/cm ³ -air) |
| θ_a | soil air content (cm ³ -air/cm ³ -soil) |

For a pure chemical, $C_{sat,soil}$ is a value above which the chemical is present in soil pore water at its aqueous solubility limit, and is present in soil pore air at its saturated vapor concentration. Equilibrium partitioning of the chemical between soil (sorbed), pore water, and pore vapors at concentrations below $C_{sat,soil,i}$ is presumed.

For mixtures of miscible chemicals that are fractionally soluble in water, including petroleum, the concentration at which NAPL will be present is a function of the mixture composition. The soil saturation limit for the mixture, using methods presented in Johnson *et al.*, (1990), Mott (1995), and Mariner (1997), is:

$$\sum_{i=1}^N \left(\frac{C_{sat,soil,T} \cdot \chi_i \cdot \rho_s}{S_i \cdot (\theta_w + K_{oc,i} \cdot f_{oc} \cdot \rho_s + H_i \cdot \theta_a)} \right) = 1 \quad [2]$$

with

| | |
|------------------|---|
| $C_{sat,soil,T}$ | soil saturation limit for the NAPL mixture, total concentration (mg/kg) |
| χ_i | mass fraction of each chemical i in the NAPL mixture (kg/kg) |
| N | the number of individual chemicals in the mixture |

Note that Eq. [2] simplifies to Eq. [1] for a single chemical. The component concentration of a chemical i at the soil saturation limit in a mixture is ($C_{sat,soil,T} \cdot \chi_i$). The soil saturation limit calculated for a pure chemical, in every case, will be greater than the chemical component concentration ($C_{sat,soil,T} \cdot \chi_i$) calculated for a mixture, that is:

$$C_{sat,soil,i} \geq C_{sat,soil,T} \cdot \chi_i$$

Eq. [1] overstates $C_{sat,soil,i}$ for components in a mixture because it does not consider effective vapor pressure and solubility limits (Rault's law) for the mixture components (USEPA, 1996). The soil saturation limits for mixtures (and pure chemicals) tabulated in this paper were calculated with computer codes included with DeVaul *et al.*, (1999). This method is consistent with the references cited above.

RESIDUAL NAPL CONCENTRATION

Our intent in this paper is to define a soil concentration, $C_{res,soil}$, below which the NAPL, if present, will not migrate due to convection or gravity. This refers to a pure chemical concentration or a total chemical mixture concentration, as applicable. This residual NAPL concentration in soil is specified as:

$$C_{res,soil} = \left(\frac{\theta_o \cdot \rho_o}{\rho_s} \right) \cdot 10^6 \frac{mg}{kg} \quad [3]$$

with

$$\theta_o = S_r \cdot \theta_T$$

and

| | |
|----------------|---|
| $C_{res,soil}$ | residual NAPL concentration in soil (mg-res/kg-soil) |
| θ_o | residual non-aqueous phase volume fraction (cm ³ -res/cm ³ -soil) |
| ρ_o | density of chemical residual non-aqueous phase liquid (g-res/cm ³ -res) |
| ρ_s | dry soil bulk density (g-soil/cm ³ -soil) |
| θ_T | soil porosity (cm ³ -void/cm ³ -soil) |
| S_r | fraction of residual non-aqueous phase filled void (cm ³ -res/cm ³ -void) |

Residual non-aqueous phase volume fraction (θ_o , or retention capacity) is similarly defined by Cohen and Mercer (1990) and Zytner *et al.*, (1993), but in dimensional units of (cm³-res/L-soil). The value of $C_{res,soil}$ is generally much larger than the soil saturation limit, $C_{sat,soil}$. Eq. [3] includes only the residual NAPL volume. Additional chemical mass within the soil matrix is contained in soil pore water and soil pore air, and is sorbed onto soil. These volumes may be included in a slightly more complicated equation consistent with the assumptions in Eqs. [1] and [2]; these terms may generally be neglected. This leaves the residual NAPL concentration in soil, $C_{res,soil}$, directly related to the residual NAPL volume fraction in soil, θ_o , or the residual NAPL fraction in the voids, S_r .

Below the residual NAPL concentration in soil, $C_{res,soil}$, capillary retention forces are greater than the gravitational forces which tend to mobilize the NAPL. These capillary forces (in this context, including surface tension effects, van der Waals, and Coulombic forces), particularly at low residual non-aqueous phase levels, may exceed the gravitational force by several orders of magnitude. The residual NAPL concentration in soil, $C_{res,soil}$, may depend on NAPL properties including liquid density, surface tension, and viscosity. It also may depend on soil properties including porosity, organic carbon fraction, moisture content, relative permeability, moisture wetting history, and soil heterogeneity.

For concentrations greater than the threshold $C_{res,soil}$ level, capillary retention forces are less than the gravitational forces, and the NAPL is mobile. Movement of NAPL in soil is beyond the scope of this paper. It is covered in a number of references, however, including Charbeneau (1999), Huntley and Beckett (1999), USEPA (1991), Cohen and Mercer (1990), and Pfannkuch (1983).

This paper describes the determination of screening values for NAPL immobility in soil. Screening values are expressed as the residual NAPL concentration in soil, $C_{res,soil}$, the non-aqueous phase volume fraction in soil, θ_o , and the residual non-aqueous phase fraction in the soil voids. Our study included a review of existing measured data on residual NAPL concentration in soil, published empirical models, and methods of field measurement.

The calculated value, $C_{sat,soil}$, as previously defined in Eqs. [1] and [2] predicts the presence or absence of a residual NAPL. Since a NAPL must be present to be mobile, it also represents a conceivable screening concentration for NAPL mobility. However, observed residual NAPL concentrations based either on laboratory measurement or physical removal of NAPL from impacted sites are typically several *orders of magnitude* higher

Table 1. Residual NAPL Concentration in Soil Compared to Soil Saturation Limit.

| Name | Ref | S _r residual NAPL in the void fraction (cm ³ /cm ³) | C _{res,soil} residual NAPL concentration in soil (mg/kg) | C _{sat,soil} soil saturation limit (mg/kg) | ρ _o liquid chemical density (g/cm ³) | MW molecular weight (g/g-mol) | S aqueous solubility (mg/L) | P _{vap} vapor pressure (mm Hg) |
|-------------------------|-----|---|---|--|---|--|--------------------------------------|--|
| trichloroethylene (TCE) | a | 0.2 | 70,000 | 1,045 | 1.46 | 131 | 1,100 | 75 |
| benzene | b | 0.24 | 53,000 | 444 | 0.88 | 78 | 1,750 | 95 |
| o-xylene | c | 0.01 | 2,000 | 143 | 0.88 | 106 | 178 | 6.6 |
| gasoline | d,e | 0.02 to 0.6 | 3,400 to 80,000 | 106 | 0.78 | 99 | 164 | 102 |
| diesel | d,f | 0.04 to 0.2 | 7,700 to 34,000 | 18 | 0.94 | 207 | 3.9 | 0.79 |
| fuel oil | d,f | 0.08 to 0.2 | 17,000 to 50,000 | 18 | 0.94 | 207 | 3.9 | 0.79 |
| mineral oil | g | 0.1 to 0.5 | 20,000 to 150,000 | 3 | 0.81 | 244 | 0.36 | 0.035 |

Notes: Unsaturated zone fine to medium sand. Nominal values θ_w = 0.12 cm³/cm³, f_{oc} = 0.005 g/g in C_{sat,soil} calculation.
a = Lin et al. (1982); b = Lenham and Parker (1987); c = Boley and Overcamp (1998); d = Fussell et al. (1981); e = Hoag and Marley (1986); f = API (1980); g = Pfannkuch (1984).

than C_{sat,soil}. The value C_{sat,soil} specifies the presence or absence of a residual phase; it does not address mobility. In this effort, we have used available data to define values for C_{res,soil} which can be conservatively used to screen sites for NAPL mobility. A comparison of calculated C_{sat,soil} values with measured values of C_{res,soil} is shown in Table 1 for selected chemicals and hydrocarbon mixtures.

The trend of C_{sat,soil} in Table 1 decreases with decreasing chemical (or mixture) solubility and vapor pressure. The measured values of residual NAPL concentration in soil and residual NAPL fraction in voids do not show a similar decreasing trend. Therefore, using a calculated C_{sat,soil} value as a screening level for the mobility of a residual phase becomes increasingly and significantly more conservative for less soluble, less volatile chemicals and chemical mixtures.

Screening levels for NAPL mobility consistent with the definition of residual NAPL concentration in soil, C_{res,soil}, have already been implemented in a number of programs. The State of Ohio [OAC 3745-300-08 Generic Numerical Standards] has promulgated rules, including values of residual NAPL concentration in soil, for several combinations of specified soil types and petroleum composition ranges. The State of Washington [WAC 173-340-747 Part VII Cleanup Standards] has proposed values based on a similar methodology. CONCAWE (1979, 1981) provides residual NAPL concentration in soil values for a range of petroleum products and soil types.

EXISTING MODELS AND METHODS

Monographs are available which detail the movement of NAPL in soils (Charbeneau, 1999; Huntley and Beckett, 1999; USEPA, 1991; Cohen and Mercer, 1993; and Pfannkuch, 1983). Several investigators have specifically developed empirical models for predicting immobile NAPL, as a residual NAPL concentration in soil, C_{res,soil}, for a limited number of NAPL types in various soil matrices. Summaries of two published approaches follow.

Hoag and Marley (1986) proposed an empirical method to estimate residual NAPL saturation values for gasoline in dry sand and in sand matrices containing moisture at field capacity. Their equations, which relate measured gasoline retention at residual saturation with soil particle surface area, are:

$$C_{res,soil} = \left(1.154 \cdot 10^{-2} \cdot d_p + 0.652 \cdot 10^{-3} \right) \cdot \frac{6}{2.65 \cdot d_p \cdot \rho_w} \cdot 10^6 \frac{mg}{kg} \quad [4a]$$

zero soil moisture

$$C_{res,soil} = \left(1.136 \cdot 10^{-2} \cdot d_p + 0.131 \cdot 10^{-3} \right) \cdot \frac{6}{2.65 \cdot d_p \cdot \rho_w} \cdot 10^6 \frac{mg}{kg} \quad [4b]$$

field capacity soil moisture

with

C_{res,soil} residual NAPL concentration in soil (mg-res/kg-soil)

d_p average sand particle diameter (cm)

ρ_w density of water (g/cm³) = 1

Eqs. [4a] and [4b] refer, respectively, to residual NAPL concentration in dry soil and soil initially at field moisture capacity. An assumption in these equations is that the soil particles and soil surface area can be defined by an average soil particle diameter (Sauter mean diameter). These authors found that changes in soil surface area adequately predicted changes in residual NAPL saturation. Smaller soil particles have greater available surface area in a given volume or weight of soil, and the associated narrower pores will result in greater capillary forces. Residual NAPL concentration in soil therefore decreases with increasing particle size. At field capacity moisture content, measured C_{res,soil} was reduced. At field capacity moisture, many of the smaller pore spaces are saturated with water. This reduces the overall pore volume available for trapping NAPL.

Eqs. [4a] and [4b] were developed using Connecticut sands sieved into three classifications; fine (d_p = 0.0225 cm), medium (d_p = 0.0890 cm) and coarse (d_p = 0.2189 cm). A fourth set of experiments was conducted using mixed sands with the mixture being made from equal portions of each of the above three classifications. Effectively, Eqs. [4a] and [4b] have been developed for data in the range of:

$$0.02 \text{ cm} < d_p < 0.22 \text{ cm}$$

Zytner *et al.*, (1993) correlated measured soil retention capacity with soil porosity, soil bulk density, and NAPL density. Their experiments included several NAPL types in a variety of natural soils. The soils were air dried (less than 1.5% moisture), saturated with NAPL, and then allowed to drain. Their empirical equation, for dry soils is:

$$C_{res,soil} = \left(1.05 \cdot \theta_T \cdot \frac{\rho_o}{\rho_s} - 0.15 \right) \cdot 10^6 \frac{mg}{kg} \quad [5]$$

with

- $C_{res,soil}$ residual NAPL concentration in soil (mg-res/kg-soil)
- θ_T soil porosity (cm³-void/cm³-soil)
- ρ_o density of chemical residual NAPL (g-res/cm³-res)
- ρ_s dry soil bulk density (g-soil/cm³-soil)

This study was limited to air dried soils and did not specifically include sand. It does, however, show a dependence of $C_{res,soil}$ on soil porosity, θ_T , and chemical density, ρ_o .

A wide range of natural soils was used in the development of Eq. [5], including sandy loam ($\theta_T = 0.45$), clay ($\theta_T = 0.466$), organic top soil ($\theta_T = 0.555$), two different peat mosses ($\theta_T \sim 0.8$), as well as mixtures of these soils. Three NAPL types were included in their work to assess the influence of NAPL density on retention capacity: tetrachloroethene ($\rho_o = 1.622$ g/cm³), trichloroethene ($\rho_o = 1.456$ g/cm³), and gasoline ($\rho_o = 0.75$ g/cm³). $C_{res,soil}$ values obtained in their study ranged from 414,000 to 6,894,000 mg/kg for PCE, 329,000 to 5,219,000 mg/kg for TCE, and 94,000 to 2,738,000 mg/kg for gasoline. Effectively, Eq. [5] has been developed for data in the range of:

$$0.23 < \left(\theta_T \cdot \frac{\rho_o}{\rho_s} \right) < 6.7 \quad [6]$$

The broad range of values for $C_{res,soil}$ can be attributed to the range in soil densities, from 0.2 g/cm³ (peat moss) to 1.5 g/cm³ (sandy loam).

Although the $C_{res,soil}$ measurements used in developing Eqs. [4] and [5] were conducted by different researchers using different soils, a comparison of dry fine sand data (Hoag and Marley, 1986; $\theta_T = 0.4$, and $\rho_s = 1.6$ g/cm³) with dry sandy loam data (Zytner *et. al.*, 1993; $\theta_T = 0.45$, $\rho_s = 1.5$ g/cm³) show very good agreement of $C_{res,soil}$ of 104,000 and 115,000 mg/kg, respectively, for gasoline.

MEASURED DATA AND COMPARISON WITH MODELS

Cohen and Mercer (1990) compiled measured residual NAPL saturation data from several investigators, including residual NAPL fraction in the voids, S_p , or residual NAPL volume fraction, θ_o , for a number of organic liquids and soil types. These values represent the residual amount of hydrocarbon remaining in soil pore volume after the soil was saturated with hydrocarbon and then allowed to drain. Values from Cohen and Mercer, with additional tabulated data from other references, are included in Table 2 (see pages 5 and 6). This table also includes additional values derived from the experimental data, including the residual NAPL concentration in soil, $C_{res,soil}$.

The values in Table 2 vary considerably between experiments, soil types, and chemicals. While this may be due to differences in laboratory test methods, it may also indicate the reasonable range in measured residual NAPL concentration in soils encountered between different soil types, chemical types, and measurement observations.

Calculated values for the soil saturation limit, $C_{sat,soil}$ for the indicated chemicals or chemical mixtures, are included in Table 2. These values are plotted in Figure 1. In all cases, $C_{res,soil}$ is greater than $C_{sat,soil}$. As a measure of immobile NAPL, $C_{sat,soil}$

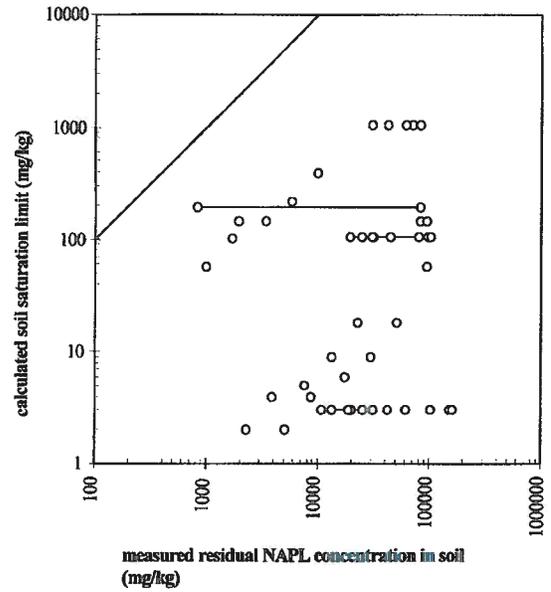


Figure 1. Comparison of data for residual NAPL concentration in soil, $C_{res,soil}$, to the calculated soil saturation limit, $C_{sat,soil}$. All plotted values are from Table 2. The solid diagonal line marks a direct correspondence between residual NAPL concentration in soil and soil saturation limit. For ranges of residual NAPL concentration in soil data in the same test series (Table 2), the upper and lower values are joined by a horizontal line. In all cases the calculated soil saturation limit is much less than the measured residual NAPL concentration in soil.

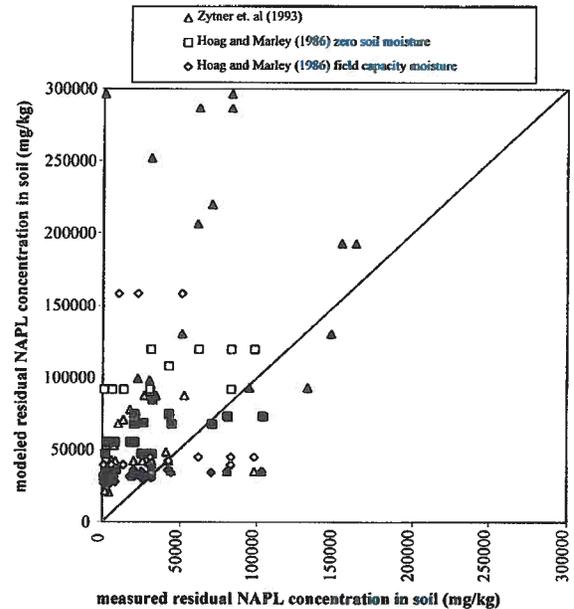


Figure 2. Comparison of data for residual NAPL concentration in soil, $C_{res,soil}$, from Table 2 to the models of Eq. [4a] Hoag and Marley (1986), zero soil moisture; Eq. [4b] Hoag and Marley (1986), field capacity soil moisture; and Eq. [5] Zytner *et al.*, (1993). Filled points indicate the data value is within the intended range of model applicability. For ranges of residual NAPL concentration in soil data (Table 2), both the upper and lower values are shown as points. The solid diagonal line marks a direct correspondence between measured and modeled residual NAPL concentration in soil. The plot indicates that the empirical models generally predict higher residual NAPL concentration in soil than the measured values given in Table 2.

Table 2. Summary values of residual NAPL concentration in soil, $C_{res,soil}$, residual NAPL volume fraction, θ_o , and residual NAPL fraction in the voids, S_r . Calculated values for soil saturation limit, $C_{sat,soil}$ are also shown. Parameters for the calculations are shown in the second part of the table.

| | NAPL | Soil Type | Ref | | Measured | | |
|-----|-------------------------|------------------------|-----|--------------------------|--|---------------------------|---------------------------|
| | | | | S_r (cm^3/cm^3) | $1000 \cdot \theta_o$ (cm^3/cm^3) | $C_{res,soil}$ (mg/kg) | $C_{sat,soil}$ (mg/kg) |
| 1. | Gasoline | coarse gravel | 1 | 0.01 | 2.5 | 1,000 | 57 |
| 2. | Gasoline | coarse sand and gravel | 1 | 0.01 | 4 | 1,697 | 102 |
| 3. | Gasoline | medium to coarse | 1 | 0.02 | 7.5 | 3,387 | 143 |
| 4. | Gasoline | fine to medium sand | 1 | 0.03 | 12.5 | 5,833 | 215 |
| 5. | Gasoline | silt to fine sand | 1 | 0.05 | 20 | 10,000 | 387 |
| 6. | Middle distillates | coarse gravel | 1 | 0.02 | 5 | 2,286 | 2 |
| 7. | Middle distillates | coarse sand and gravel | 1 | 0.02 | 8 | 3,879 | 4 |
| 8. | Middle distillates | medium to coarse | 1 | 0.04 | 15 | 7,742 | 5 |
| 9. | Middle distillates | fine to medium sand | 1 | 0.06 | 25 | 13,333 | 9 |
| 10. | Middle distillates | silt to fine sand | 1 | 0.1 | 40 | 22,857 | 18 |
| 11. | Fuel oils | coarse gravel | 1 | 0.04 | 10 | 5,143 | 2 |
| 12. | Fuel oils | coarse sand and gravel | 1 | 0.05 | 16 | 8,727 | 4 |
| 13. | Fuel oils | medium to coarse | 1 | 0.08 | 30 | 17,419 | 6 |
| 14. | Fuel oils | fine to medium sand | 1 | 0.1 | 50 | 30,000 | 9 |
| 15. | Fuel oils | silt to fine sand | 1 | 0.2 | 80 | 51,429 | 18 |
| 16. | Light oil & gasoline | soil | 2 | 0.18 | 72 | 40,800 | 9 (a) |
| 17. | Diesel & light fuel oil | Soil | 2 | 0.15 | 60 | 34,000 | NE (b) |
| 18. | Lube & heavy fuel oil | Soil | 2 | 0.2 | 80 | 53,067 | NE |
| 19. | Gasoline | coarse sand | 3 | 0.15 to 0.19 | 61 to 77 | 24,954 to 31,609 | 106 |
| 20. | Gasoline | medium sand | 3 | 0.12 to 0.27 | 48 to 109 | 19,767 to 44,476 | 106 |
| 21. | Gasoline | fine sand | 3 | 0.19 to 0.6 | 76 to 240 | 31,065 to 98,100 | 106 |
| 22. | Gasoline | Graded fine-coarse | 3 | 0.46 to 0.59 | 184 to 236 | 80,500 to 103,250 | 106 |
| 23. | Mineral oil | Ottawa sand | 4 | 0.11 | 39 | 20,116 | 3 |
| 24. | Mineral oil | Ottawa sand | 4 | 0.14 | 49 | 25,602 | 3 |
| 25. | Mineral oil | Ottawa sand | 4 | 0.172 | 60 | 31,454 | 3 |
| 26. | Mineral oil | Ottawa sand | 4 | 0.235 | 82 | 42,975 | 3 |
| 27. | Mineral oil | glacial till [NA] | 4 | 0.15 to 0.28 | 30 to 56 | 13,500 to 25,200 | 3 |
| 28. | Mineral oil | glacial till | 4 | 0.12 to 0.21 | 24 to 42 | 10,800 to 18,900 | 3 |
| 29. | Mineral oil | alluvium [NA] | 4 | 0.19 | 95 | 61,071 | 3 |
| 30. | Mineral oil | Alluvium | 4 | 0.19 | 95 | 61,071 | 3 |
| 31. | Mineral oil | loess [NA] | 4 | 0.49 to 0.52 | 240 | 154,000 to 163,800 | 3 |
| 32. | Paraffin oil | coarse sand | 5 | 0.12 | 48 | 27,000 | |
| 33. | Paraffin oil | fine sediments | 5 | 0.52 | 229 | 147,086 | |
| 34. | Paraffin oil | Ottawa sand | 5 | 0.11 to 0.23 | 39 | 20,382 to 42,618 | |
| 35. | Trichloroethene | medium sand | 6 | 0.2 | 78 | 70,448 | 1045 |
| 36. | Trichloroethene | fine sand | 6 | 0.15 to 0.2 | 65 to 86 | 62,344 to 83,125 | 1067 |
| 37. | Trichloroethene | loamy sand | 7 | 0.08 | 33 | 30,713 | 1057 |
| 38. | Tetrachloroethene | Fine/med. beach sand | 8 | 0.002 to 0.20 | 1 to 82 | 830 to 83,025 | 195 |
| 39. | O-Xylene | Coarse sand | 9 | 0.01 | 3 | 1,936 | 143 |
| 40. | Gasoline | Sandy loam | 10 | 0.42 to 0.59 | 189 to 266 | 94,500 to 132,750 | |
| 41. | Tetrachloroethene | Sandy loam | 10 | 0.85 | 383 | 413,000 | |
| 42. | Trichloroethene | Sandy loam | 10 | 0.75 to 0.92 | 338 to 412 | 328,000 to 401,208 | |

Notes: 1 = Fussell et al. (1981); 2 = API (1980); 3 = Hoag and Marley (1986); 4 = Pfannkuch (1984); 5 = Convery (1979); 6 = Lin et al. (1982); 7 = Cary et al. (1989); 8 = Poulsen and Kueper (1992); 9 = Boley and Overcamp, (1998); 10 = Zytner et al. (1993).

(a) - Assumed 50:50 mixture diesel and gasoline to estimate $C_{sat,soil}$. (b) - NE = Not estimated, composition data not available.

Between reported S_r or θ_o , the italicized values represent the calculated term. These values were converted to concentrations in soil using available values for NAPL density, soil bulk density and porosity, as shown in the table.

Table 2. (continued) Values for soil properties used in the calculations.

| | Hydrocarbon NAPL | Soil Type | θ_T Soil Porosity (cm ³ /cm ³) | θ_w Pore Water (cm ³ /cm ³) | f_{oc} Fraction of Organic Carbon (f_{oc}) | ρ_s Soil Bulk Density (g/cm ³) | ρ_o Liquid Density (g/cm ³) | d_p Soil Particle Size (mm) |
|-----|---------------------------|------------------------------|--|---|---|---|---|-------------------------------------|
| 1. | Gasoline | coarse gravel | 0.28 | 0.02 | 0.001 | 1.75 | 0.7 | 2 to 4 |
| 2. | Gasoline | coarse sand and gravel | 0.35 | 0.03 | 0.002 | 1.65 | 0.7 | 0.5 to 4 |
| 3. | Gasoline | medium to coarse sand | 0.39 | 0.04 | 0.003 | 1.55 | 0.7 | 1 to 0.25 |
| 4. | Gasoline | fine to medium sand | 0.41 | 0.043 | 0.005 | 1.5 | 0.7 | 0.5 to 0.1 |
| 5. | Gasoline | silt to fine sand | 0.44 | 0.045 | 0.01 | 1.4 | 0.7 | 0.25 to 0.002 |
| 6. | Middle distillates | coarse gravel | 0.28 | 0.02 | 0.001 | 1.75 | 0.8 | 2 to 4 |
| 7. | Middle distillates | coarse sand and gravel | 0.35 | 0.03 | 0.002 | 1.65 | 0.8 | 0.5 to 4 |
| 8. | Middle distillates | medium to coarse sand | 0.39 | 0.04 | 0.003 | 1.55 | 0.8 | 1 to 0.25 |
| 9. | Middle distillates | fine to medium sand | 0.41 | 0.043 | 0.005 | 1.5 | 0.8 | 0.5 to 0.1 |
| 10. | Middle distillates | silt to fine sand | 0.44 | 0.045 | 0.01 | 1.4 | 0.8 | 0.25 to 0.002 |
| 11. | Fuel oils | coarse gravel | 0.28 | 0.02 | 0.001 | 1.75 | 0.9 | 2 to 4 |
| 12. | Fuel oils | coarse sand and gravel | 0.35 | 0.03 | 0.002 | 1.65 | 0.9 | 0.5 to 4 |
| 13. | Fuel oils | medium to coarse sand | 0.39 | 0.04 | 0.003 | 1.55 | 0.9 | 1 to 0.25 |
| 14. | Fuel oils | fine to medium sand | 0.41 | 0.043 | 0.005 | 1.5 | 0.9 | 0.5 to 0.1 |
| 15. | Fuel oils | silt to fine sand | 0.44 | 0.045 | 0.01 | 1.4 | 0.9 | 0.25 to 0.002 |
| 16. | Light oil and gasoline | soil | 0.4 | 0.04 | 0.005 | 1.5 | 0.75 | |
| 17. | Diesel and light fuel oil | Soil | 0.4 | | | 1.5 | 0.9 | |
| 18. | Lube and heavy fuel oil | Soil | 0.4 | | | 1.5 | 0.9 | |
| 19. | Gasoline | Coarse sand | 0.4 | 0.04 | 0.002 | 1.6 | 0.7 | 1 to 0.5 |
| 20. | Gasoline | Medium sand | 0.4 | 0.04 | 0.002 | 1.6 | 0.7 | 0.5 to 0.25 |
| 21. | Gasoline | fine sand | 0.4 | 0.04 | 0.002 | 1.6 | 0.7 | 0.25 to 0.1 |
| 22. | Gasoline | well graded fine-coarse sand | 0.4 | 0.04 | 0.002 | 1.6 | 0.7 | 1 to 0.1 |
| 23. | Mineral oil | Ottawa sand [NA] | 0.35 | No water | 0.002 | 1.7 | 0.9 | 0.5 |
| 24. | Mineral oil | Ottawa sand [NA] | 0.35 | No water | 0.002 | 1.7 | 0.9 | 0.35 |
| 25. | Mineral oil | Ottawa sand [NA] | 0.35 | No water | 0.002 | 1.7 | 0.9 | 0.25 |
| 26. | Mineral oil | Ottawa sand [NA] | 0.35 | No water | 0.002 | 1.7 | 0.9 | 0.18 |
| 27. | Mineral oil | glacial till [NA] | 0.2 | No water | 0.002 | 2 | 0.9 | |
| 28. | Mineral oil | glacial till | 0.2 | 0.02 | 0.002 | 2 | 0.9 | |
| 29. | Mineral oil | alluvium [NA] | 0.5 | No water | 0.002 | 1.4 | 0.9 | |
| 30. | Mineral oil | Alluvium | 0.5 | 0.03 | 0.001 | 1.4 | 0.9 | |
| 31. | Mineral oil | loess [NA] | 0.49 | No water | 0.002 | 1.4 | 0.9 | |
| 32. | Paraffin oil | coarse sand | 0.4 | | | 1.6 | 0.9 | 1 to 0.5 |
| 33. | Paraffin oil | fine sediments | 0.44 | | | 1.4 | 0.9 | 0.05 to 0.002 |
| 34. | Paraffin oil | Ottawa sand | 0.35 | | | 1.7 | 0.9 | 0.5 to 0.18 |
| 35. | Trichloroethene | medium sand | 0.39 | 0.04 | 0.003 | 1.6 | 1.46 | 0.5 to 0.25 |
| 36. | Trichloroethene | fine sand | 0.43 | 0.04 | 0.005 | 1.5 | 1.46 | 0.25 to 0.1 |
| 37. | Trichloroethene | loamy sand | 0.41 | 0.06 | 0.005 | 1.4 | 1.46 | |
| 38. | Tetrachloroethene | fine to medium beach sand | 0.41 | 0.04 | 0.005 | 1.6 | 1.62 | 0.5 to 0.1 |
| 39. | O-Xylene | Coarse sand | 0.33 | 0.04 | 0.003 | 1.6 | 0.88 | 1 to 0.5 |
| 40. | Gasoline | Sandy loam | 0.45 | | | 1.5 | 0.75 | |
| 41. | Tetrachloroethene | Sandy loam | 0.45 | | | 1.5 | 1.62 | |
| 42. | Trichloroethene | Sandy loam | 0.45 | | | 1.5 | 1.46 | |

Notes: Porosity data and particle size information (ranges) estimated from USEPA (1991); pore water data adapted from Carsel and Parrish, (1988); f_{oc} data adapted from Wiedemeier et al., (1999).

underpredicts measured values of $C_{res,soil}$ by a factor ranging from 5 to over 50,000. As was noted in Table 1, the difference between $C_{sat,soil}$ and $C_{res,soil}$ increases with decreasing NAPL volatility and decreasing aqueous solubility.

A comparison of the data in Table 2 for residual NAPL concentration in soil, $C_{res,soil}$ to the models of Eq. [4a], [4b], and [5] is shown in Figure 2. Within the applicable range of values in the original references, both models predict values of $C_{res,soil}$ which are, on average, biased high relative to the comparable values listed in Table 2. In all cases, excepting point 38 (tetrachloroethene) in Table 2, for Eq. [4a], the model to data ratio ranges from 0.7 to 69; for Eq. [4b], the ratio ranges from 0.3 to 27; for Eq. [5], the model to data ratio ranges from 0.3 to 11. Point 38 has an exceptionally broad range of measured $C_{res,soil}$ values in the same soil.

Both the models of Zytner *et al.*, (1993) and Hoag and Marley (1986) are correlations based on measured data. The indicated bias between the models and data of Table 2 could be due to differences in data measurements methods, or may indicate the reasonable range in variability for this type of measurement.

SCREENING VALUES FOR RESIDUAL NAPL CONCENTRATION

Based on the model to data comparisons of the last section, it is possible to specify conservative screening values for NAPL mobility based on a range of qualifying information. In many cases the screening levels will be very conservative estimates of mobility. In such cases, site-specific measurements may be used to refine the estimate, if necessary. Such measurements, for example, could include observation (or lack thereof) of floating and migrating hydrocarbon in shallow groundwater wells surrounding a known NAPL source area.

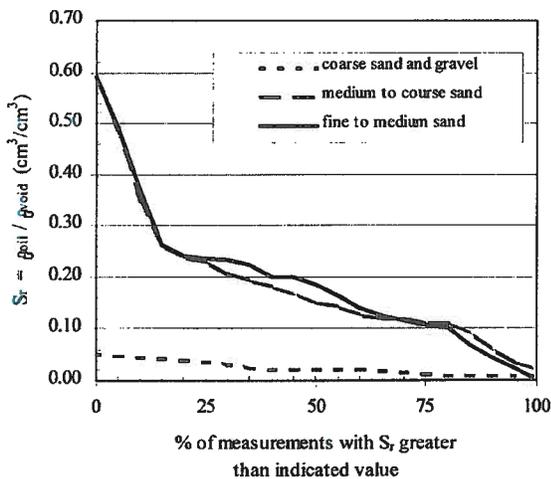


Figure 3. Cumulative distribution for measured residual NAPL void fraction, S_r , as a function of soil type. These cumulative histograms are based on the data in Table 2. Values for the "medium to coarse sand" and the "fine to medium sand" are very similar over the distribution. The "coarse sand and gravel" shows much lower values and narrower distribution of S_r over the range of different experiments. Tolerance limits for these distributions are given in Table 3.

Table 3. Screening values for residual phase void fraction as a function of soil type. The tabulated values are based on distributions of data from Table 2 for each soil type. The 95% statistical tolerance limit indicates that 5% of individual measurements showed lower values for S_r ; the 50% tolerance limit is the median value for the soil type. The 90% tolerance limit is sufficiently conservative for most screening applications. The distribution of values is plotted in Figure 3.

| Soil type | Indicated statistical tolerance limit | | |
|------------------------|---|------|------|
| | 95% | 90% | 50% |
| | residual NAPL fraction in the voids, S_r , (cm^3-res/cm^3-void) | | |
| coarse sand and gravel | 0.01 | 0.01 | 0.02 |
| medium to coarse sand | 0.04 | 0.06 | 0.15 |
| fine to medium sand | 0.02 | 0.05 | 0.19 |

Table 4. Residual Saturation Screening Values. Values are tabulated for medium to coarse sand and represent lower limits from Table 2. If a tolerance limit is needed, or for chemicals not listed (but with densities in the range of 0.7 to 1.5 g/cm^3 , including petroleum products and crude oil), we suggest the use of the S_r parameters in Table 3 as screening values.

| | Name | S_r residual NAPL fraction in the voids (cm^3/cm^3) | $C_{res,soil}$ residual NAPL concentration in soil (mg/kg) |
|-------|-------------------------|---|--|
| (3.) | Gasoline | 0.02 | 3,000 |
| (8.) | Middle distillates | 0.04 | 8,000 |
| (13.) | Fuel oils | 0.08 | 17,000 |
| (39.) | O-xylene | 0.01 | 2,000 |
| (35.) | Trichloroethylene (TCE) | 0.2 | 70,000 |

Note: Data row from Table 2 is indicated.

Several histograms of measured residual NAPL void fraction, S_r , as a function of soil type, are shown in Figure 3. These histograms are based on the relevant data in Table 2 and provide a basis for estimating conservative values of S_r within a specified statistical tolerance limit. Numerical values are given in Table 3. For example, with a medium to coarse sand, in specifying a screening level of $S_r = 0.06$, we would expect 90% of individual samples with equivalent NAPL concentrations below this level to be immobile in this soil type.

We expect that the tolerance limits in Table 3 and Figure 3 are biased conservatively, given that the Table 2 data showed lower residual NAPL concentration in soils than the empirical correlations of Eqs. [4] or [5]. The data in Table 2 is for NAPLs with densities ranging from about 0.7 to 1.5 g/cm^3 . The screening values for residual NAPL fraction in the voids, S_r , in Table 3, should be valid and reasonably conservative for this range in NAPL density.

Consolidated minimum values for S_r are shown in Table 4 for the various NAPL types in Table 2 listed as "medium sands". Again, these should be reasonably conservative screening values for NAPL mobility, for the indicated pure chemicals and hydrocarbon mixtures. No tolerance limits are specified for the Table 4 values, given the sparse data available when the screening values are qualified by both soil type and NAPL composition. If a tolerance limit is needed, or for chemicals not listed in Table 4 (with densities in the range of 0.7 to 1.5 g/cm^3 including petroleum and crude oil), we suggest the use of the S_r parameters in Table 3 as screening values. A tolerance limit of 90% is reasonable in most cases.

These screening values are intended to be worst-case estimates for mobility. Higher values may be applicable on a site-specific basis. For example, with an adequate distance in unsaturated

soil between the lower depth of a mobile NAPL and groundwater, it may also be reasonable to account for potential NAPL redistribution in the unsaturated soil layer. This redistribution would decrease the concentrations of mobile NAPL to concentrations in soil equivalent to S_r . After this redistribution, an acceptable distance between the deepest expected NAPL penetration and the historical top boundary of the water table capillary fringe must still remain.

These screening values, as already discussed, are intended for use in estimating conservative limits of NAPL mobility. The data of Table 2 may be used for other purposes, such as relating a known released volume of NAPL to an equivalent soil volume at the residual concentration level. While it is not the purpose of this paper to detail this type of calculation, the variability of an estimated residual concentration level, as illustrated in Figure 3, clearly needed to be considered.

SUMMARY AND CONCLUSIONS

Screening values describing residual saturation of NAPLs in unconsolidated vadose zone soils have been tabulated. These values are proposed for use in estimating concentrations of immobile NAPL in soil. The values, in Tables 3 and 4, are based on measured, published values for residual NAPL concentrations in soil, $C_{res,soil}$, in the unsaturated soil zone.

Another value, the soil saturation limit, $C_{sat,soil}$, has already found use as a screening level for NAPL mobility. $C_{sat,soil}$ is a calculated value estimating the presence of a residual NAPL. Data in this paper shows $C_{sat,soil}$ is a factor up to 50,000 times less than the residual NAPL concentration in soil, $C_{res,soil}$. For screening immobile NAPL concentrations the soil saturation limit is exceptionally conservative. We would instead recommend use of the values in Tables 3 and 4.

A complete site assessment, in addition, would also include evaluation of other potential transport mechanisms, including soluble dissolution into mobile soil pore water, and volatilization into soil pore air. These transport mechanisms, as noted previously, are discussed elsewhere.

Use of residual NAPL concentration in soil values for screening immobile NAPL presumes homogenous soils and soil properties. Consolidated soil matrices, macropores, and fractures will greatly affect the flow and movement of NAPL and must be recognized when these screening values are applied. Further, we note that the values have been developed using a limited data set, from multiple authors, and no attempt has been made to judge bias or error in the individual measurement techniques.

ACKNOWLEDGEMENT

Support for preparing this document from American Petroleum and GRI (formerly the Gas Research Institute) under GRI Contract No. 5097-210-3874 is gratefully acknowledged.

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