GENERAL STANDARD

FOR

SOIL POLLUTION CONTROL

DEC. 1997

This standard specification is reviewed and updated by the relevant technical committee on Oct. 2005(1) and Jan. 2015(2). The approved modifications are included in the present issue of IPS.

FOREWORD

The Iranian Petroleum Standards (IPS) reflect the views of the Iranian Ministry of Petroleum and are intended for use in the oil and gas production facilities, oil refineries, chemical and petrochemical plants, gas handling and processing installations and other such facilities.

IPS is based on internationally acceptable standards and includes selections from the items stipulated in the referenced standards. They are also supplemented by additional requirements and/or modifications based on the experience acquired by the Iranian Petroleum Industry and the local market availability. The options which are not specified in the text of the standards are itemized in data sheet/s, so that, the user can select his appropriate preferences therein

The IPS standards are therefore expected to be sufficiently flexible so that the users can adapt these standards to their requirements. However, they may not cover every requirement of each project. For such cases, an addendum to IPS Standard shall be prepared by the user which elaborates the particular requirements of the user. This addendum together with the relevant IPS shall form the job specification for the specific project or work.

The IPS is reviewed and up-dated approximately every five years. Each standards are subject to amendment or withdrawal, if required, thus the latest edition of IPS shall be applicable

The users of IPS are therefore requested to send their views and comments, including any addendum prepared for particular cases to the following address. These comments and recommendations will be reviewed by the relevant technical committee and in case of approval will be incorporated in the next revision of the standard.

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GENERAL DEFINITIONS:

Throughout this Standard the following definitions shall apply.

COMPANY:

Refers to one of the related and/or affiliated companies of the Iranian Ministry of Petroleum such as National Iranian Oil Company, National Iranian Gas Company, National Petrochemical Company and National Iranian Oil Refinery And Distribution Company.

PURCHASER:

Means the “Company” where this standard is a part of direct purchaser order by the “Company”, and the “Contractor” where this Standard is a part of contract documents.

VENDOR AND SUPPLIER:

Refers to firm or person who will supply and/or fabricate the equipment or material.

CONTRACTOR:

Refers to the persons, firm or company whose tender has been accepted by the company.

EXECUTOR:

Executor is the party which carries out all or part of construction and/or commissioning for the project.

INSPECTOR:

The Inspector referred to in this Standard is a person/persons or a body appointed in writing by the company for the inspection of fabrication and installation work.

SHALL:

Is used where a provision is mandatory.

SHOULD:

Is used where a provision is advisory only.

WILL:

Is normally used in connection with the action by the “Company” rather than by a contractor, supplier or vendor.

MAY:

Is used where a provision is completely discretionary.

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0. INTRODUCTION

Cleaning up hydrocarbon based liquids and refined products release from pipelines,oil production units, Desalter plants, pumping Station, Tank farms and drilling operation in upstream part and other pollutants from oil and petrochemical refineries and above ground/ under ground storage tanks in down stream part of Oil, Gas, and Petrochemical industries, typically involves using several corrective actions and strategies. Short term emergency measures may involves imminent actions to control acute safety and health hazards such as potential explosions and toxications. After the imminent danger has been eliminated, longer term corrective actions involve cleaning up pollutants that have entered the surface and subsurface environment.

Petroleum products in the subsurface may be trapped between soil particles in the unsaturated zone, floating on the water table or dissolved in ground water in the saturated zone. The focus of this standard is on long-term strategies for cleaning up petroleum products in unsaturated or saturated zones. When the spill occurs some kind of soil clean up is typically necessary.

In this standard, some of the subjects are adapted from the following specifications and handbooks:

“ENVIRONMENTAL ENGINEERING”

(FIFTH EDITION)

JOSEPH A. SALVATO, P.E., DEE

Formerly Commissioner, Division of Sanitary Engineering

New York State Department of Health, Albany, N.Y. Sanitary and Public Health Engineer.

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Encinitas California.

FRANKLIN J. AGARDY, Ph.D.

President Forensic Management Associates San Mateo, California.

"Cleanup of Petroleum Contaminated Soils at Underground Storage Tanks",

by Warren J. Lyman, David C. Noonan, Patrick J. Reidy (1990).

ROYAL DUTCH/SHELL

DEP	"Design and Engineering Practice"
DEP 31.40.60 11-Gen. (1194)	"Pipeline Leak Detection"
DEP 31.40.40.38-Gen.	"Hydrostatic Pressure Testing of New Pipelines"

1. SCOPE

In this Standard the following matter of soil pollution control is discussed:

a) To provide authorities concerned on how to assess site conditions in the unsaturated zone and where a petroleum product release has occurred, information needed to localized where in the unsaturated zone petroleum product is located, and also the removal of petroleum products from the unsaturated zone at a given site.

b) To assess on the technologies designed specifically for clean-up of the saturated zone.

c) To provide a structural methodology for evaluation and potential consequences of a leak in a pipeline. The methodology that is intended to assist pipeline operators in assessing the need to install pipeline leak detection facilities, and an overview of available pipeline leak detection techniques.

d) The requirements of Islamic Republic of Iran Environmental Department for soil pollution prevention shall be considered in engineering design and site selection of Oil, Gas, and Petrochemical facilities(Soil Quality Standard References and Guidelines, by: Department of Environment and Health Ministry, 1393). Under no circumstances soil pollutants elements shall exceed the allowable limits in this standard.

The Standard is classified into three sections as follows:

Section I:	Unsaturated Zone
Section II:	Saturated Zone
Section III:	Pipeline Leak Detection

Note 1:

This standard specification is reviewed and updated by the relevant technical committee on Oct. 2005. The approved modifications by T.C. were sent to IPS users as amendment No. 1 by circular No. 298 on Oct. 2005. These modifications are included in the present issue of IPS.

Note 2:

This standard specification is reviewed and updated by the relevant technical committee on Jan. 2015. The approved modifications by T.C. were sent to IPS users as amendment No. 2 by circular No. 442 on Jan. 2015. These modifications are included in the present issue of IPS.

2. REFERENCES

Throughout this Standard the following dated and undated standards/codes are referred to. These referenced documents shall, to the extent specified herein, form a part of this standard. For dated references, the edition cited applies. The applicability of changes in dated references that occur after the cited date shall be mutually agreed upon by the Company and the Vendor. For undated references, the latest edition of the referenced documents (including any supplements and amendments) applies.

IPS (IRANIAN PETROLEUM STANDARDS)

IPS-E-PR-730	"Engineering Standard for Process Design Plant Waste Water Treatment & Recovery Systems"
IPS-E-PR-771	"Engineering Standard for Process Requirements of Heat Exchanging Equipment"

EPA (ENVIRONMENTAL PROTECTION AGENCY USA)

EPA	"Estimating Air Emissions from Petroleum under Storage Tank Cleanups"

ANSI/ASME (AMERICAN NATIONAL STANDARD INSTITUTE/AMERICAN SOCIETY OF MECHANICAL ENGINEERS)

ANSI/ASME B 31-8	"Gas Transmission and Distribution Piping Systems"

3. DEFINITIONS AND TERMINOLOGY

Terms used in this Standard are defined below:

3.1 Absorption

The penetration of atoms, ions or molecules into the bulk mass of a substance.

3.2 Adsorption

The retention of atoms, ions or molecules onto the surface of another substance.

3.3 Aquifer

A geologic formation capable of transmitting significant quantities of groundwater under normal hydraulic gradients.

3.4 Aquitard

A geologic formation that may contain groundwater but not capable of transmitting significant quantities of groundwater under normal hydraulic gradients.

3.5 Attenuation

Attenuation is to reduce or lessen in amount (e.g., a reduction in the amount of contaminants in a plume as it migrates from the source).

3.6 Biodegradation

A process by which microbial organisms transform or alter through enzymatic action the structure of chemicals introduced into the environment.

3.7 Biomass

The amount of living matter in a given area or volume.

3.8 Bulk density

The amount of mass of a soil per unit volume of soil; where mass is measured after all water has been extracted and total volume includes the volume of the soil itself and the volume of air space between the soil grains.

3.9 Capillary suction

Process where water rises above the water table into the void spaces of a soil due to tension forces between the water and soil particles.

3.10 Capillary fringe

The zone of a porous medium above the water table within which the porous medium is saturated but is at less than atmospheric pressure. The capillary fringe is considered to be part of the vadose zone, but not of the unsaturated zone.

3.11 Confined aquifer

An aquifer under greater than atmospheric pressure, bounded above and below by relatively impermeable formations.

3.12 Confining layer

A geologic formation exhibiting low permeability that inhibits the flow of water.

3.13 Consolidated soil

When a soil is subjected to an increase in pressure due to loading at the ground surface, a re-adjustment in the soil structure occurs. The volume of space between the soil particles decreases and the soil tends to settle or consolidate over time.

3.14 Constituent

An essential part or component of a system or group: examples are an ingredient of a chemical system, or a component of an alloy.

3.15 Critical success factors (CSFs)

Are parameters that influence the likelihood of success of a particular method.

3.16 Curie

Curie is equal to 3.7×10^{10} Bq (exactly) (see note below).

Note:

bquerel is SI unit of radioactivity .Bq is equal of one decaying of atoms per second and one curie will be equal of 3.7×10^{10} decay per second.

3.17 Downgradient

In the direction of decreasing static head.

3.18 Drawdown

Lowering of the water table due to withdrawal of groundwater from a well.

3.19 Fluid

Substances which are transported through a pipeline in liquid and/or gaseous phase.

3.20 Fluid conductivity

The constant of proportionality in Darcy's Law relating the rate of flow of a fluid through a cross-section of porous medium in response to a hydraulic gradient. Fluid conductivity is a function of the intrinsic permeability of a porous medium and the kinematic viscosity of the fluid which flows through it. Fluid conductivity has units of length per time (cm/sec.).

3.21 Free product

A contaminant in the unweathered phase, where no dissolution or biodegradation has occurred.

3.22 Field capacity

The percentage of water remaining in the soil 2 or 3 days after gravity drainage has ceased from saturated conditions.

3.23 Hard liquid

A liquid with a vapor pressure below the prevailing atmospheric pressure, e.g. stabilized crude oil.

3.24 Henry's law

The relationship between the partial pressure of a compound and the equilibrium concentration in the liquid through a constant of proportionality known as Henry's Law Constant. See partial pressure.

$$C = kP_{gas}$$

where

C is the solubility of a gas at a fixed tempreture in a particular solvent (in units of M or mlgas/l).

k is Henry's low costant (often in units of M/atm).

P_{gas} is the partial pressure of the gas (often in units of atm).

3.25 Heterogeneous

Varying in structure or composition and having different properties in different locations or directions.

3.26 Hydraulic conductivity

The constant of proportionality in Darcy's law relating the rate of flow of water through a cross-section of porous medium in response to a hydraulic gradient. Also known as the coefficient of permeability, hydraulic conductivity is a function of the intrinsic permeability of porous medium and the kinematic viscosity of the water which flows through it. Hydraulic conductivity has units of length per time (cm/sec.).

3.27 Hydraulic gradient

The change in piezometric head between two points divided by the horizontal distance between the two points, having dimensions of length per length (cm/cm). See piezometric head.

3.28 Infiltration

The downward movement of water through a soil from rainfall or from the application of artificial recharge in response to gravity and capillarity.

3.29 In situ treatment

In situ treatment means treatment of the soil in place, i.e., they are not dug up. The excavation of contaminated soils usually adds significant expense to a site remediation.

3.30 Interfacial tension

Phenomena occurring at the interface of a liquid and gas where the liquid behaves as it if were covered by an elastic membrane in a constant state of tension. The tension is due to unbalanced attractive forces between the liquid molecules at the liquid surface.

3.31 Leak

An uncontrolled fluid release from a pipeline and other sources.

3.32 Leak consequences

The result of a pipeline leak and other sources in terms of human safety and damage to the environment. Economic loss such as cost of repair and deferred production are not taken into account in the leak consequence evaluation methodology given in this Standard.

3.33 Leak expectancy

The probability of occurrence of a leak.

3.34 Moisture content

The amount of water or lost from the soil upon drying to a constant weight, expressed as the weight per unit weight of dry soil or as the volume of water per unit bulk volume of the soil. For a fully saturated medium, moisture content equals the porosity; in the vadose zone, moisture content ranges between zero and the porosity value for the medium. See porosity, vadose zone, saturated zone.

3.35 Molecular diffusion

Process where molecules of various gases tend to intermingle and eventually become evenly dispersed.

3.36 Molecular weight

The amount of mass in mole of molecules of a substance determined by summing the masses of the individual atoms comprising the molecule. One mole is equivalent to 6.02×10^{23} the molecules.

3.37 Non-Aqueous Phase Liquid (NAPL)

Contaminants that remain as the original bulk liquid in the subsurface.

3.38 Octanol-water partition coefficient (K_{ow})

A coefficient representing the ratio of solubility of a compound in octanol to its solubility in water. As Kow increases, water solubility decreases.

3.39 Permeability

A measure of a soils resistance to fluid flow. Permeability, along with fluid viscosity and density are used to determine fluid conductivity.

3.40 Phase

The physical form in which a substance is found. The three major phases are liquid, vapor and dissolved in pore water.

3.41 Piezometric head

The level to which water from a given aquifer will rise by hydrostatic pressure. For the uppermost unconfined aquifer, the piezometric head is identical to the water table elevation. For confined aquifers, the piezometric head can be above or below the water table.

3.42 Pipeline

A system of pipes and other components used for the transportation of fluids, between (but excluding) plants. A pipeline extends from pig trap to pig trap (including the pig traps and associated pipework and valves), or, if no pig trap is fitted, to the first isolation valve within the plant boundaries or a more inward valve if so nominated.

3.43 Porosity

The volume fraction of a rock or unconsolidated sediment not occupied by solid material but usually occupied by water and/or air. Porosity is a dimensionless quantity.

3.44 Pressure gradient

A pressure differential in a given medium, which tends to induce movement from areas of higher pressure to areas of lower pressure.

3.45 Refractory index

A measure of the ability of a substance to be biodegraded by bacterial activity.

3.46 Residual saturation

The amount of water or oil remaining in the voids of a porous medium and held in an immobile state by capillary and dead-end pores.

3.47 Saturated zone

The zone of the soil in which all space between the soil particles is occupied by water, including the capillary zone.

3.48 Soft liquid

A liquid with a vapor pressure above the prevailing atmospheric pressure, e.g. ethylene, NGL, LPG, etc.

3.49 Soil sorption coefficient

A measure of the preference of an organic chemical to leave the dissolved aqueous phase in the soil and become attached or adsorbed to soil particles as organic carbon.

3.50 Sorption

A general term used to encompass the process of absorption, adsorption, ion exchange, and chemisorption.

3.51 Stratigraphy

The study of original succession and age of subsurface layers; dealing with their form, distribution, composition, and physical and chemical properties.

3.52 Surfactant

Natural or synthetic chemicals that have the ability to promote the wetting, solubilization, or emulsification of various organic chemicals.

3.53 Technical integrity

The state of a system which exists when, under specified operating conditions, there is no foreseeable risk of its failure endangering people, the environment or asset value.

3.54 Unconfined aquifer

An aquifer that is under atmospheric pressure. It is usually the uppermost aquifer in the subsurface with its upper limit being the water table.

3.55 Upgradient

In the direction of increasing static head.

3.56 Vadose zone

The portion of a porous medium above the water table within which the capillary pressure is less than atmospheric and the moisture content is usually less than saturation. The vadose zone includes the capillary fringe.

3.57 Vapor pressure

The equilibrium pressure exerted on the atmosphere by a liquid or solid at a given temperature. Also a measure of a substance’s propensity to evaporate or give off flammable vapors. The higher the vapor pressure, the more volatile the substance.

3.58 Viscosity

In flowing liquids the existence of internal friction or the internal resistance to relative motion of the fluid particles with respect to each other must be considered; this resistance is called viscosity.

3.59 Volatilization

The process of transfer of a chemical from the water or liquid phase to the air phase. Solubility, molecular weight, and vapor pressure of the liquid and the nature of the air-liquid/ water interface affect the rate of volatilization.

3.60 Water table

The water surface in an unconfined aquifer at which the fluid pressure in the voids is at atmospheric pressure.

3.61 Weathering

The process where a complex compound is reduced to its simpler component parts, transported through physical processes, or biodegraded over time.

Abbreviations and Symbols

ALARP Principle	As low as is Reasonably Practicable
ASPIN	Assessment of Pipeline Integrity
API	American Petroleum Institute
BOD	Biochemical Oxygen Demand
CDM	Camp Dresser & Mckee Inc.
CFM	Cubic Feet per Minute
COD	Chemical Oxygen Demand
CSF	Critical Success Factor
ECF	Environmental Consequence Factor
EPA	U.S. Environmental Protection Agency
FRED	Fire Release Exposure and Dispersion
GAC	Granular Activated Carbon
LPG	Liquefied Petroleum Gas
MAOP	Maximum Allowable Operating Pressure
NAPL	Non-Aqueous Phase Liquid
NGL	Natural Gas Liquid
OPCO	A Group Operating Company.
PAC	Powdered Activated Carbon
PC	Personal Computer
POTW	Publicly Owned (Waste Water) Treatment Work
ROV	Remotely Operated Vehicle
SCF	Safety Consequence Factor
SMYS	Specified Minimum Yield Strength
SPLD	Statistical Pipeline Leak Detection
UST	Underground Storage Tank
UT	Ultrasonic Testing
USD	United States Dollar
VOCs	Volatile Organic Compounds

ZOC	Zone of Contribution

Note:

Further abbreviations and symbols used in leak consequence modeling are defined in Appendix A.

C_a	Concentration of contaminant in soil [cm^3/cm^3]
C_i	Unit of curie: 3.7 × 10^{10} Bq
C_w	Concentration of Contaminant in Pore Water [mg/l]
K_{oc}	Soil/Water Partitioning Coefficient
K_{ow}	Octanol/Water Partitioning Coefficient
pH	Indicates Alkaline or Acid Conditions in Log Units
RI	Refractory Index

List of Symbols

A	mm^2	Area of leak hole
d	Mm	Diameter of leak hole
D	Inch	Pipeline nominal diameter
ECF	—	Environmental consequence factor
E_1	—	Fluid persistence/seepage factor
E_2	—	Climate correction factor for liquids
E_3	USD/m^3	Clean-up and other associated costs for liquids
h	m	Water depth
I_g	—	Ignition factor
K	—	Ratio of specific heats for a gas, (Cp/Cv)
L_e	—	Leak expectancy
L_m	ton	Potential leak mass
LR	kg/s	Leak rate
L_s	km	Section length
MW	kg/kg-mol	Molar mass of gases
P_{in}	bar (ga)	Fluid pressure in the pipeline (gage)
P_{out}	bar (ga)	Back-pressure outside the pipeline (gage)
P_c	bar	Critical pressure of a gas for choked flow through an orifice
π	—	3.1416
Q	10^3 m^3/h	Fluid flow rate (for gases, under standard reference conditions, i.e. 15°C and 1.01325 bar)
Ro	kg/m^3	Fluid density
SCF	—	Safety consequence factor
S_1	—	Fluid hazard factor
S_2	—	Population density factor
T	hour	Time elapsed between the onset of a leak and shut-down of pumps/compressors

T_g	°C	Average gas temperature
T_m	°C	Average ambient temperature
Z	—	Compressibility factor

4. UNITS

This standard is based on international system of units (SI), as per IPS-E-GN-100 except where otherwise specified.

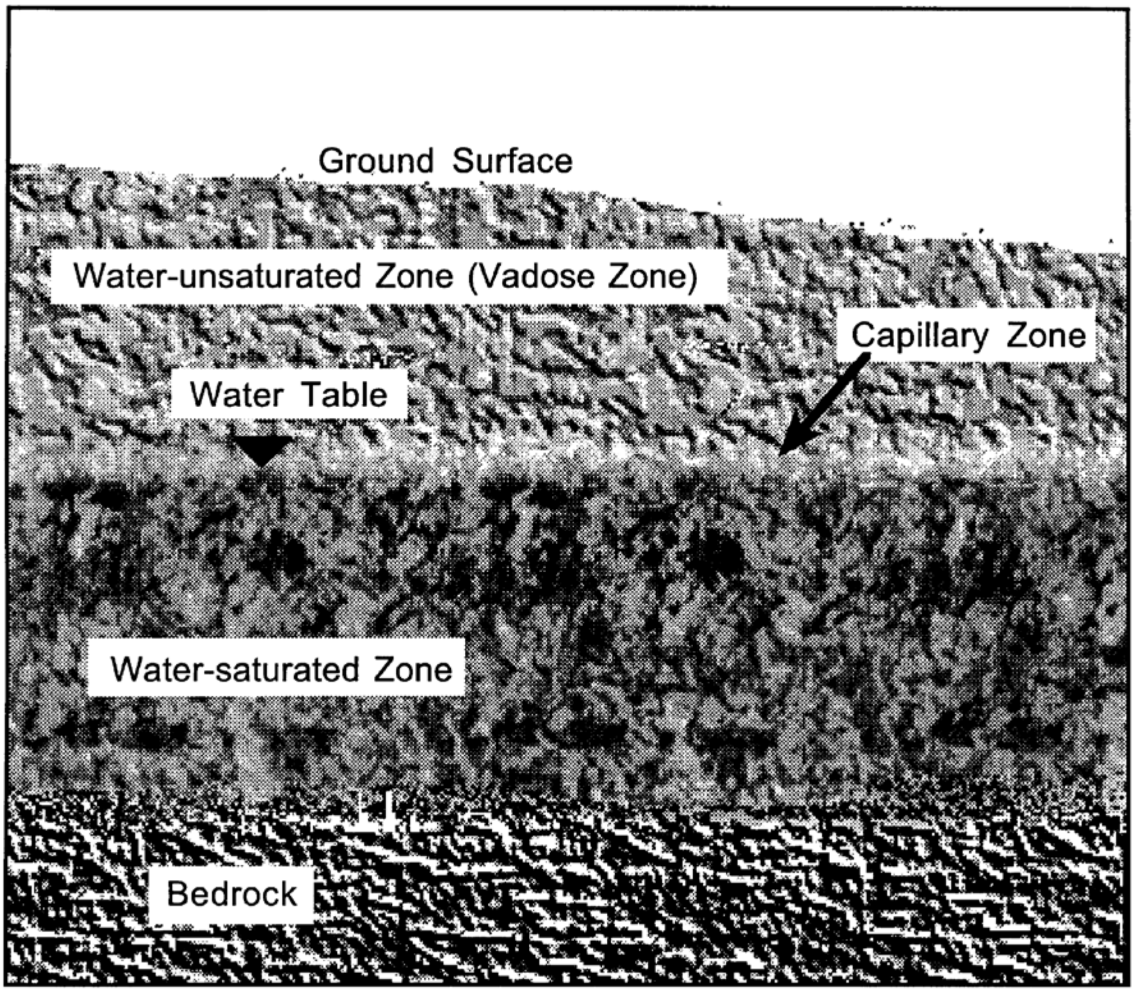
5. SOIL ZONES

The soil subsurface is commonly divided into three zones, based on their air and water content (see Fig. 1). From the ground surface down to an aquifer water table, soils contain mostly air in the pore spaces, with some adsorbed and capillary-held water. This region is called the *water unsaturated zone* or *vadose zone*.

From the top of the water table to bedrock, soils contain mostly water in the pore spaces. This region is called the *saturated zone*.

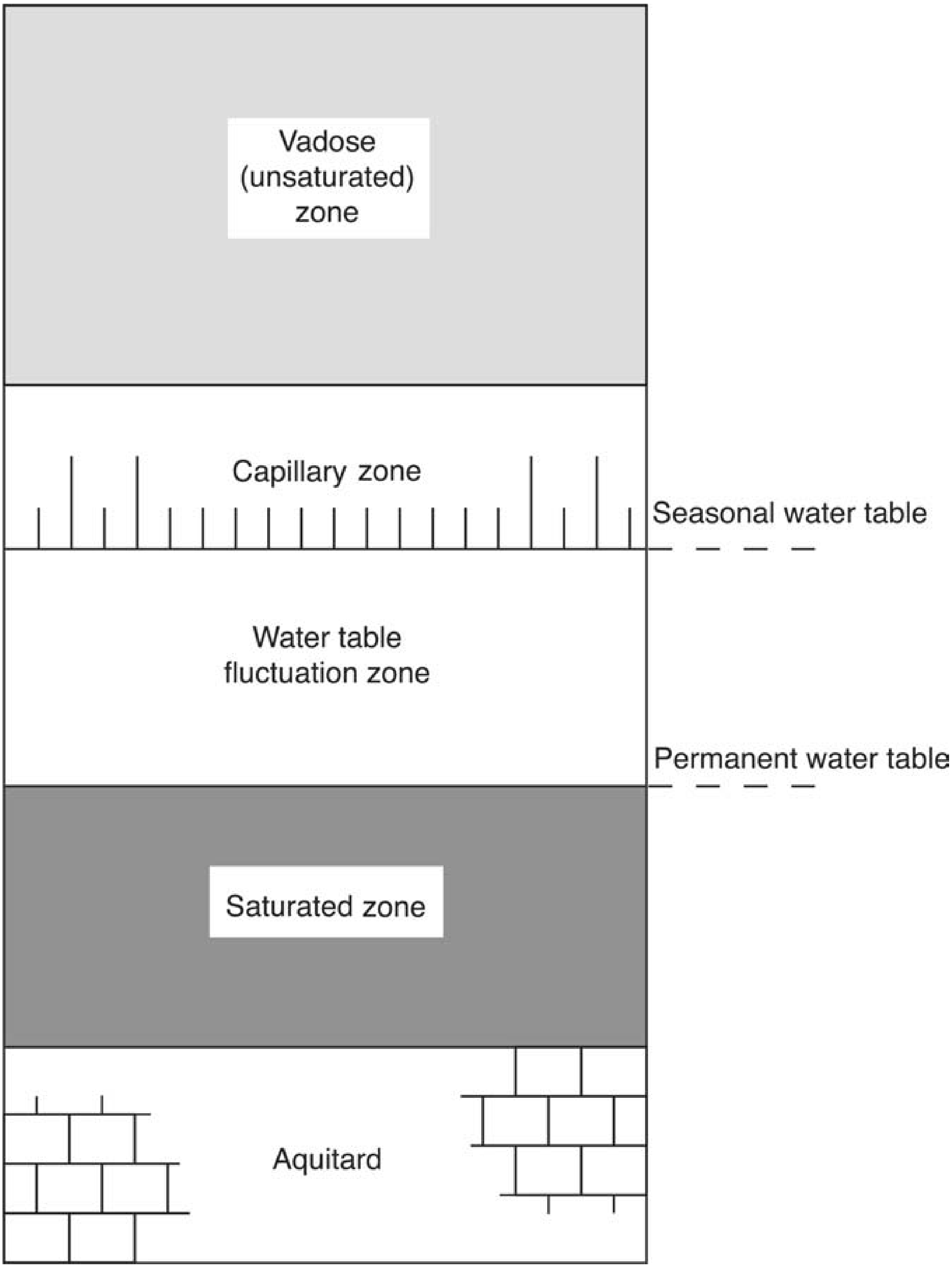
Between the vadose and saturated zones, there is a transition region called the *capillary zone,* where water is drawn upward from the water table by capillary forces. The thickness of the capillary zone depends on the soil texture - the smaller the pore size, the greater the capillary rise. In fine gravel (2-5 mm grain size), the capillary zone will be of the order of 2.5 centimeters thick. In fine silt (0.02-0.05 mm grain size), the capillary zone can be 200 centimeters or greater.

The saturated zone lies above the solid bedrock, which is impermeable except for fractures and cracks. The region of the subsurface overlying the bedrock is generally unconsolidated porous, granular mineral material.



SOIL ZONES IN THE SUBSURFACE REGION

Fig. 1



CROSS-SECTION OF A SOIL COLUMN SHOWING DIFFERING MOISTURE REGIMES

Fig. 2

“**Fundamentals of Site Remediation: For Metal and Hydrocarbon-Contaminated Soils by** *John Pichtel”*

SECTION I

UNSATURATED ZONE

6. UNSATURATED ZONE

6.1 General

Unsaturated zone is the portion of a porous, usually above the water table in an unconfined aquifer, within which the moisture content is less than saturation and the capillary pressure is less than atmospheric pressure and the unsaturated zone does not include the capillary fringe.

A good understanding of the conditions in the unsaturated zone is essential when selecting an appropriate soil treatment technology. By site assessment which reveal analysis of basic hydrologic, geologic, and chemical data measurements collected at the site of interest. The following points shall be considered.

a) What was released? Where? (time since petroleum released).

b) Currently, where in the unsaturated zone is most of the petroleum product likely to be?

c) How much petroleum product is likely to be present in different locations and phases?

d) How mobile are the constituents of the contaminant, and where are they likely to travel and at what rate?

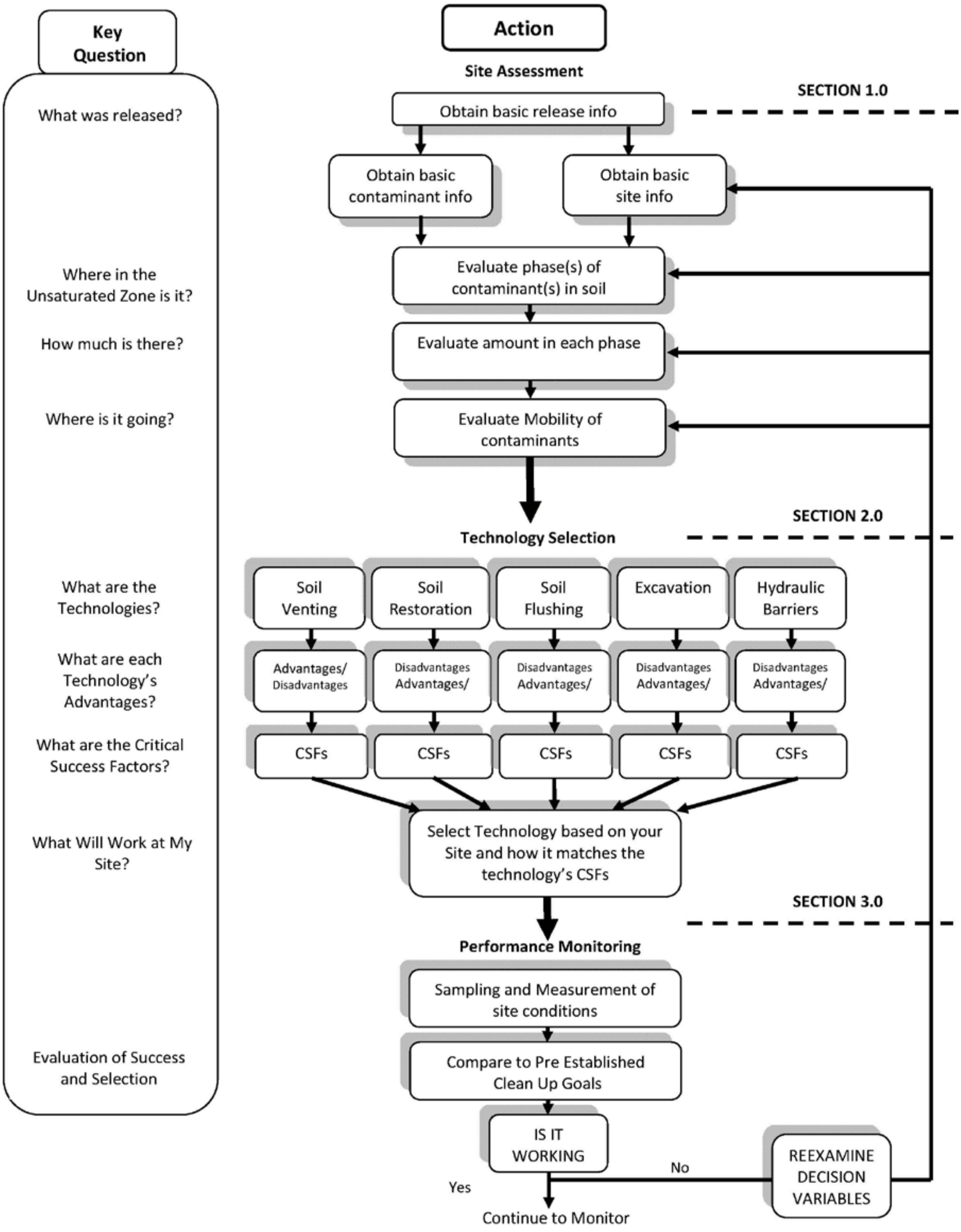
6.2 Organization Responsibility

Contractors or other parties who have responsibility for cleaning up the unsaturated zone as shown in Fig. 3 shall consider three main components as given below:

a) Site assessment;

b) Technology selection;

c) Monitoring and follow-up measurements.



AN OVERVIEW OF THE APPROACH

Fig. 3

6.3 Limitation

Several significant limitations regarding its content and its precision are given below:

1) Estimates are for relative assessments

How much of the release is likely to be in each phase in unsaturated zone, and which technologies are more likely to be effective.

2) Petroleum hydrocarbons as contaminants

Since petroleum products comprise most of the materials stored in USTs, therefore special focus is given to gasoline.

3) Situ treatment

After a contaminated soil has been excavated, the soil can also be treated above ground using many of the same techniques described for in situ applications (see Clause 8.5).

7. SITE ASSESSMENT

7.1 SITE INVESTIGATIONS

The remediation process begins with a site investigation. The purpose of the investigation is to define, as completely as possible, the nature of the hazardous materials on site, their location(s), the degree of contamination (if any),and the extent of the contamination (in both soil and water, recognizing that contamination can, and indeed does, manifest itself in surface waters and sediments as well as in ground waters). Once the scope of any contamination is identified, the steps required to eliminate or isolate the contaminant source(s), remove the contamination, and prevent further spread of the contamination are specified and required by law. Having said that, the actual process is a bit more complicated.

The data collected should be used to gain the behavior of the contaminant in the subsurface. When dealing with the unsaturated zone, the data are primarily used to determine the mobility of the contaminant and which phase(s) it is likely to be in. Mobility of petroleum product in the unsaturated zone is related to:

a) The potential for the various phases of contaminant to move through the subsurface.

b) The potential for the petroleum product to change from one phase into another.

To choose an effective clean-up technology for soils contaminated by petroleum, it is necessary to collect certain basic information about the released product and the subsurface environment, and these are:

1) What contaminants were released?

Knowledge of the type of product released, its physical and chemical properties, and its major chemical constituents is required.

2) Where is the petroleum product currently?

Distribution of petroleum product within the unsaturated zone, i.e., as a vapor in soil gas, as a residual liquid, or dissolved in pore water.

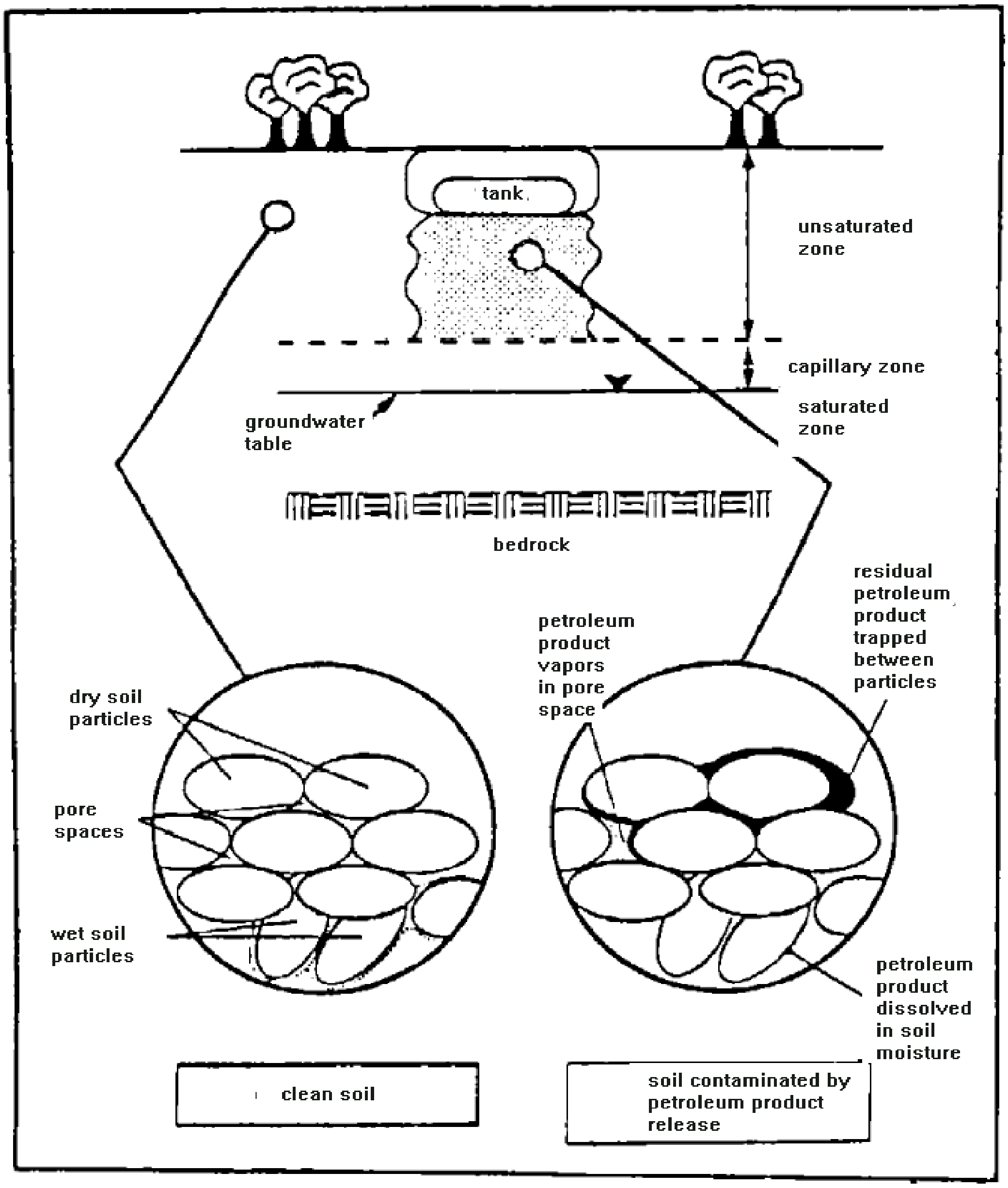
3) How much petroleum product is in each phase?

Immediately after a release (weeks to months) most of the product will exist as a residual liquid, significant fractions will volatilize and dissolved in existing pore water or infiltrating rain water.

4) Where is the petroleum product going?

Mobility effects not only extent the potential of a release, but also make the effectiveness of any treatment scheme that depends on mobilizing the contaminants difficult to remove them (e.g. vacuum extraction).

These four questions provide a framework for decision, and more information can often improve the selection process. As a whole petroleum product in unsaturated zone exist only in three phase as shown in Fig. 4.



REPRESENTATION OF THREE DIFFERENT PHASES IN WHICH PETROLEUM PRODUCT CAN BE FOUND IN UNSATURATED ZONE

Fig. 4

7.2 Gathering Release Information

The questions listed in Table 1 provides a starting point for finding the mobility and phase distribution of the product in the subsurface. For more above ground spills, the answers to questions in Table 1 are usually easy to obtain.

Petroleum products include a variety of fuel types, each with different physical and chemical properties. In addition, each fuel type is a mixture of many constituent compounds which have properties that can be quite different from those of the mixture. Mobility of different contaminant's must be known to determine over spilled fuel (e.g., "Will this contaminant spread quickly and reach the water table?"), its partitioning ("Will this contaminant vaporize and pose explosion hazards?") and its degradation potential ("Will this contaminant be biodegraded easily in the unsaturated zone?"). These factors are an important part of the technology selection process.

TABLE 1 - BASIC RELEASE INFORMATION ASSUMED TO BE KNOWN

INFORMATION NEEDED	WHY INFORMATION IS IMPORTANT
What contaminants were released?	Physical and chemical properties differ for each contaminant, leading to varying phase partitioning, mobility, and degradation characteristics for each contaminant. Corrective action selection is tied to these characteristics.
How much was released?	The amount released directly affects the phases in which in the contaminant may be found. The volume of spilled product can help the user to evaluate whether the contaminant has reached the saturated zone and estimate the level of contamination in the unsaturated zone.
What was the nature of the release (quick spill/slow leak)?	Phase partitioning and mobility of the released contaminant are both affected by the nature of the release. As a result, selection of appropriate corrective actions may differ for quick spills versus leaks over extended period of time.
How long since the release?	Contaminants "weather" over time, that is, change in composition and properties due to processes such as degradation, volatilization, and natural flushing from infiltrating rainfall. This change in composition and properties directly affects the physical and chemical properties of the bulk contaminant.
How was the release detected?	May provide insight into above questions and areal extent and distribution of contamination in the subsurface.

7.3 Gathering Site-Specific Information

7.3.1 Site-specific information pertains primarily to the hydrologic and geologic characteristics of the site. Geologic characteristics can vary greatly, even over short distances, therefore it is essential to make the accurate estimates of soil parameters through numerous field data. Table 2 lists site-specific data that are needed to conduct a site assessment. This table lists the essential data needed to assess the site.

7.3.2 Default values obtained via tables, figures, and other data-for many of the parameters. These default values enable users of this Standard to make estimates of the critical parameters on the timely basis for a preliminary site assessment.

TABLE 2 - SITE-SPECIFIC PARAMETERS TO GATHER

PARAMETER (UNITS)	DEFAULT SOURCE	IMPORTANT FOR DETERMINING
Soils porosity (%)	Table 3, Fig. 6	Mobility, phase
Particle density (g/cm³)	Table 3	Mobility, phase
Bulk density (g/cm³)	Table 3	Mobility, phase
Hydraulic conductivity (cm/sec.)	Table 3	Mobility, phase
Air conductivity	Table 3	Mobility, phase
Permeability (cm²)	Table 3	Mobility, phase
Soil moisture content (%)	Fig. 5	Mobility, phase
Local depth to groundwater (ft)	Easy to measure or through site or local records	Phase
Soil temperature (°C)	Fig. 5	Mobility, phase
Soil pH	Measure	Bacterial activity
Rainfall, runoff, and infiltration rate (cm/day)	Local precipitation and evaporation records	Mobility, phase composition
Soil surface area (m²/g)	Table 4	Mobility, phase
Organic content composition (%)	Measure	Mobility, phase
Fractures in rock	Local records	Mobility

7.3.3 Site-specific data shall be obtained whenever possible. If a quick initial assessment is needed it is often necessary to evaluate alternatives without the need of field data or when only incomplete data are available. In these cases, approximations is useful. Tables 3 and 4 (see note) provide typical values for several of the parameters listed in Table 2 for various types of soil and rock. These tables can be used to select default values in the absence of measured values. Fig. 5 provides water holding properties by soil type. An estimate of the moisture content of a particular soil can be made by using a typical field capacity value from the range of values shown on Fig. 5.

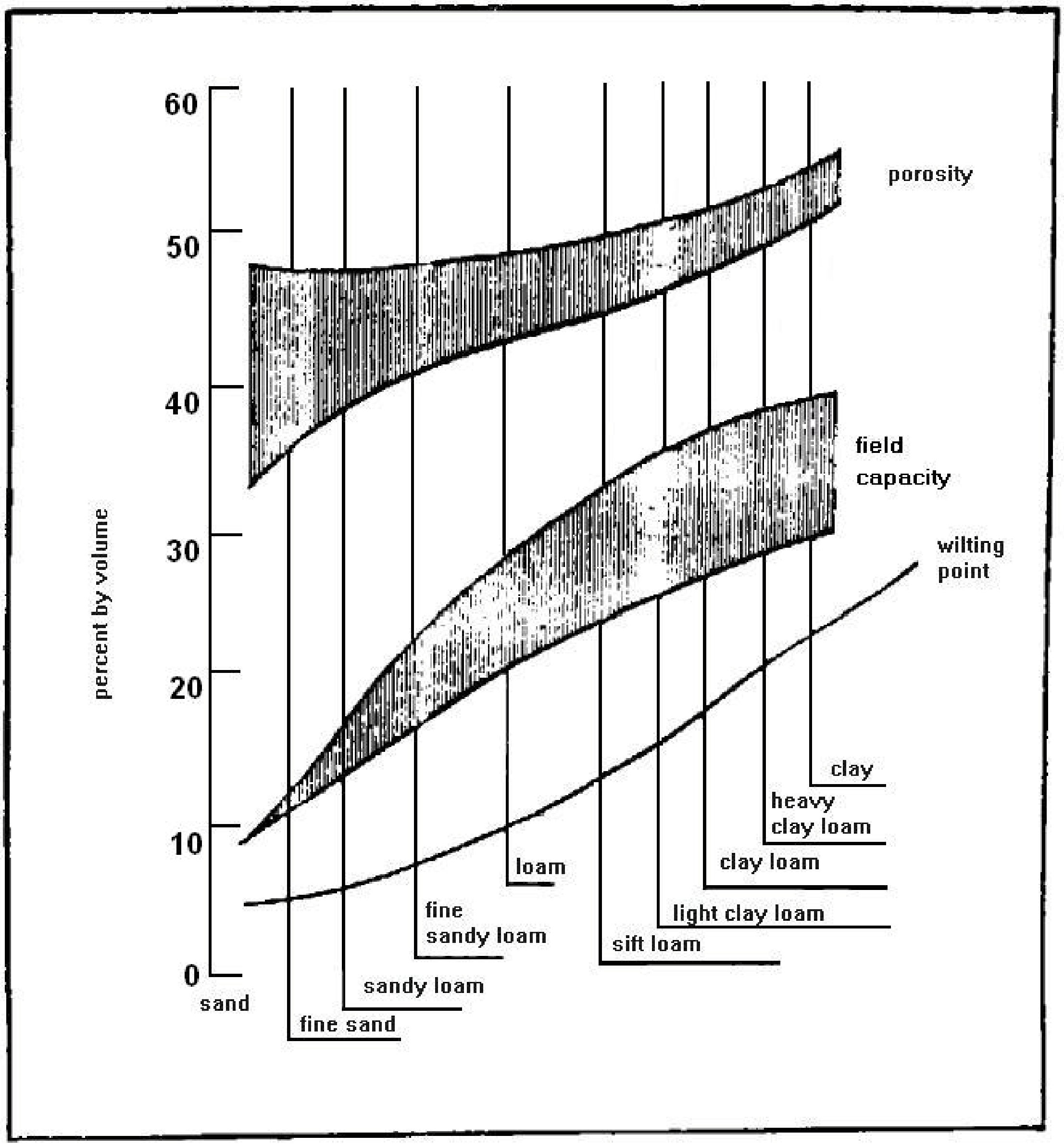
7.4 Gathering Contaminant-Specific Information

7.4.1 In addition to release-related and site related information, a site assessment shall include knowing of the physical and chemical properties of the contaminants released. To a large extent, contaminant properties govern's partitioning in the subsurface; what phase(s) it is likely to reside in, how it is likely to move away from the site, and whether it is likely to degrade significantly over time.

Table 5 (see Note) lists contaminant-specific data that are needed to conduct a site assessment. To illustrate, assume the liquid density of gasoline is needed. The user can locate liquid density in Table 5 (see Note) and find that the default source in Table 7. Moving to Table 7, the typical value for automotive gasoline in the liquid density column is 0.73 g/cm³.

Note:

All tables marked (see Note) are included in reference book given in Source.("Cleanup of Petroleum Contaminated Soils at Underground Storage Tanks", by Warren J. Lyman, David C. Noonan, Patrick J. Reidy (1990).)



WATER-HOLDING PROPERTIES OF VARIOUS SOILS ON THE BASIS OF THEIR TEXTURE
Fig. 5

7.4.2 Hydraulic conductivity of soil directly affects a contaminant's mobility or ability to move away from the release site in the (Non-Aqueous Phase Liquid) NAPL and dissolved phases.

A high rainfall infiltration rate can cause contamination to move from one phase to another. Some hydrocarbons will dissolve in the infiltrating rain water, and reducing the residual liquid portion of the contamination while increasing the amount of contaminant dissolved in pore water.

Soil temperature shall also affects contaminants mobility, contaminants vapor pressure, and therefore the ease with which contaminants move into air spaces in soil, increases with increasing temperature.

7.4.3 Evaluating Contaminant Mobility

Mobility of the contaminants in a site assessment focuses on unsaturated zone and also between phases. Many in-situ corrective actions depend on mobilizing contaminants.

The factors that control mobility of contaminants differ for each phase, are as given below:

a) Residual liquid contaminant

The movement of bulk liquids in the unsaturated zone is dominated by three factors:

1) Gravity

Where exerts a direct downward force, the magnitude of which depends only on the density of the contaminant.

2) Pressure gradients

Where generally result from infiltrating liquid (precipitation and contaminants), and most often act in the same direction as gravity.

3) Capillary suction

Where depends on the soil characteristics and the forces it generates act in all direction, although not equally.

In addition to these three major forces, other physical, chemical, and environmental factors can influence a liquid’s mobility in the unsaturated zone (see Table 3 of this Standard).

b) Contaminant vapors

Vapors are generally mobile in the unsaturated zone. The degree of mobility greatly depends on the air-filled porosity of the soil. Several other factors also influence vapor transport in the unsaturated zone as listed in Table 4 of this Standard.

Contaminants vapors may be mobilized by several natural or induced processes or forces as indicated below:

1) Bulk transport due to pressure gradients.

2) Bulk transport due to vapor density gradients.

3) In-situ generation of gases or vapors.

4) Molecular diffusion due to concentration gradients.

Vapor density differences is important only when liquid contaminant of sufficient volatility is present. For example, the density of air saturated with gasoline vapors (i.e. in contact with liquid gasoline) is about 1,950 g/m³ at 20°C, moist air has a density of about 1,200 g/m³ at 20°C. In the absence of other driving forces, heavier (contaminant containing) vapors should tend to migrate down-ward in the unsaturated zone. The driving force (density difference) will diminish as the vapors become more diluted.

TABLE 3 - FACTORS TO EVALUATE THE MOBILITY OF LIQUID CONTAMINANTS

FACTOR	UNITS	SITE INTERESTED	INCREASING MOBILITY ⟶		
RELEASE RELATED					
● Time since release	Months		Long (>12)	Medium (1-12)	Short (<1)
SITE-RELATED					
● Hydraulic Conductivity	cm/sec		Low ($<10^{-5}$)	Medium (10^{-5}-10^{-3})	High ($>10^{-3}$)
● Soil Porosity	% Soil Volume		Low (<10)	Medium (10-30)	High (>30)
● Soil Surface Area	m^2/g		Low (<0.1)	Medium (0.1-1)	High (>1)
● Soil Temperature	°C		Low (<10)	Medium (10-20)	High (>20)
● Rock Fractures	---		Absent	---	Present
● Moisture Content	% Volume		Low (<10)	Medium (10-30)	High (>30)
CONTAMINANT-RELATED					
● Liquid Viscosity	cPoise		Low (<2)	Medium (2-20)	High (>20)
● Liquid Density	g/cm^3		Low (<1)	Medium (1-2)	High (>2)

TABLE 4 - FACTORS TO EVALUATE THE MOBILITY OF CONTAMINANT VAPORS

FACTOR	UNITS	SIT INTERESTED	INCREASING MOBILITY ⟶		
SITE-RELATED					
● Air Filled Porosity	% Volume		Low (<10)	Medium (10-30)	High (>10)
● Total Porosity *	% Volume		Low (<10)	Medium (10-30)	High (>30)
● Water Content *	% Volume		Low (<10)	Medium (10-30)	High (>30)
● Depth Blow Surface	meters		Deep (>10)	Medium (2-10)	High (<2)
CONTAMINANT-RELATED					
● Vapor Density	g/m^3		Low (<50)	Medium (50 to 500)	High (>500)

*** The total porosity less that fraction filled with water equals the air filled porosity.**

c) Contaminant dissolved in pore water

Table 5 lists factors that can help to determine the relative mobility of contaminants dissolved in pore water in the unsaturated zone. The factors that govern mobility of contaminants is identical as described in 7.5.1(a).

As with Table 3, the site related factors in Table 5 of this Standard may vary with depth. If information about the soil profile is available, this can be completed for each distinct soil group. Otherwise, a best estimate of actual conditions must be made to complete the preliminary assessment.

TABLE 5 - FACTORS TO EVALUATE THE MOBILITY OF CONTAMINANTS IN PORE WATER

FACTOR	UNITS	SITE INTERESTED	INCREASING MOBILITY →		
SITE-RELATED					
● Hydraulic Conductivity	cm/sec		Low (10^{-5})	Medium (10^{-5}-10^{-3})	High (>10^{-3})
● Moisture Content	% Volume		Low (<10)	Medium (10-30)	High (>30)
● Rainfall Infiltration Rate	cm/day		Low (<0.05)	Medium (0.05-0.1)	High (>0.1)
● Soil Porosity	% Volume		Low (<10)	Medium (10-30)	High (>30)
● Rock Fractures	---		Absent	---	Present
● Depth Blow Surface	meters		Shallow (<2)	Medium (2-10)	Deep (>10)
CONTAMINANT-RELATED					
● Water Solubility	mg/l		Low (<100)	Medium (100 to 1000)	High (>1000)

8. TECHNOLOGY SELECTION

This section describes five technologies used to remediate UST sites:

a) Soil venting,

b) Biorestoration,

c) Soil Flushing,

d) Hydraulic Barriers,

e) Excavation.

8.1 Soil Venting

Soil venting is a general term that refers to any technique that removes contaminated vapors from the unsaturated zone. Venting may be passive or active. Passive venting is usually used for removal of methane gas.

Active venting uses an induced pressure gradient to move vapor through the soil and is more effective than passive venting. For more details reference shall be made to cleanup of petroleum contaminated soils at underground storage tanks by Warren J. Lyman, David C. Noonan, Patrick J. Reidy, 1990.

8.2 Biorestoration

In situ biorestoration of the unsaturated zone is a process where oxygen and nutrients are added to contaminated soil to promote the breakdown of contaminants. In some cases, specially acclimated, commercially available, bacteria may also be introduced to the subsurface, but this is not a common procedure. Bacteria capable of biodegrading petroleum hydrocarbons are commonly found in subsurface soils. Natural breakdown of petroleum hydrocarbons is likely to occur whenever they are introduced to the subsurface, but without the addition of nutrients and oxygen biodegradation occurs very slowly.

8.3 Soil Flushing

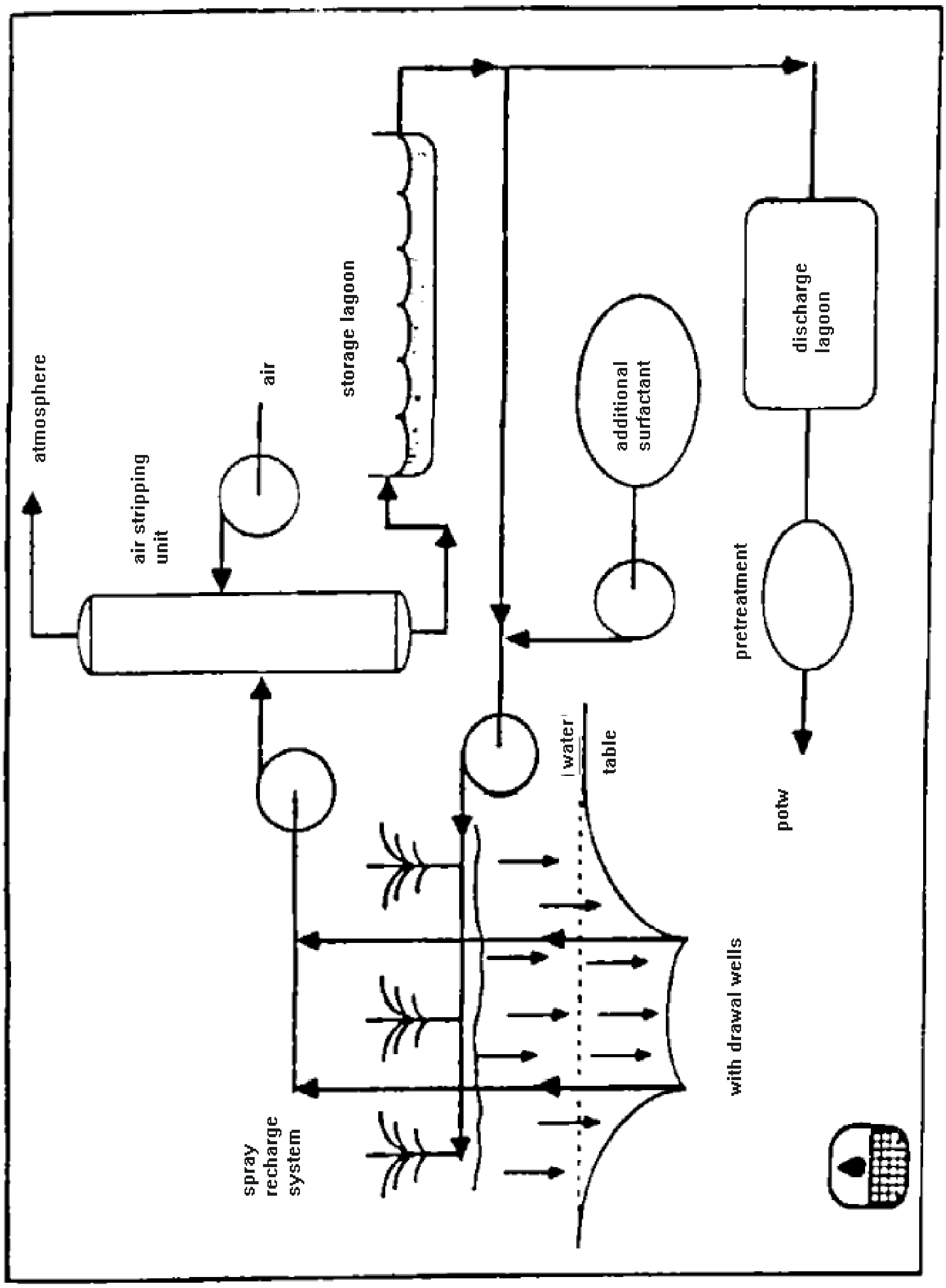
Soil flushing refers to the in situ process where the zone of contamination is flooded with water or a watersurfactant mixture in order to dissolve the contaminants into the water or otherwise mobilize the residual contaminant to the water table. The contaminants are then brought to the surface for treatment by strategically placed extraction wells. The wells must be located such that the groundwater is completely controlled hydraulically, to ensure that the leached or mobilized contaminants do not escape once they reach the groundwater. Fig. 6 shows a schematic diagram of a soil flushing system.

One soil flushing method removes contaminants by using water to dissolve the liquid, sorbed, or vapor contaminants. These process are controlled by the contaminants solubilities and Henry's law constants.

A second soil flushing method mobilizes contaminants existing as free product in the soil pores, and adsorbed to the soil. Contaminants found in these phases can be mobilized by the pressure gradient of the infiltrating flushing water. The viscosity and density of contaminants control the extent to which a compound may be mobilized as free product. This type of soil flushing would be expected to remove a greater portion of gasoline than heating oil or fuel oil, because gasoline is less viscous than either of the other two petroleum products. Many of the constituents of gasoline are also more soluble than those of fuel oil or heating oil and would be more readily mobilized in the dissolved phase as well.

8.4 Hydraulic Methods

Typically a trench is dug into the contaminated soil and residual liquid will began to seep into the trench. An impervious layer can be placed at the base of the trench to prevent re-infiltration of the product. As the product accumulates, it can be pumped out or removed manually, maintaining a gradient which facilitates further seepage into the trench see Fig. 7



SCHEMATIC DIAGRAM OF SOIL FLUSHING SYSTEM

Fig. 6

8.5 Excavation

Excavation is an alternative to the in-situ treatment methods. Excavation soil may be treated off site, or disposed of (land field) without treatment. Treated soil is sometimes placed back in the excavation at the site. At present, excavating contaminated soil is more common than in situ treatment. Excavation, however, has many drawbacks not faced with in situ methods as follows:

a) Excavating contaminated soils allows uncontrolled release of contaminant vapors to the atmosphere, increasing exposure risks (EPA, 1989);

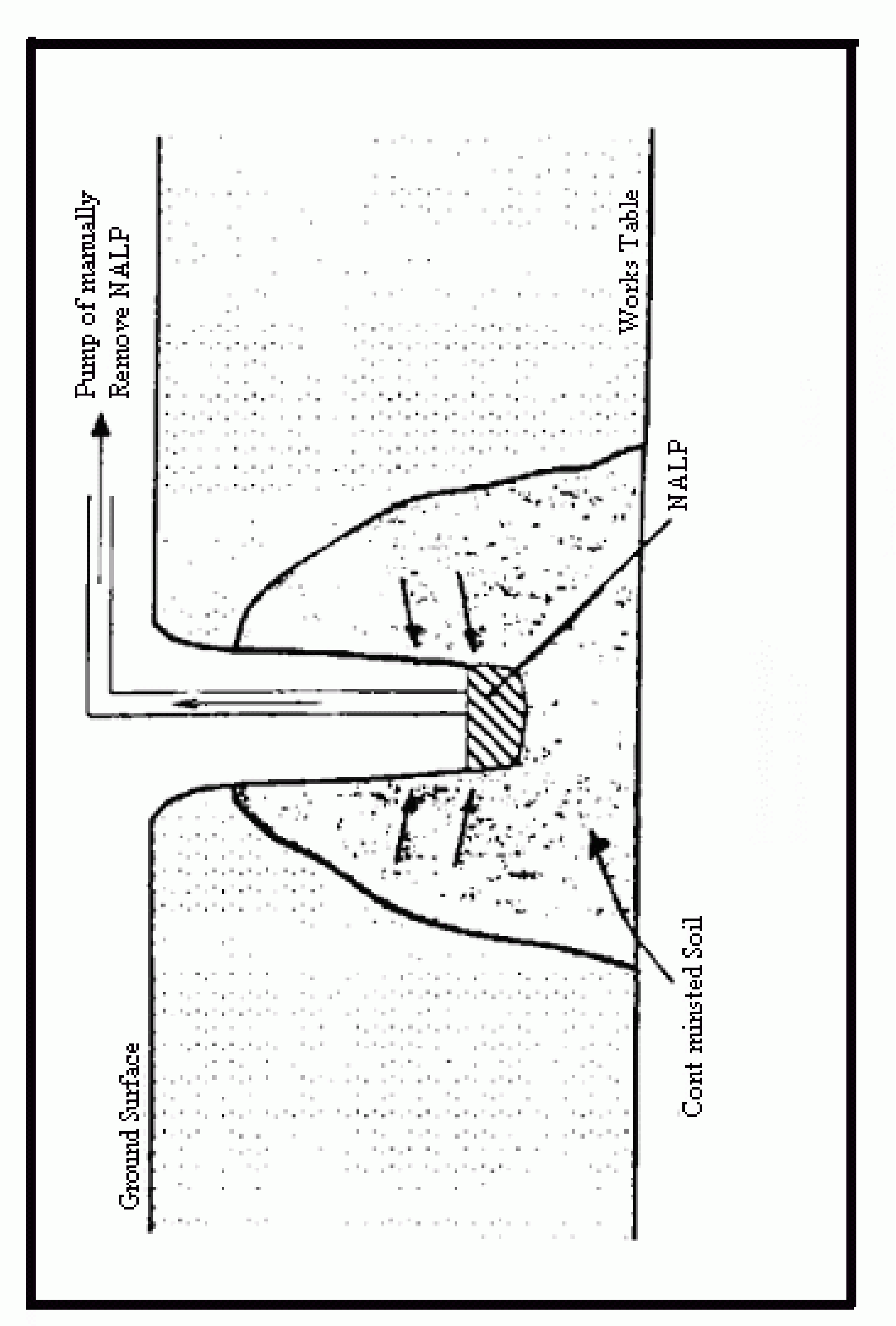
b) Above-and below-ground structures-buried utility lines, sewers and water mains and buildings can pose real problems of contamination extends near or below the structures;

c) Above-ground treatment methods tend to more expensive than in situ methods;

d) Disposal of contaminated soil is becoming increasingly difficult, and in some regulatory regions the soil is considered a hazardous waste;

e) A source of backfill is required to fill the excavation.

Excavation is a well known technique; and it has the ability to remove most or all of the contamination from the site.



SCHEMATIC DIAGRAM OF A TYPICAL HYDRAULIC BARRIER SYSTEM
Fig. 7

SECTION II

SATURATED ZONE

9. SATURATED ZONE

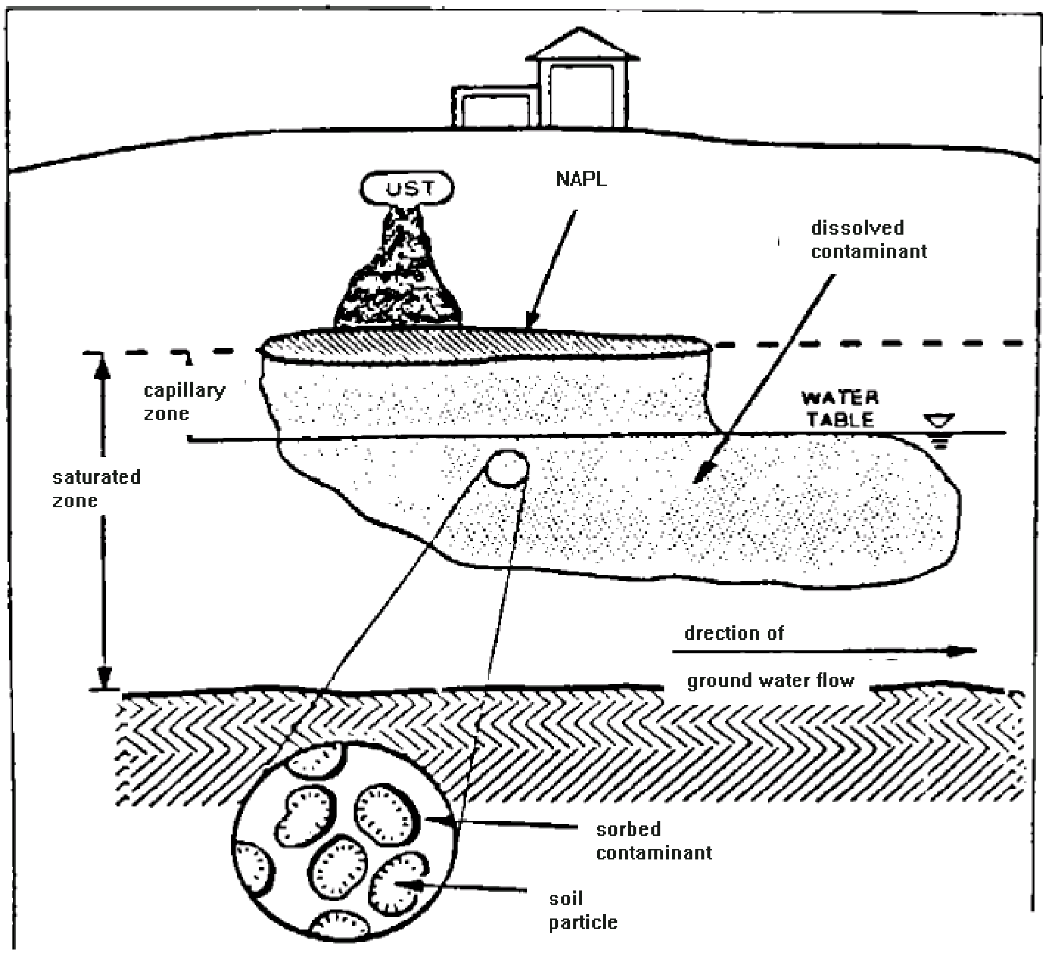
9.1 General

Saturated zone is defined as the zone below the ground surface in which all pore spaces are filled with water. Petroleum products reaching the saturated zone are subject to greatly increased mobility of the contaminant, particularly in the horizontal direction. Mobilization of the contaminants increases the magnitude of clean-up efforts and the opportunity for liability. Petroleum products found in the saturated zone are exclusively defined in three phases as follows:

a) Non-aqueous phase liquid (NAPL);

b) Dissolved in groundwater (dissolved phase);

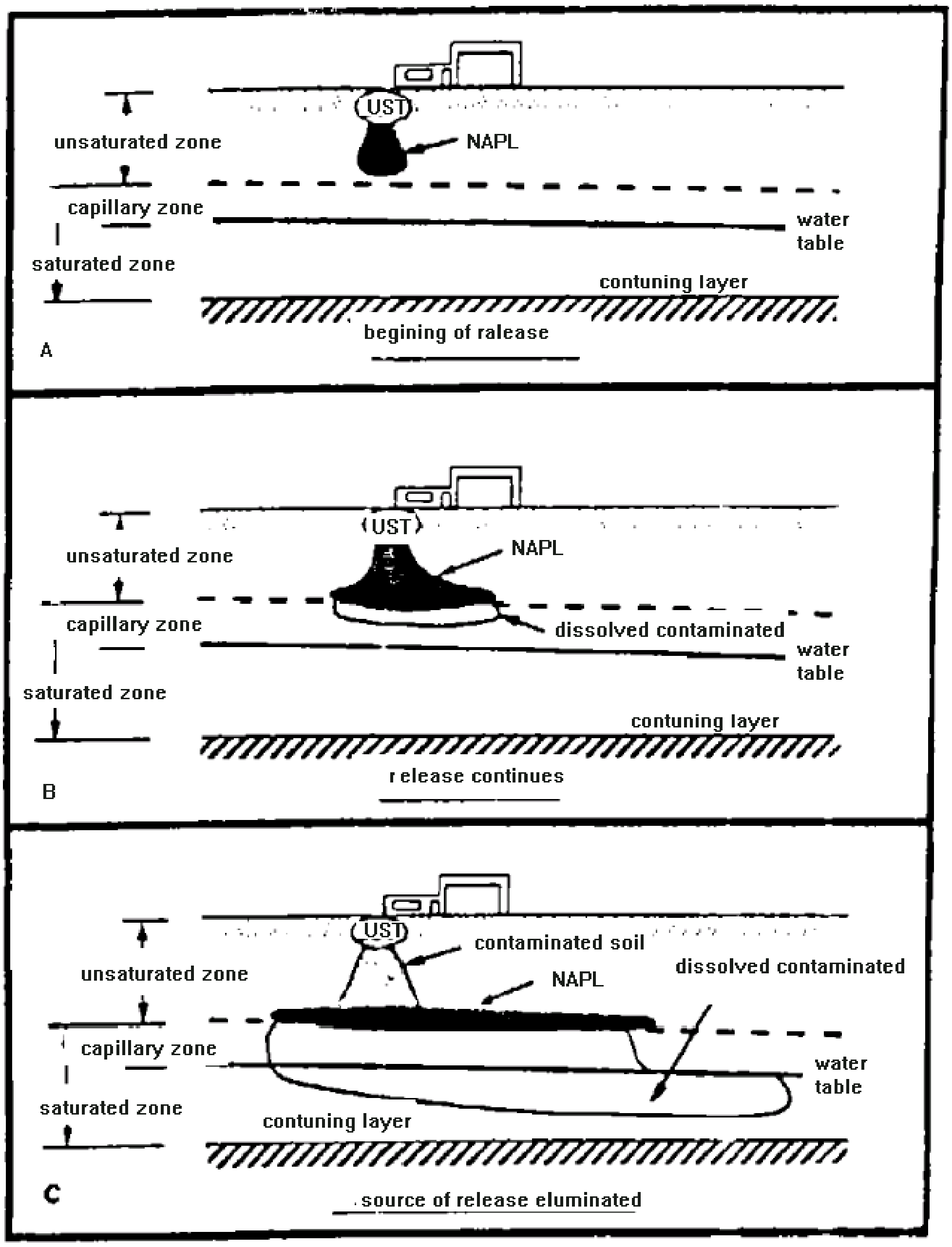
c) Sorbed to soil particles (solid phase). See Fig. 8.



THREE CONTAMINANT PHASES IN THE SATURATED ZONE

Fig. 8

Fig. 9 shows a typical sequence of events in the first stages of a release as they relate to the saturated zon.



PROGRESSION OF A TYPICAL PETROLEUM PRODUCT RELEASE FROM AN UNDERGROUND STORAGE TANK

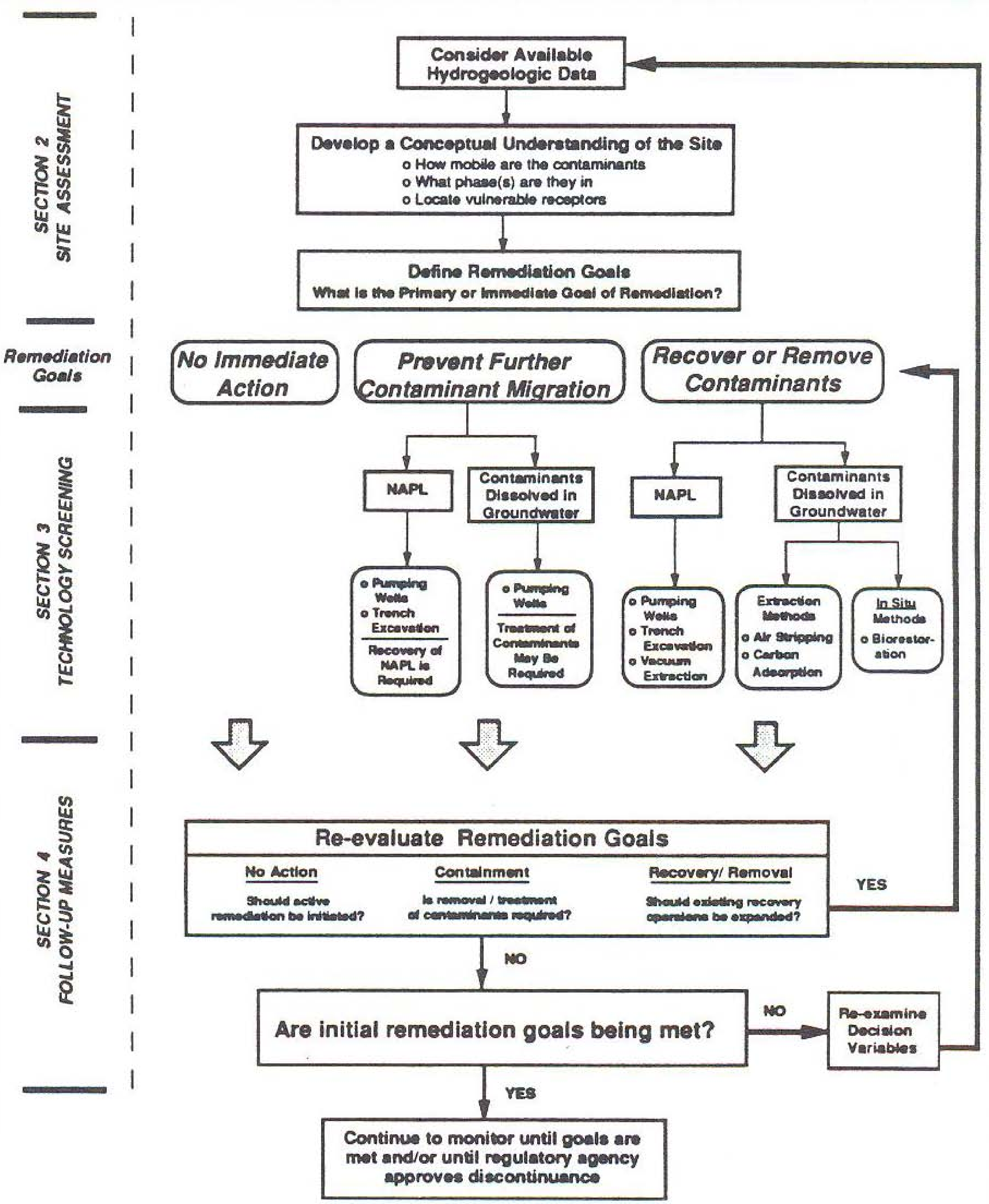
Fig. 9

Fig. 10 shows an over view of basic components of the approach in this Standard and trace the following objectives:

1) Site assessment;

2) Technology screening;

3) Follow up measures.



LOGIC DATA

AN OVERVIEW OF THE APPROACH

Fig. 10

Refer to: "Cleanup of Petroleum Contaminated Soils at Underground Storage Tanks", by Warren J. Lyman, David C. Noonan, Patrick J. Reidy (1990).

10. SITE ASSESSMENT

10.1 General

After emergency measures have been accomplished at a site, the first step in a remediation plan shall be to gain a general view of conditions at the site. A preliminary investigation shall always be carried out before any sampling or analysis is specified. The aim of a preliminary investigation should be:

a) To check the likelihood of contamination that may affect the suitability of the site for a specific use or any proposed future use;

b) To identify whether any special procedures and precautions may need to be taken during operations;

c) To provide the information from which an effective investigation of the site can be made.

10.2 Gathering Release Information

With reference to Clause 7.1, Table 1 which provides a familiarity with the site assessment, same questions should be followed:

10.3 Gathering Site-Specific Information

See Clause 7.3.1.

10.4 Gathering Contaminant-Specific Information

10.4.1 Petroleum products are a mixture of many compounds. In general, remediation efforts are usually tied to one or more individual constituents which shall be targeted:

a) When the phase of contamination being evaluated is other than the original NAPL.

b) If the mixture has "weathered considerably".

c) Assessment on a compound that is thought to present the greatest potential threat.

d) To design a treatment system.

10.4.2 Properties of the NAPL mixture shall be targeted:

a) When the phase of contamination being evaluated is the original NAPL;

b) To evaluate the physical movement of NAPL through the subsurface.

10.5 Evaluating Contaminant Phase in the Saturated Zone

10.5.1 Petroleum products reaching the saturated zone will primarily be found in one of the three phases:

1) Non-aqueous phase liquid (NAPL),

2) Dissolved in groundwater,

3) Sorbed to soil particles.

If the release is large, almost all of the petroleum product will exist as NAPL, but over a time, portion of the NAPL will transfer to the dissolved and sorbed phases.

If the release is small, all the NAPL may be trapped in the unsaturated zone.

10.5.2 Volume of floating NAPL

Volume determinations of floating hydrocarbons are typically obtained by the following equation:

$$V_N = A_N T_N n \qquad \text{(Eq. 1)}$$

Where:

A_N is areal extent of the NAPL plume;

T_N is average thickness of the NAPL plume; and

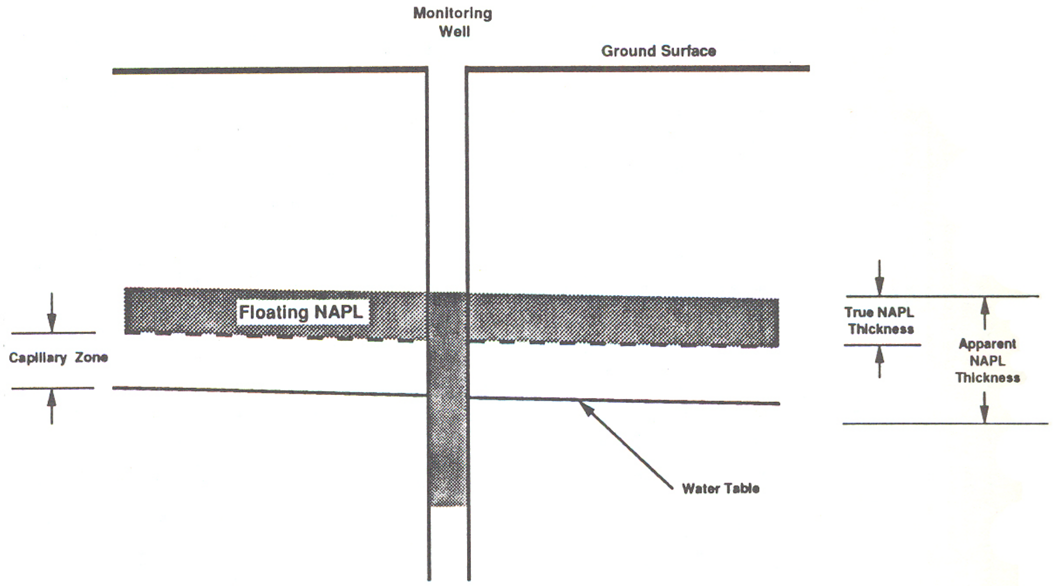
N is effective porosity of the soil formation.

NAPL thickness is fairly difficult to estimate accurately because the apparent thickness of the plume, as measured in a monitoring well, is typically greater than the true thickness. NAPL thickness will also vary throughout the plume, particularly if pumping wells are installed to contain the plume. Measuring plume thickness at several locations allows a better estimate of the average thickness.

Fig.11 is a schematic diagram of a typical monitoring well within a free floating contaminant plume. The apparent thickness is generally greater than the true thickness because the actual free product plume outside the well floats on the capillary zone above the water table rather than on the water table itself. Capillary forces within the well are virtually non-existent and the product within the well floats on the water table.

10.5.3 Mass of dissolved and sorbed contaminants in groundwater

To estimate the mass of dissolved contaminants, the dissolved plume volume and average concentration must be known. This requires numerous samples from wells throughout the plume, both horizontally and vertically. Sorption of dissolved contaminants slows the center of mass of the plume relative to ground-water movement. This does not mean that the dissolved contaminant velocity is less than that of groundwater. Rather, the dissolved concentrations at the front of the plume are lessened due to adsorption, causing the plume center of mass to move slower than ground-water flow.



APPARENT VERSUS TRUE FLOATING NAPL THICKNESS IN A GROUNDWATER MONITORING WELL

Fig. 11

Refer to: "Cleanup of Petroleum Contaminated Soils at Underground Storage Tanks", by Warren J. Lyman, David C. Noonan, Patrick J. Reidy (1990).

10.6 Evaluating Contaminant Mobility

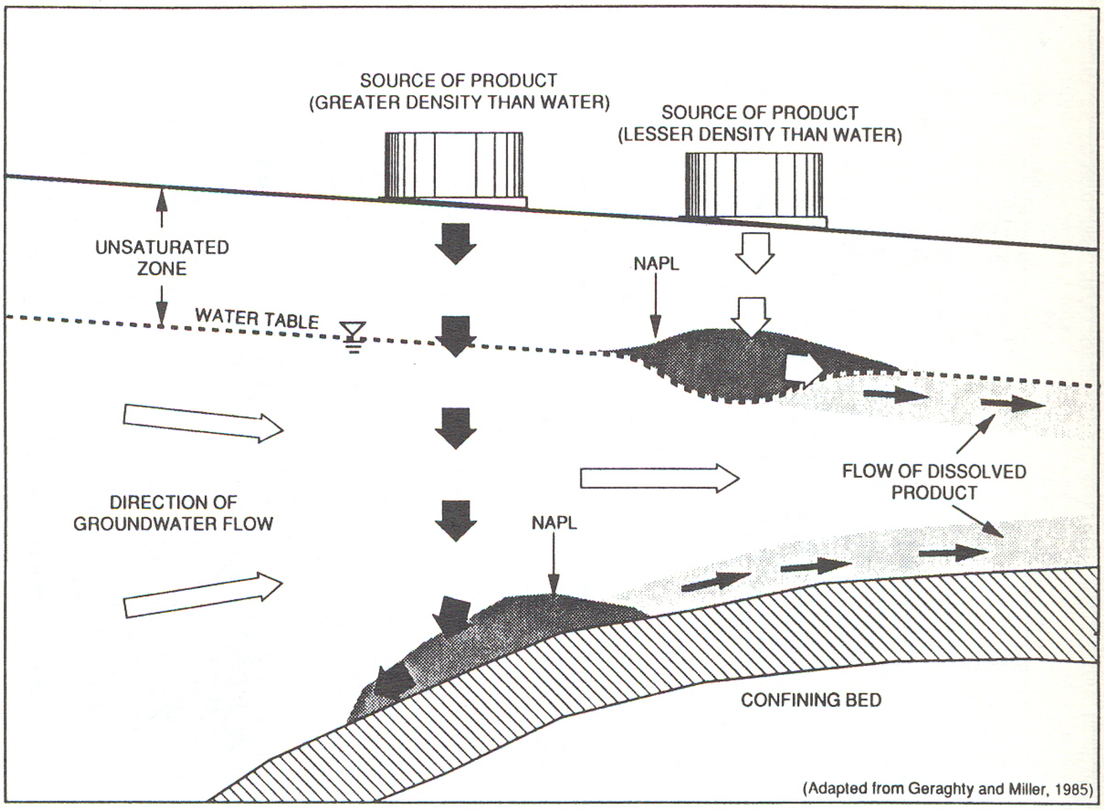
10.6.1 Implementing an effective remedial technology for saturated zone requires an understanding of how for the contaminants have traveled (vertically as well as horizontally) and the direction and velocity of plume movement.

The liquid and dissolved contaminant phases are highly mobile while sorbed contaminants are relatively immobile.

10.6.2 Extent of contaminant plume

Since the NAPL and dissolved contaminant can move at different rates and in different directions in the subsurface, the two phases may need to be delineated separately. Delineation of the down-gradient and lateral extent of the plume is generally more important than of the upgradient extent because movement in the up-gradient direction is generally limited.

Most petroleum products are less dense than water and will float on the water table in the bulk liquid phase. However, if denser than water, the contaminant will sink through the aquifer until it reaches an impermeable barrier. The areal extent of a denser than water contaminant plume is more difficult to estimate. Floating product will move in the same general direction as groundwater, but movement of dense contaminants at the bottom of the aquifer is controlled by the grade of the impermeable barrier and may be different than groundwater movement. Fig. 12 shows how the effects of density can influence contaminant migration. The flow direction of the denser than water bulk liquid is opposite that of the groundwater, but the dissolved component travels with the groundwater.



(Adapted from Geraghty and Miller, 1985)

THE EFFECT OF DENSITY ON CONTAMINANT PLUME MIGRATION

Fig. 12

Refer to: "Cleanup of Petroleum Contaminated Soils at Underground Storage Tanks", by Warren J. Lyman, David C. Noonan, Patrick J. Reidy (1990).

If all the monitoring wells at a site are screened at or near the water table, they might not intercept a dissolved plume flowing deeper in the aquifer. Also, the entire dissolved plume may not be contained if the pumping rate is not adequate or recovery wells are not installed deep enough. A dissolved plume may exist relatively deep in the aquifer if the vertical component of groundwater flow is large. This is most prevalent at sites where the water table is relatively flat and the recharge rate is high. Infiltrating rain water acts to "push" the plume down below the water table. Fig. 13 shows some of the ways poorly planned well installation can hinder the effectiveness of a remediation system.

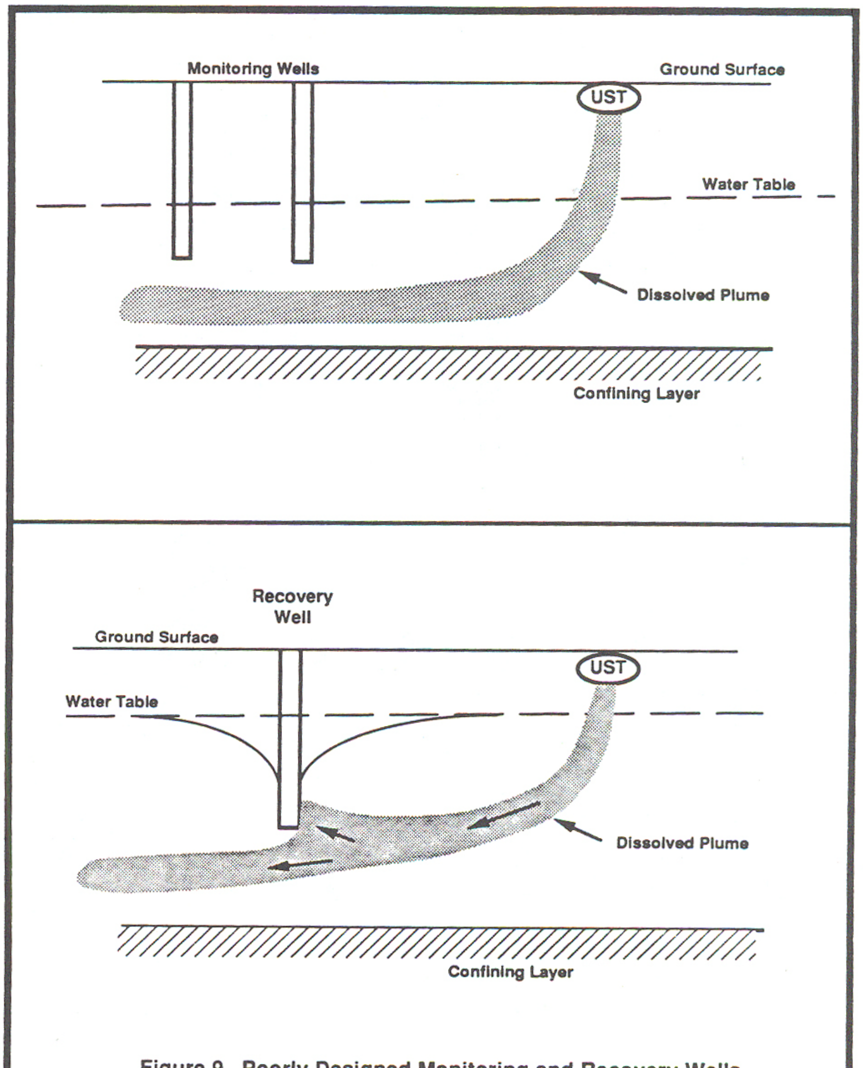


Figure 9. Poorly Designed Monitoring and Recovery Wells

POORLY DESIGNED MONITORING AND RECOVERY WELLS

Fig. 13

Refer to: "Cleanup of Petroleum Contaminated Soils at Underground Storage Tanks", by Warren J. Lyman, David C. Noonan, Patrick J. Reidy (1990).

10.6.3 Mobility of contamination in the saturated zone

The important factors that influences NAPL and dissolved products to move through the subsurface are as follows:

a) Subsurface stratigraphy, aquifer saturated thickness;

b) Local topography, location of nearby water bodies;

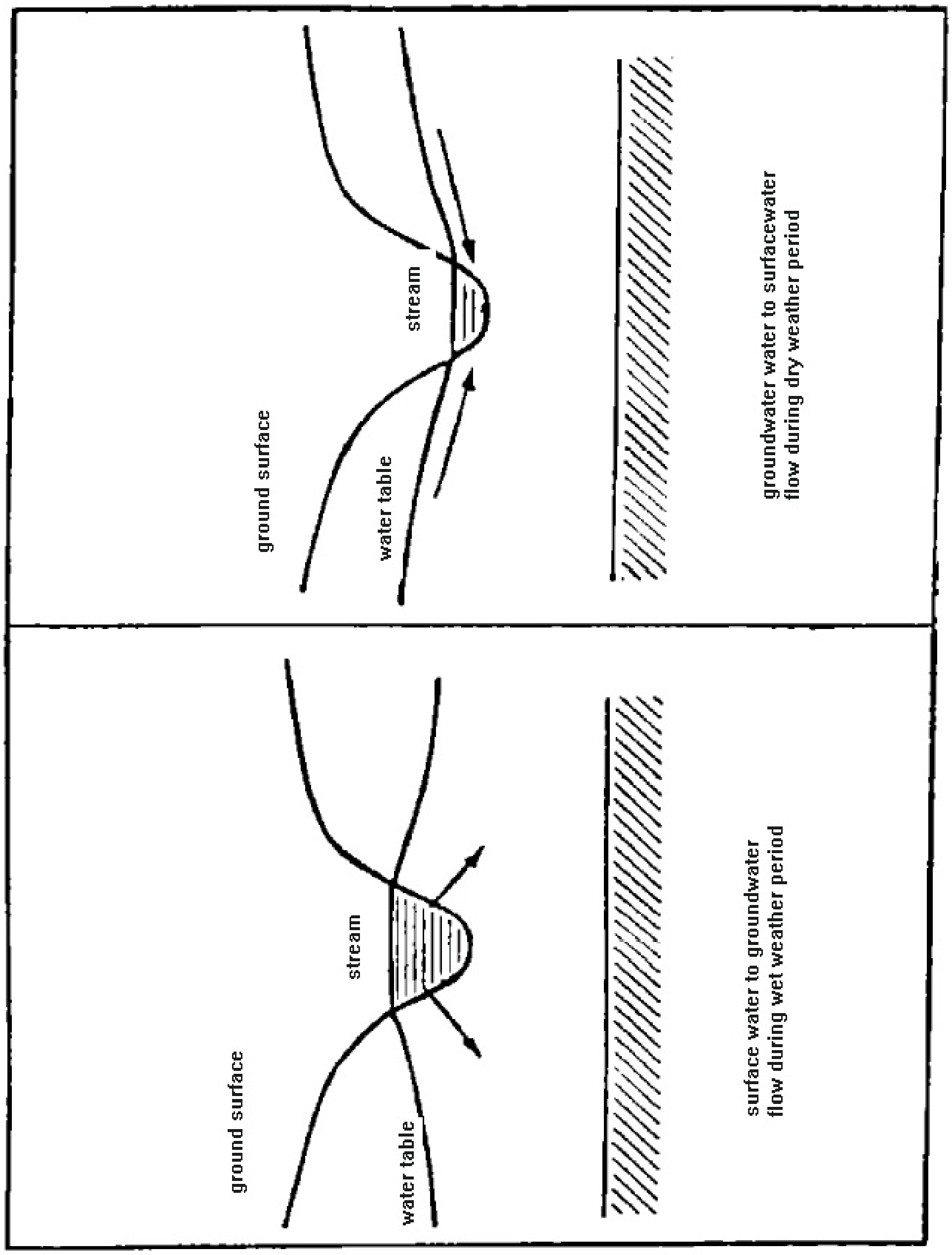
c) Location, depth, and pumping rates of nearby wells;

d) Regional and local groundwater flow direction(s), water table gradients (potentiometric head differences);

e) Hydraulic conductivity of formation(s); and

f) Density and viscosity of the bulk product or its constituents.

The above data can be used to estimate how quickly, and in what directions contaminant plumes will travel. Groundwater flow direction is important in predicting where a contaminant is likely to migrate, and with seasonal changes, the water levels can affect flow patterns as illustrated in Fig. 14.



SEASONAL VARIATIONS IN FLOW BETWEEN GROUNDWATER AND SURFACE WATER BODIES

Fig. 14

10.7 Setting Remediation Goals

An effective remediation plan should call for all phases of a clean-up. If the goal of remediation is to return the site to pre-release conditions, there are several typical clean-up phases that are likely to be implemented as follows:

a) Emergency responses are a first priority to ensure that no immediate health or safety threat exists;

b) Containment of the dissolved and NAPL contaminants limits the extent of contamination and facilitates restoration efforts;

c) Removal and/or treatment of subsurface contamination must be accomplished;

d) Site monitoring program shall be set up to detect any changes of incompletment restoration.

e) The requirements of Islamic republic of Iran department of environment for soil pollution prevention shall be considered in the remediation plan.

11. TECHNOLOGY SELECTION

11.1 General

There are a variety of ways to direct effort to a release of petroleum product into the environment. No immediate action is necessary to a full scale remediation effort to restore the environment to pre-release conditions. A typical remediation plan that has restoration to pre-release conditions have three main components as follow:

a) Containment of NAPL and/or dissolved product

Migration of contaminants can be prevented through trench excavation which is effective only for containment of NAPL and also pumping wells which contain both NAPL and dissolved product.

b) NAPL removal

NAPL recovery is often accomplished in conjunction with either trench excavation or pumping well installation.

c) Dissolved product removal

Groundwater treatment methods can be either above-ground or in situ. The above-ground method in this Standard are air stripping and carbon adsorption. In situ treatment is where contaminants are treated or removed without disturbing the subsurface or bringing groundwater above ground.

11.2 Containing NAPL and/or Dissolved Contaminant

Two methods are described for preventing further migration of subsurface contaminants in this Standard:

a) Trench excavation;

b) Pumping well installation.

11.2.1 Trench excavation

A very simple way to prevent migration of floating NAPL is to dig a trench downgradient of the plume. As the NAPL reaches the trench, it can be intercepted, removed, and disposed of, thereby preventing migration beyond the trench.

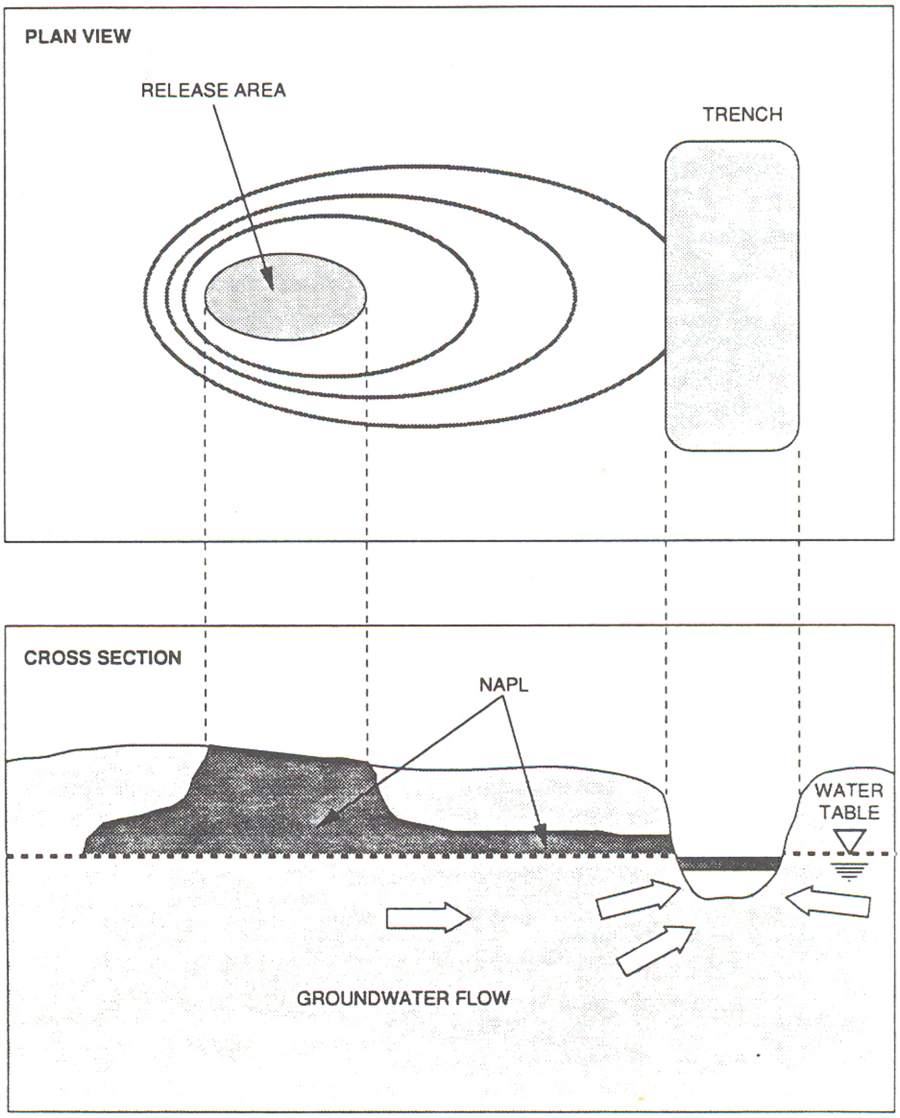
At minimum, implementing a trench excavation containment system requires the following information:

a) Direction of plume;

b) Depth to water table;

c) Down-gradient and lateral extent of the NAPL plume.

Fig. 15 shows schematic plan and section views of typical trench excavation operation. The trench is dug to a depth of a meter or so below the water table and shall be long enough to intercept the full lateral extent of the plume. The trench must also be perpendicular to local groundwater flow direction.



SCHEMATIC DIAGRAM OF TRENCH EXCAVATION

Fig. 15

Refer to: "Cleanup of Petroleum Contaminated Soils at Underground Storage Tanks", by Warren J. Lyman, David C. Noonan, Patrick J. Reidy (1990).

11.2.2 Pumping well installation

Pumping wells are an effective and commonly used method for containing a contaminant in the saturated zone. Unlike trenches, pumping wells are effective in containing dissolved contaminants and denser than water NAPL as well as floating NAPL. This method artificially lower the water table at the site, drawing local groundwater and contaminants to the well.

The two most important considerations in this method are well location and pumping rate. To determine location and pumping rate, site hydrogeology, vertical and areal extent of contamination must be known. Each pumping well has a Zone of Contribution (ZOC), within which local groundwater will flow towards the well. To prevent contaminant migration, the well configuration and pumping rate must be such that the contaminant plume is completely contained within the wells ZOC. If the contaminant plume is very large or soil conditions prevent adequate pumping rates, several wells may be required to fully contain the plume. Fig. 16 shows a typical pumping well used to prevent contaminant migration.

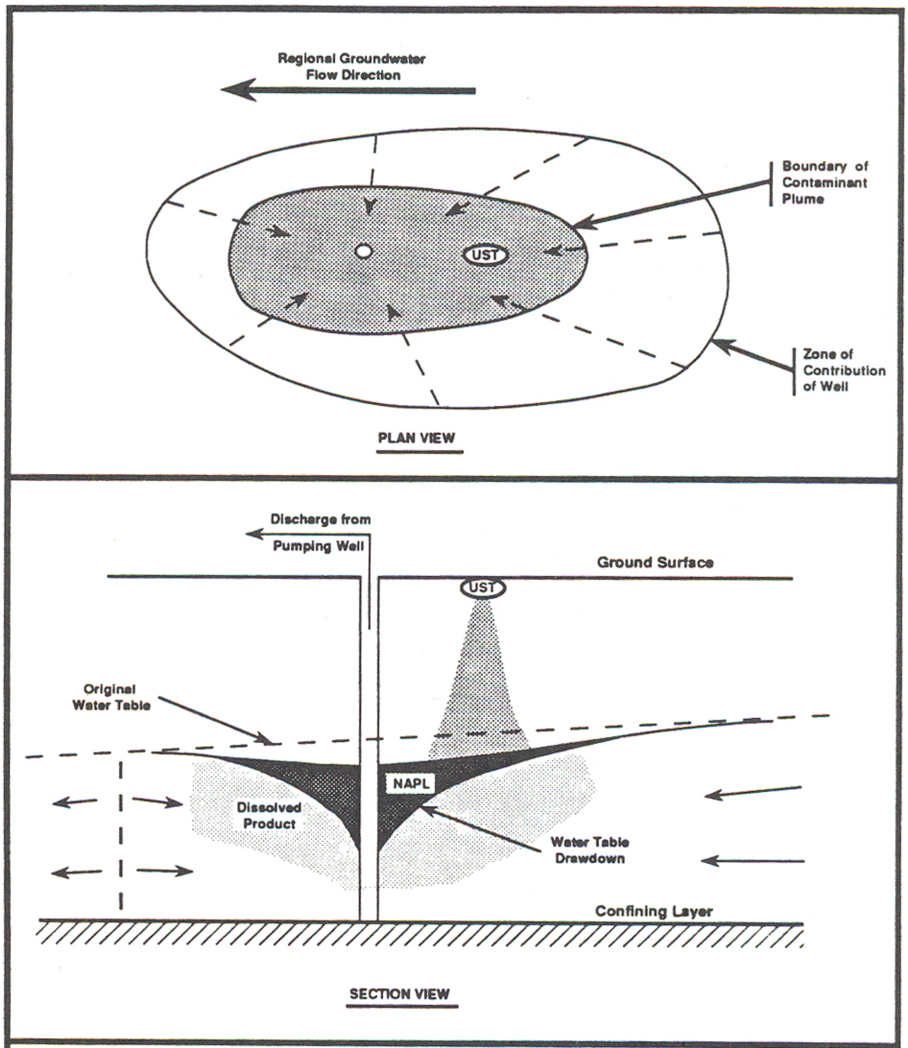
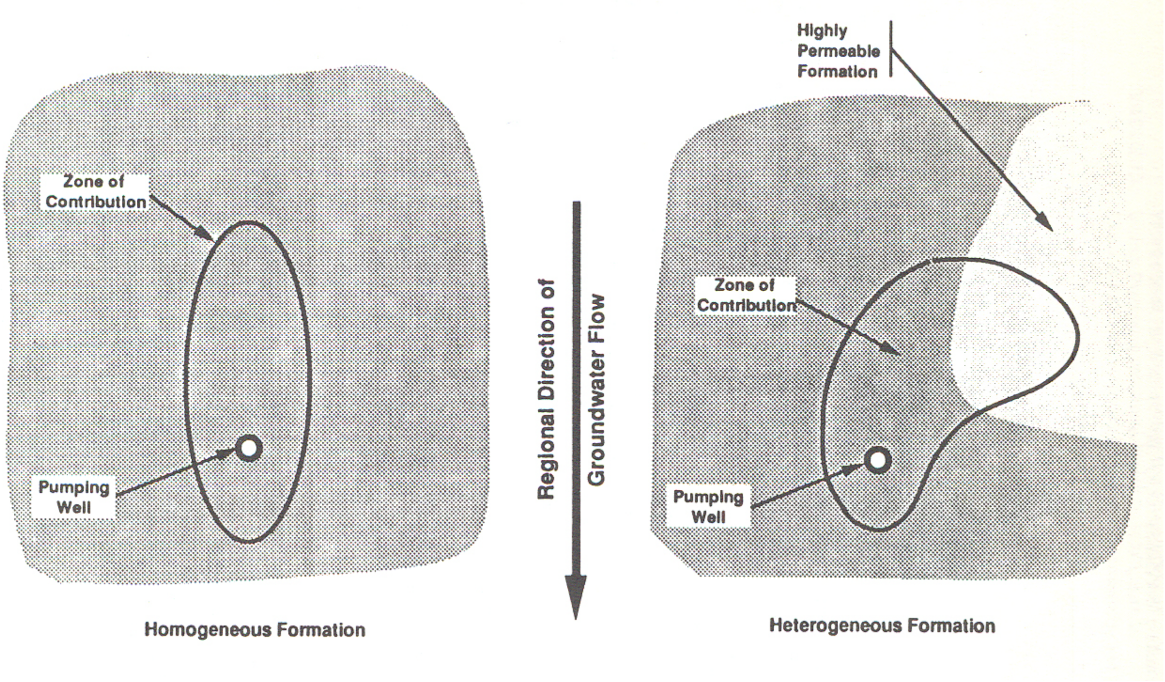


Figure 16. Schematic Diagram of a Pumping Well Used to Contain Petroleum Products in the Saturated Zone

SCHEMATIC DIAGRAM OF A PUMPING WELL USED TO CONTAIN PETROLEUM PRODUCTS IN THE SATURATED ZONE
Fig. 16

Refer to: "Cleanup of Petroleum Contaminated Soils at Underground Storage Tanks", by Warren J. Lyman, David C. Noonan, Patrick J. Reidy (1990).



DISTORTION OF THE ZONE OF CONTRIBUTION OF A PUMPING WELL DUE TO A HETEROGENEOUS FORMATION

Fig. 17

Refer to: "Cleanup of Petroleum Contaminated Soils at Underground Storage Tanks", by Warren J. Lyman, David C. Noonan, Patrick J. Reidy (1990).

Hydraulic conductivity due to complex stratigraphy varies for different types of formations, and estimating the average hydraulic conductivity of such a site is difficult. Therefore extent of the ZOC will not be equal in all directions and could result in poor location of wells see Fig. 17.

11.3 Recovery of Floating NAPL

11.3.1 Recovery of NAPL floating on the water table is a common part of site remediation when a release of petroleum products reaches the saturated zone. There are several methods used to recover floating NAPL. The most common of these use are a pumping of oil/water separation scheme, depending on the containment method implemented at the site and vacuum extraction. Each of these methods is discussed below.

11.3.1.1 NAPL recovery with trench excavation

The two most common types of equipment used to recover NAPL from trenches are skimmers and filter separators. Skimmers floats over the water surface and automatically pump NAPL off from water surface. Filter separators work much like skimmers except that the filter, allows only petroleum product to pass through it.

11.3.1.2 NAPL recovery with pumping well installation

The two main types of recovery systems involving pumping wells are single pump and dual pump systems. In single pump system, one pump is used to both contain the plume and recover NAPL. For dual systems, one pump is used to create a depression in the water table and another to remove NAPL floating on water table see Fig. 18.

11.3.1.3 Vacuum extraction of floating NAPL

Vacuum extraction, more commonly associated with treatment of the unsaturated zone. As the NAPL floats on the water table some of the contaminant will transfer from the liquid phase to the vapor phase. The rate of natural volatilization depends primarily on the vapor pressure of the contaminants and the volume of air spaces in the soils above the NAPL plume. Vacuum extraction enhances natural volatilization by removing the vapors from the soil and bringing them to the surface. This creates a disequilibrium between the liquid and vapor phases and allows volatilization to continue at a greater rate. As shows in Fig. 19, a schematic diagram of a typical vacuum extraction system designed to remove floating NAPL.

11.4 Treatment of Contaminants Dissolved in Groundwater

11.4.1 Above-ground treatment

Above-ground treatment of groundwater is generally accomplished by installing extraction or recovery wells that bring the groundwater to the surface where it can be treated (i.e., pump and treat). The two most commonly used aboveground treatment technologies are:

- **a)** Air stripping;
- **b)** Carbon adsorption;

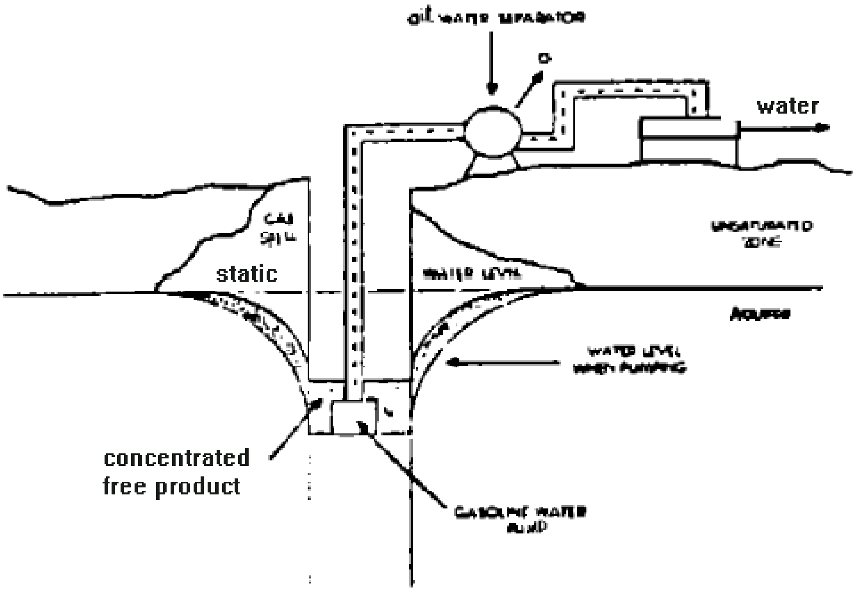
Which shall be discussed below.

For further information see IPS-E-PR-730 "Process Design of Plant Waste Water Treatment and Recovery System" and page 172 of the book "clean up of petroleum contaminated soils at underground storage tanks".

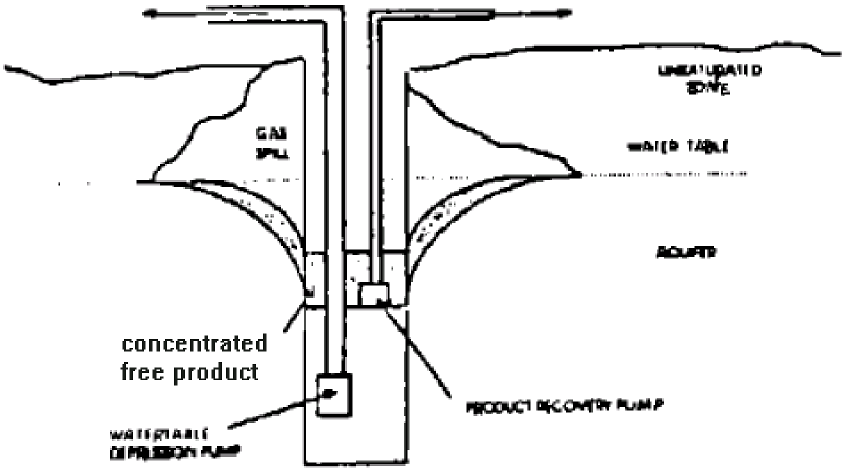
11.4.1.1 Air stripping

Air stripping is the generic term used to describe several similar above-ground methods for treating contaminated groundwater. The facts behind this method are its cost-effectiveness, straightforward design and also the concepts are well understood.

single pump system

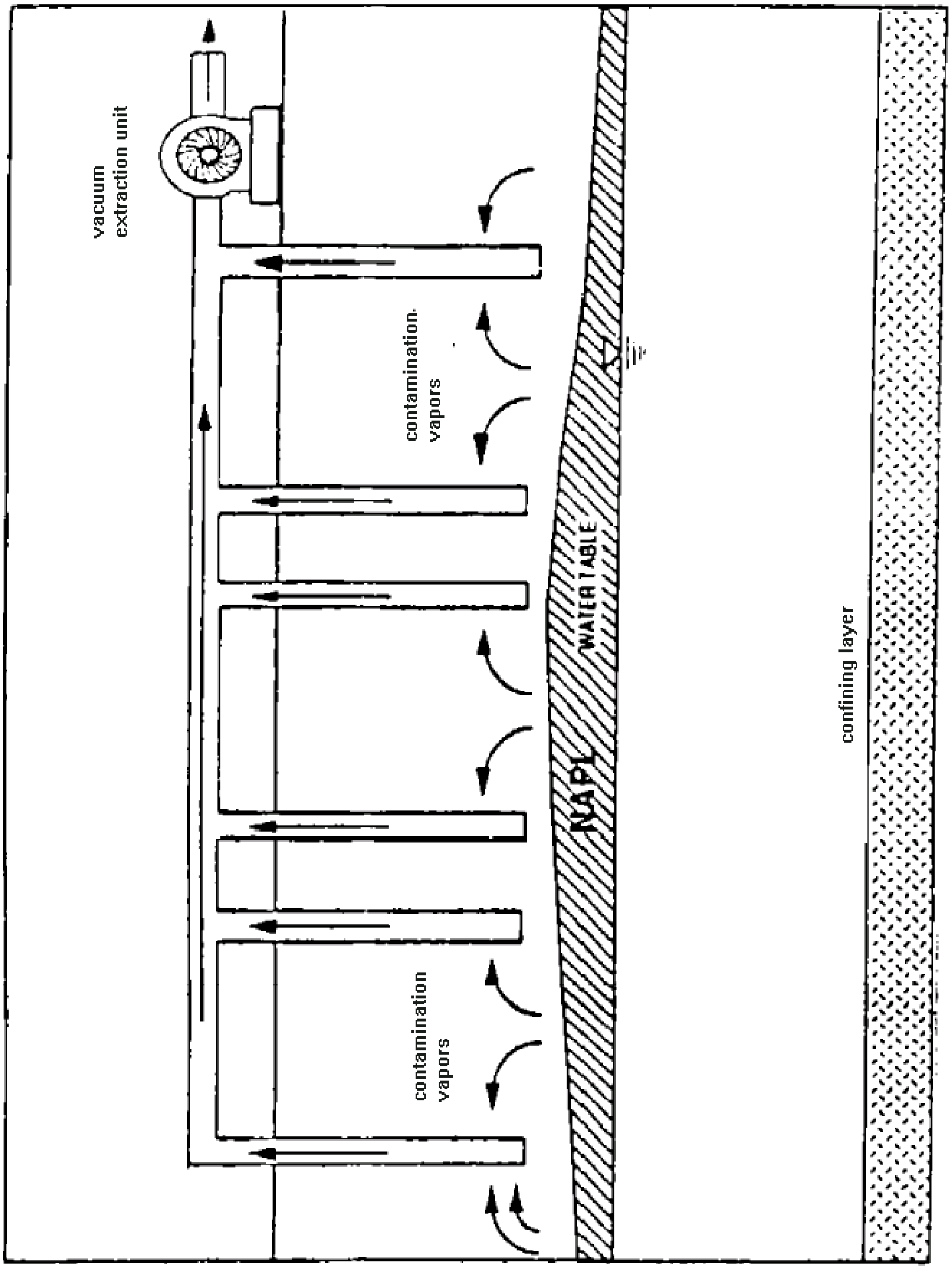


dual pump system



SINGLE PUMP AND DUAL PUMP GASOLINE RECOVERY SYSTEMS

Fig. 18



SCHEMATIC DIAGRAM OF A VACUUM EXTRACTION SYSTEM FOR RECOVERING FLOATING NAPL

Fig. 19

There are four common air stripping methods as follows:

a) Diffused aeration

The contaminated groundwater is channeled through a large holding tank or pond with one or more diffuser pipes along the bottom. Air is pumped through the diffuser pipes and bubbles up through the tank, providing a medium into which the dissolved contaminant can volatilize.

b) Tray aeration

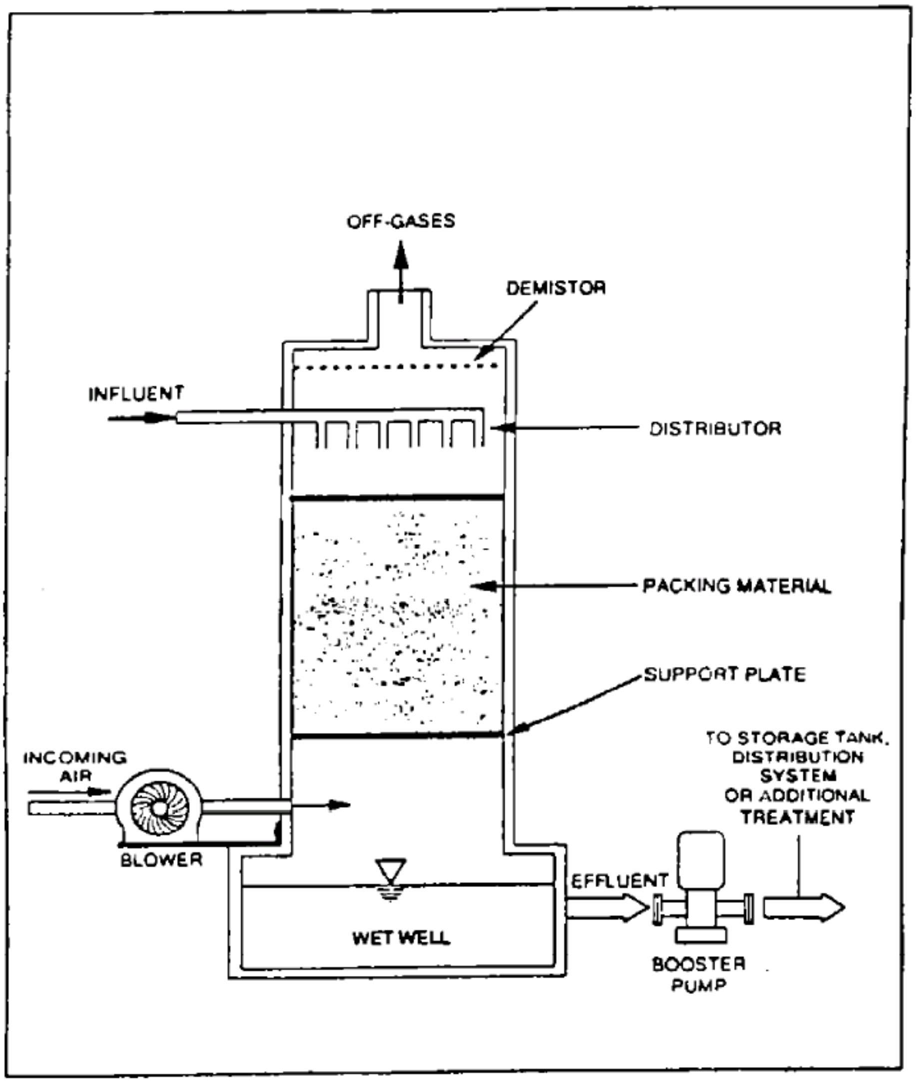
Is not as efficient in removing volatile organic as other air stripping methods, but because of its simplicity and low maintenance, it is sometimes used as a pre-treatment for other methods.

c) Spray aeration

Contaminated groundwater is sprayed through nozzles over a pond or basin, greatly increasing the surface area of the water. As the water falls back to the pond, Volatile Organic Compounds (VOCs) are transferred to the atmosphere.

d) Packed tower

Packed tower of the air stripping methods, pack tower work best at removing Volatile Organic Compounds (VOCs) from groundwater and they are often the most cost effective method as well. Therefore towers are the most widely used air stripping method.



TYPICAL PACKED TOWER AIR STRIPPER
Fig. 20

A typical packed tower is shown in Fig. 20. Contaminated groundwater is pumped to the top of the column and allowed to flow by gravity down through the packing material while uncontaminated air is pumped up through the column.

11.4.1.2 Activated carbon adsorption

Like air stripping, activated carbon is commonly used to remove VOCs from contaminated groundwater. The effectiveness of carbon as a treatment process is due to its ability to function as a adsorbent for molecules dissolved in water. This ability is largely due to carbon's large internal surface area.

Two forms of carbon are used to treat water:

a) Powdered Activated Carbon (PAC)

Is dispersed freely into the water and subsequently filtered out. It used mostly as drinking water treatment but rarely for treatment of contaminated groundwater, because it is not easily reused.

b) Granular Activated Carbon (GAC)

GAC is coarser than powdered carbon and is typically contained in a cylindrical unit. Contaminated water is passed through the unit until the adsorption capacity of the carbon is spent. The granular carbon can then be regenerated for future use.

Design of a GAC system is not as straightforward as for air stripping because of the complex interaction of the factors influencing removal efficiency.

SECTION III

PIPELINE LEAK DETECTION

12. METHODOLOGY FOR PIPELINE LEAK CONSEQUENCE EVALUATION

12.1 General

The methodology given in this Standard only evaluates the potential safety and environmental consequences of a leak, and not the direct economic consequences related to repair and deferred production/transportation. The latter consequences are in general not reduced by the presence of a leak detection system and may be evaluated objectively whereas the safety and environmental consequences are assessed, when necessary, on a more subjective basis.

The potential consequences of a leak are a function of various parameters related to the pipeline, its location and the type of fluid that is transported. By comparing the outcome of the safety and environmental consequence evaluation with a leak consequence classification the pipeline operator is able to determine the pipeline leak detection facilities required for the pipeline. The reduction in leak consequences as a result of a decreased time for leak detection and system shutdown can be demonstrated with the methodology given in this Standard.

The methodology presented in this Standard will not provide an absolute quantitative assessment of the consequences of a potential leak, but intends to rank pipelines on the basis of potential leak consequences.

A pipeline is not expected to leak if it is properly designed, constructed, operated and maintained. Experience has shown, however, that despite all preventive measures taken pipelines do occasionally leak. Therefore, even when authorities have no requirements for pipeline leak detection systems, the pipeline asset holder should formulate his own requirements based on a structured, quantified approach.

Proper pipeline management should ensure technical integrity of a pipeline in order to prevent failures and fluid releases. If a release does occur regardless of the measures taken to safeguard the pipeline integrity and the inspections to verify their effectiveness, e.g., by damage due to third party activity, a leak detection system should make the operator aware of this.

A leak detection system in itself has no effect whatsoever on the leak expectancy of a pipeline and will only make the operator aware of the occurrence of a leak, enabling him to take remedial actions in order to limit the consequences of the release.

Installation of a leak detection system should not be given the first priority when a pipeline has a high leak expectancy; measures shall be taken to reduce the probability of a leak to as low as is reasonably practicable (ALARP principle).

The need for a leak detection system should not be related to the risk level itself but should be evaluated by assessing the potential reduction in failure risk due to reduced safety and environmental consequences in case a leak occurs.

12.2 Evaluation of Leak

12.2.1 The leak consequence evaluation in this Standard is a simplified version of the leak. The leak consequences are assessed by combining:

- Factual input data, such as fluid pressure, density, etc.;
- Assumed input data, such as most likely leak to hole size, time to detect a leak and shutdown operation, etc.;
- Factors such as fluid hazard factor, population density factor, etc.;
- Calculated parameters, such as fluid release rate, fluid release amount etc.

The factors used in the assessment are based on expert operation.

The safety consequences are assessed based on the potential leak rate, the possibility of ignition, the population density and the hazardous characteristics of the fluid, and are expressed as a Safety Consequence Factor (SCF). The environmental consequences are assessed on the basis of the potential leak volume, the persistence and/or seepage of the fluid into the environment and the clean-up cost and other costs associated with the environmental consequences of a leak. The persistence and/or seepage of the fluid is adjusted by a climate correction factor. The environmental consequences are expressed as an Environmental Consequence Factor (ECF).

Since the conditions will normally vary along the length of the pipeline, the pipeline is divided into sections and the safety and environmental consequences of a potential leak are evaluated for each section. For example, on offshore pipelines the leak detection requirements are the highest close to the platform with regard to limiting safety consequences, whilst for environmental consequences the requirements are often the highest in the shore approach area. Special leak detection techniques focusing on these different criteria should be used in the respective locations.

Other parameters will also vary along the pipeline, such as internal pressure, most likely hole size, time to detect a leak, water depth, etc. The worst conditions within a particular section are assumed to be valid over the whole section length.

The safety and environmental consequences of a leak are assumed to be pipeline section length dependent, since the potential number of leaks is length dependent.

The requirements for a leak detection system should be by classifying the safety and environmental consequence factors as "low", "medium" or "high".

The threshold levels between the "low" and "medium", and the "medium" and "high" categories have been initially defined but not verified and confirmed.

The need to install a leak detection system on pipelines is evaluated primarily on the basis of the safety and environmental consequences of a leak. The leak expectancy (L_e) is applied in this evaluation as a secondary parameter, see Table 6.

TABLE 6 - LEAK EXPECTANCY; L_e

LEAK EXPECTANCY		L_e FACTOR
INPUT	**MEANING**	
HH	Very High	$\sqrt{3}$
H	High	$\sqrt{2}$
N	Neutral	1
L	Low	$1/\sqrt{2}$
LL	Very Low	$1/\sqrt{3}$

12.2.2 Potential leak rate and leak mass

12.2.2.1 General

The actual amount of fluid released in case of a leak might range from very small to very large, depending on the leak rate, the presence of a leak detection system, the time to shut down pumps or compressors and the presence and mode of operation of valves.

In the methodology the leak size, i.e. the size of the hole in the pipeline wall, is a variable input parameter. The user can select the most likely hole size on the basis of potential failure modes, for example, hole of 50 mm caused by the impact of a tooth of a backhole excavator. The leak rate is then calculated as the fluid mass flow through the hole.

As part of the leak consequence evaluation, the potential leak mass is calculated using a number of assumptions. The calculated leak rate is assumed to continue until the leak is detected and the first remedial actions have been taken, such as closing block valves or shutting down pumps or compressors. The reducing leak rate during the remedial actions after valve closure or pump or compressor shutdown is not incorporated in this methodology, since this would complicate the assessment to a level which would be outside the scope of this leak consequence evaluation methodology.

Note:

The effect of this assumption is not as large as it seems, since for both gas and liquid lines the consequences of a leak mainly refer to the time period between the onset of the leak and the system shutdown.

The safety consequences of a fluid release are governed by the leak rate, whereas the environmental consequences are related to the leak volume.

12.2.2.2 Formula for potential leak rate and leak mass

The formula is covered in Shell Standard Code No. 31-40-60-11 Gen. (1994).

12.3 Safety Consequence Factor

12.3.1 Parameters governing the consequences of a leak with regard to safety are:

- Potential leak rate	(L_R)
- Ignition factor	(I_g)
- Fluid hazard factor	(S1)
- Population density factor	(S2)
- Section length	(L_S) in meters.

The probability of ignition depends on the fluid hazard factor (S1) and population density (S2) and will increase with increasing time to detect a leak and shut down (t in hours).

The ignition factor is given by:

$$I_g = [1 - \left(\frac{0.6}{e^{0.36 \times t}}\right)] \times \sqrt{\frac{S_1 \times S_2}{10}}$$

Table 7 gives a list of fluid types, with fluid hazard factors (S1) assigned to each fluid type.

TABLE 7 - FLUID HAZARD FACTOR; S1

FLUID	APPROX. DENSITY [kg/m³] AT 15°C and 1 bar	APPROX. VAPOR PRESSURE [bar (abs)] AT 0°C	FLUID HAZARD FACTOR; S1
Crude oil-heavy	875-1000	0.3	0.5
Fuel oil	920-1000	0.01	1
Gas oil/diesel	850	0.01	1
Crude oil-light	700-875	0.55	1
Kerosene/naphtha/gasoline	700-790	0.01-1.2	5
NGL (condensate)	600-700	0.1-1.0	8
LPG	500-600	0.2-1.5	10
LNG	420	4-6	10
Ethylene	1.6		10
Natural gas	1.1		6
Sour natural gas (>0.5% H_2S)	1.1		10

12.3.2 For onshore pipelines the population density around the pipeline is evaluated on the basis of location classes as defined in ANSI/ASME B31.8:

Location Class 1:	Areas such as waste land, deserts, mountains, grazing land, farmland and sparsely populated areas.
Location Class 2:	Fringe areas around cities and towns, industrial areas, ranches or country estates.
Location Class 3:	Suburban housing developments, shopping centers, residential areas, industrial areas, and other populated areas not meeting Location Class 4 criteria.
Location Class 4:	Areas where multistorey buildings are prevalent, and where traffic is heavy or dense and where there may be numerous other utilities underground.

For more detailed information about definition of these location classes, refer to ANSI/ASME B31.8.

For the safety consequences assessment for offshore pipelines, a distinction is drawn between the following pipeline locations:

- Open sea
- Shore approach
- Risers and pipeline sections on a platform and in the safety zone around a platform for an unmanned platform or complex.
- Similar to the above but for a manned platform or complex.

Table 8 lists the pipeline location classes and gives the population density factors (S2) assigned to the various locations. The Safety Consequence Factor, (SCF), of a leak is calculated by:

$$\mathbf{SCF = L_R \times L_e \times I_g \times S1 \times S2 \times L_S/100}$$

Note:

The value 100 merely reduces the result to a number between 1 and 1000.

TABLE 8 - POPULATION DENSITY FACTOR; S2

AREA CLASSIFICATION	POPULATION DENSITY FACTOR; S2
Onshore Location Class (as per ANSI/ASME B31.8)	
Class 1	1
Class 2	4
Class 3	8
Class 4	10
Offshore	
Open sea	1
Shore approach	5
Risers and safety zone (unmanned platforms)	6
Risers and safety zone (manned platforms)	10

12.4 Environmental Consequence Factor

12.4.1 The environmental consequence factor depends on the following parameters:

- Potential leak mass (L_m)
- Persistence/seepage factor (E1)
- Climate correction factor (E2)
- Clean-up and/or other associated costs (E3).

The environmental consequence factor is only applicable to pipelines transporting liquids, i.e. air pollution and potential fire damage is not included in the evaluation.

The environmental consequences of a pipeline leak are expressed and quantified for practical reasons in terms of associated consequential money costs (USD) related to clean-up, compensation, etc. These depend on the volume of fluid released, the type of fluid, the environment category and the type of contingency plans.

The amount of liquid released is adjusted by a factor which reflects the persistence of the liquid in the environment. This factor depends on the fluid type, the climate and whether the leak is offshore or onshore.

It is assumed that the environmental damage is related to the liquid fluid components that remain in the environment after evaporation of the lighter fractions.

For onshore leaks the damage to the environment caused by the persistence of the fluid is affected by the type of crude oil. Light crude will seep into the ground more easily than heavy crude, and it is therefore more harmful and more difficult and costly to remove.

12.4.2 The assessment of clean-up costs is based on costs for light crude. The cost for another fluid is calculated by multiplying the persistence factor for offshore leaks (which depend on the fluid density), or other persistence/seepage factor for onshore leaks.

It is assumed that in an offshore leak of light condensate with a density of 600 kg/m³, or of any other hydrocarbon with a lower density, the total amount of fluid will evaporate under atmospheric conditions, and thus for those offshore leaks the persistence factor is zero.

For denser fluids, the offshore persistence factor E1 may be calculated from the formula:

$$E_1 = 0.004 \times \text{density } (15°\text{C}, 1 \text{ bar}) - 2.4$$

The onshore persistence/seepage factor E1 may be calculated from the formula:

Density <850 kg/m³: $E_1 = 0.0022 \times \text{density } (15°\text{C}, 1 \text{ bar}) - 0.88$

Density $\geq$850 kg/m³: $E_1 = 0.0013 \times \text{density } (15°\text{C}, 1 \text{ bar}) + 2.1$

The factors for onshore leaks are estimated from expert option. These relationships are shown in Fig. 21.

The climate correction factor, E2 in Table 9 allows for the relationship between liquid evaporation and the ambient temperature.

The clean-up cost and other associated costs for a liquid spill are expressed per unit volume in Table 10. The environment categories identified and associated clean-up cost and/or other consequential costs for light crude are given in USD/m³.

The costs, quoted in 1993 money terms, have been estimated by experts using North Sea experience. They are assumed to be applicable worldwide.

Possible fines and other intangible costs related to the possible damage to the environment, e.g. loss of goodwill and credibility, are not included in the above costs. These should either be evaluated as a separate cost in an economic consequence evaluation or incorporated into the methodology by increasing the "clean-up and/or other associated costs" (E3) values. Actual costs are not included since they will be principal dependent.

The environmental consequence factor (ECF) of a leak is calculated from the formula:

$$ECF = (L_m \times 1000/R_o) \times L_e \times L_s \times E1 \times E2 \times E3/100000$$

Note:
The value 100000 merely reduces the result to a number between 1 and 1000.

12.4.3 PC spreadsheet

The methodology for pipeline leak consequence evaluation has been incorporated in a PC spreadsheet.

The input parameters are:

Pipeline: Onshore or offshore
Length, split into sections
Water depth
Population density factor, derived from Table 8, per pipeline section

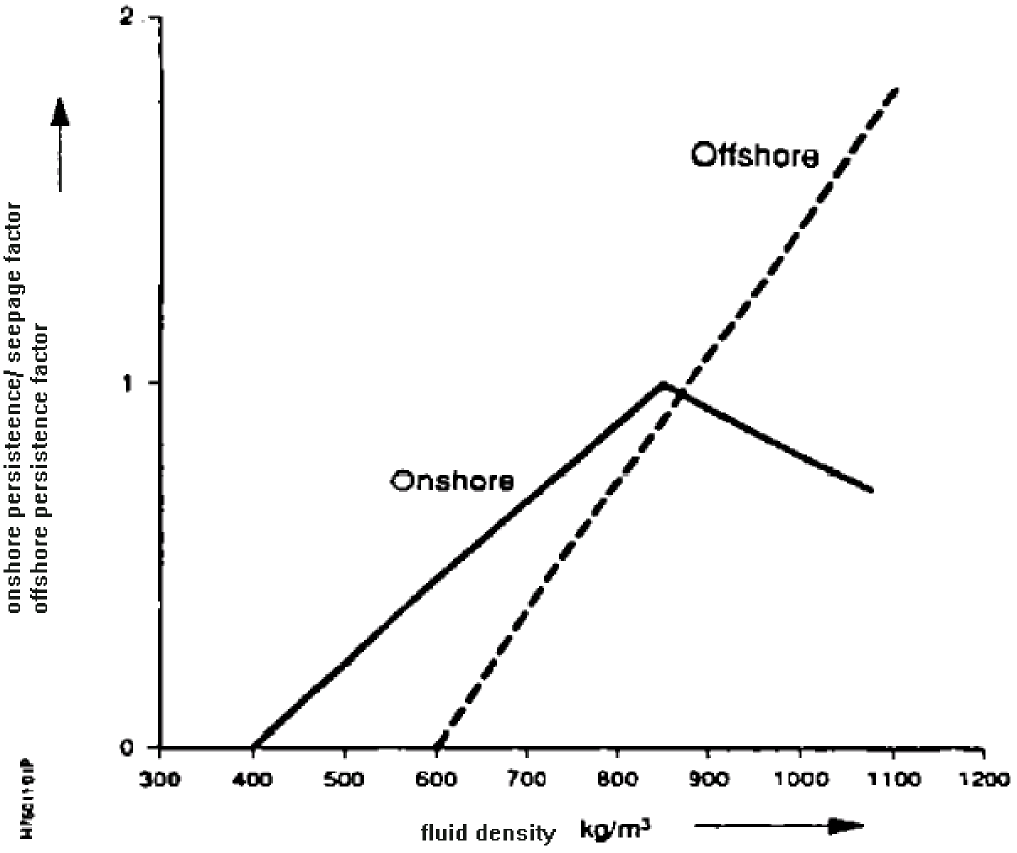
Fluid: Liquid or gas
Fluid hazard factor, derived from Table 7
Liquids only: Average ambient temperature
Density

Gases only: Average gas temperature
Ratio of specific heats (Cp/Cv)
Compressibility factor
Gas molecular weight

Operation: Pressure at pipeline inlet and outlet
Fluid flow rate
Assumed leak hole size
Leak expectancy
Time to detect leak and shut down pumps or compressors
Liquid clean-up cost and/or other associated costs, derived from Table 10.

The spreadsheet contains the equations used in the evaluation in which the pipeline is divided over a maximum of ten sections. The results also show the rating of the two overall consequence factors versus the threshold levels. For sample Printouts Form reference shall be made to DEP 31.40.60.11 (1994) for following cases:

- An onshore natural gas line;
- An onshore gasoline line;
- An offshore crude oil line;
- An onshore HP ethylene line.



PERSISTENCE FACTOR (OFFSHORE) AND PERSISTENCE/SEEPAGE FACTOR (ONSHORE)

Fig. 21

TABLE 9 - CLIMATE CORRECTION FACTOR FOR PERSISTENCE/SEEPAGE FACTOR; E2

CLIMATE	**AVERAGE ANNUAL TEMPERATURE (°C)**	**CORRECTION FACTOR E2**
Warm	≥ 20	0.75
Moderate	>5 - <20	1.0
Cold	≥ 5	1.25

TABLE 10 - CLEAN-UP AND/OR OTHER ASSOCIATED COSTS; E3

CLIMATE

ENVIRONMENT		CLEAN-UP COSTS; E3 [USD/m³]	REMARKS
Offshore	>40 km from shore	13	a
	5-40 km from shore	110 or 240	b
	<5km from shore	3500	c
	Standard terrain	630	
	Water course areas	2200	
	Designated environmentally sensitive areas	2500	

Remarks:

a: Based on surveillance of the released fluid only, whilst allowing self-degradation.

b: Value depend on remedial actions:

	Costs:
Chemical dispersant treatment	110 USD/m³
(Dispersant and application)	
Containment and recovery:	Costs:
(Equipment, deployment, recovery, transport and disposal)	240 USD/m³

c: Including coastal clean-up, fishing and tourism compensation and amenity impact.

13. LEAK DETECTION TECHNIQUES

13.1 General

13.1.1 Leak detection techniques are based on either continuous or intermittent measurements of specific parameters. Intermittent leak detection methods are often able to detect smaller leak rates compared with continuous leak detection techniques.

Some continuous techniques can only detect transient pipeline conditions during the onset of a leak, and will not be able to identify the presence of a leak at a later time.

For some intermittent techniques fluid transportation through the pipeline needs to be interrupted. Using intermittent techniques, the detection time of a leak will be completely dependent on the frequency of inspection.

Techniques for detection of leaks in liquid lines offer better performance than those for gas pipelines, which in turn are better than those for two-phase pipelines.

The conflicting balance of sensitivity to leaks and false alarms will determine the sensitivity setting of the leak detection system. Large leaks can normally be detected more rapidly than small ones. To maintain the user’s confidence in the system, avoiding false alarms should have a higher priority than attempting to shorten the leak detection time or reducing the minimum detectable leak rate.

The performance of pipeline leak detection techniques is dependent on fluid type, operating pressure including fluctuations, batch or continuous operation, pipeline length and size, metering accuracy, etc.

To decide which technique to adopt depends on a detailed case by case evaluation. If the consequences of a leak are considered significant then the more sophisticated techniques of leak detection are required. It may be necessary to deploy more than one leak detection technique in order to achieve the overall leak detection performance that is required.

Leak detection systems are categorized into the following groups according to their inherent principle of leak detection:

a) Balancing of pipeline mass input versus output,

b) Pressure and/or flow analysis,

c) Monitoring of characteristic signals generated by a leak,

d) Off-line leak detection.

A summary of the capabilities and application of the various leak detection techniques is given in Table 11.

13.2 Balancing of Mass Input Versus Output

13.2.1 This category of leak detection systems relies on the fact that in a leak-free pipeline the fluid mass flow into the pipeline equals the flow out. Using this mass balance principle the flow-in and flow-out measurements are continuously monitored for any variations over a time interval. Volume flow readings should either be corrected for density or pres- sure and temperature variations to reference mass flows. To eliminate the effect of flow variations during normal operation, the flow readings should be averaged (totalised) over discrete time periods.

The uncorrected mass balance method can be applied only under steady state operations as it does not allow for changes in the pipeline inventory, i.e. line pack variation. Its accuracy depends largely on the accuracy of the flowmeters and on the steadiness of operations.

In addition to the inlet and outlet flow measurements, the corrected mass balance method uses a correction factor for any changes in the pipeline inventory. Pressure and, if necessary, temperature measurements at intervals along the pipeline are used for calculating the correction factor. The capability for detecting small leaks depends upon the number and accuracy of measurements along the length of the pipeline.

An alternative method is dynamic simulation, which is a model-assisted balance method. A real time computer model calculates the inventory of the pipeline and the line pack variations of the pipeline under steady-state and transient operating conditions. It will correct not only for pressure and temperature effects but also for changes in fluid properties, such as where different batches of fluids are present in the pipeline at the same time. A difference between the mass balance predicted by the model and that actually measured indicates the presence of a leak. Also, unexpected flow and/or pressure trends are used as indicators of the occurrence of a leak.

The dynamic simulation method is similar to the corrected mass balance system. The main difference is that the dynamic simulation method calculates the pipeline inventory whereas the corrected mass balance method interpolates between the measurements along the pipeline. The latter is usually considered to be less accurate because of the inherent accumulation of measurement errors.

The sensitivity of these methods is generally good. Their disadvantage is that they have limited capabilities for locating the leak.

To develop a statistical pipeline leak detection (SPLD), the system does not need complicated modeling of the pipeline inventory, it continuously calculates the statistical probabilities of a leak based on fluid flow and pressure measured at the inlet and outlet of a pipeline. Depending on the control and operation of a pipeline, the statistical technique is used to identify changes in the relationship between the pipeline pressure and flow which always occur when there is a leak.

The SPLD system works as a statistical filter, which is applied to a pipeline input/output balance and which decides between a leak-free and a leak-present hypothesis. Major advantages of this system are its simplicity and robustness compared with other software based techniques. The SPLD system can run on a PC, and is capable of discriminating between fluctuations due to operational variations of the pipeline and the actual occurrence of a leak; it is thus very reliable for leak detection. The SPLD system has been commercialized since October 1991. The statistical filter of the SPLD system can also be combined with a commercially available dynamic simulation method, which makes the latter even more reliable. This combined statistical and dynamic simulation leak detection system is at present the most sophisticated leak detection system available.

13.2.2 Pressure and/or flow analysis

The operation of a pipeline can be characterized by the flow of the fluid and the pressure gradient along the pipeline. Pressure drop and flow along a pipeline are related to the flow resistance of the pipeline. A leak will alter the pressure drop profile of a pipeline and therefore affect the "normal" pressure and flow relationships. Detection of such alterations can be used to indicate the occurrence of a leak.

If a large leak occurs, particularly in the upstream part of a pipeline, the inlet pressure will drop. Observation of a lower than expected inlet pressure indicates the presence of a leak. Detection of low pressure is usually connected to an automatic shut-down system. To avoid false alarms the system is usually set such that only major leaks can be detected.

A leak will result in an increase in flow upstream and a decrease in flow downstream of the leak. As a result of this the pressure gradient will increase upstream and decrease downstream of the leak. The occurrence of a discontinuity in the pressure gradient, which is calculated from the pressure readings along the pipeline, is an indication of a large leak. The rate of change of pressure and flow readings can also be monitored and used to detect sudden changes which indicate the occurrence of a leak.

The combined pressure decrease/flow increase method uses the fact that a leak in an operational pipeline will cause an increase in the flow and a decrease in the pressure upstream of the leak. The simultaneous occurrence of both is an indication of a leak.

TABLE 11 - SUMMARY OF THE CAPABILITIES AND APPLICATION OF LEAK DETECTION TECHNIQUES

LEAK DETECTION METHOD	LEAK TYPE	MODE OF OPERATION	RESPONSE TIME	LEAK LOCATION CAPABILITY	ROBUSTNESS	RELIABILITY	COST	REMARKS
Low Pressure	gas: full bore ruptures liquid: major leaks	any	seconds to minutes		good	poor	low	high thresholds required to avoid false alarms
Change in pressure / flow	gas: major leak liquid: large leaks	steady state	seconds to minutes	Offshore: None Onshore: Between block valves if pressure readings available	good	poor	low	
Wave alert	gas: medium to large leaks liquid: small to medium leaks	steady and transient state	seconds to minutes	within 1 km, depending on transducer spacing	good	poor	medium	detects only the onset of a leak
Mass or volume balance	gas and liquid: medium to large leaks	steady state	minutes to hours	none	good	poor	low	
Corrected mass or volume balance	gas and liquid: small, medium and large leaks	steady and transient state	minutes to hours	Offshore: None Onshore: Between block valves	good	medium	medium	
Statistical pipeline leak detection (SPLD)	gas and liquid: small, medium and large leaks	steady and transient state, shut in	minutes to hours	at best within 5 % of distance between pressure meters	good	good	medium	low probability of false alarm
Dynamic simulation model	gas and liquid: small, medium and large leaks	steady and transient state, shut in	minutes to hours	at best within 10 % of pipeline length	poor	poor	high	high false alarm rate
Acoustic techniques	liquids: large leaks (on- line), small to medium leaks (shut-in)	steady state	depends on monitoring frequency	within 1 km	good	medium	high	hard liquids only
Static pressure test	hard liquids: small leaks soft liquids: medium leaks gas: large leaks	during shut in	hours to days	none, between block valves	good	poor	low	capabilities depend on length and temperature effects
Sniffer tube, hydrocarbon sensing-cables	all fluids, including multiphase: small leaks	any	hours	within 100 m for hydrocarbon sensing cables	good	good	high	short lines only

Leak rate categories used in Table 11:

Full bore rupture:	≥100% of flow	Medium leak:	5-25% of flow
Major leak:	50-100% of flow	Small leak:	1-5% of flow
Large leak:	25-50% of flow		

Refer to: “PIPELINE LEAK DETECTION” , DEP 31.40.60.11-Gen, September 2002, (DEP Circular 41/08 has been incorporated)

13.2.3 Monitoring of characteristic signals generated by a leak

A suddenly occurring leak will cause a sudden pressure drop at the leak location in the pipeline. This sudden pressure drop will create a pressure wave traveling at sonic velocity both upstream and downstream from the leak. Detection of this pressure wave is an indication of the occurrence of a leak. The response time of this negative pressure wave technique is very short because it responds to waves that travel at sonic velocities (in crude oil, approximately 1000 m/s). When the wave is detected both upstream and downstream of the leak, the location of the leak may be calculated from the time difference of detection by the nearest sensors on either side of the leak location. The system will only respond to an instantaneously occurring leak of measurable size. In practice the sensitivity can be poor because the alarm thresholds are often set high to avoid false alarms triggered by pressure transients generated by upstream or downstream processing plant or other noise producing installation, such as pump or compressor stations.

A system which is less sensitive to pipeline noise than the negative pressure wave system uses dual transducers which filter out noise signals. The system is made directional, i.e., it detects signals originating from either the upstream or the downstream direction of the pipeline. This is achieved by installing the two transducers at an appropriate from each other and using an electronic signal subtracting system.

Leak detection based on negative pressure wave techniques will only detect the initiation of a leak and not its presence. If the pressure wave created at the moment of leak initiation is not detected, the leak will not be noticed.

Liquid escaping under pressure through a small opening produces supersonic noise. An ultrasonic leak detection pig, which is equipped with hydrophones and data recording, can detect and locate the presence of a leak. A very small leak, down to 10 l/hr, can be detected and fairly accurately located with this technique. Being intermittently operated, the response time will depend on the frequency of running the ultrasonic leak detection pig.

A hydrocarbon-permeable tube (sniffer tubes) can be laid in close proximity along the pipeline. Small leaks of hydrocarbons from the pipeline which have permeated into the tube will be detected when the tube is periodically purged into a gas analyzer.

Hydrocarbon-sensing cables can be laid along the pipeline. Electrical properties of the cable change when hydrocarbons come in contact with the cable. Contact with water does not affect the properties of the cable.

A prototype system for the measurement of methane in sea water has been developed. The device, which is mounted on a ROV, extracts dissolved gas from a continuous flow of water and determines the methane content using infrared absorption techniques.

Remote sensing of hydrocarbon emissions, e.g. using an infrared technique from an aircraft is becoming commercially available. Particularly for gas and multi-phase pipelines, this offers a powerful alternative to ground based patrolling techniques.

13.2.4 Off-line leak detection

Intelligent pigs have been developed for detection and location of leaks in a pipeline using flow direction recognition in a blocked-in pressurized pipeline. This bi-directional pig has an opening through the body with a sensitive flow meter and a transmitter. By locating the pig at various point along the line and using aboveground interpretation of the flow measurements through the pig, the leak can eventually be located. Locating the leak, however, is time consuming and the line should be equipped with pumping or pressurizing facilities at both ends. This system is of interest for pipelines larger than 8 inches in diameter when a small leak has been detected but its location is unknown.

An alternative to the above technique for pipelines smaller than 8 inches is a bi-directional pig equipped with a differential pressure transducer and a transmitter. When located in the pipeline the pig measures the pressure drop on either side. The leak will be on the side at which the pressure drops more rapidly.

The pressure in a blocked-in pressurized pipeline will drop when there is a leak. For a static pressure leak test the pipeline, or a section of it, is pressurized with the transported hydrocarbon fluid to the MAOP. If pressurizing to a higher level is required the leak test shall be done with water for safety and environmental reasons. After pressurizing, the block valves are closed and the pressure and temperature are monitored for a specified period of time (24 hour minimum). A differential static pressure test can be carried out if block valves are equipped with differential pressure transducers. A difference in the rate of pressure drop in two adjacent sections that cannot be explained by temperature effects, inaccuracy of readings or valve leakage is an indication of a leak.

There are uncertainties about the advantages and disadvantages of pressure testing existing pipelines for condition monitoring purposes at pressure higher than the MAOP.

The advantage of pressure testing at high pressures for leak detection is that an existing leak is detected more easily. Also, long defects which have almost broken the surface can be opened, resulting in a leak which is also detected. The disadvantage is the risk that existing defects might be enlarged and/or activated to grow, possibly leading to failures during normal pipeline operations following the pressure test.

Note:

Pressure testing above the MAOP is primarily done for strength testing in order to avoid a pipeline rupture (DEP 31.40.40.38-Gen.).

13.2.5 Sound which is generated when liquid is forced through a small opening during pressure testing can be detected by acoustic monitoring. For pipelines transporting hard liquids, leak detection by an acoustic reflectometry method is feasible. The technique is based on the phenomenon that a pressure wave traveling through a pipeline is reflected at the position of a leak, due to a local change of acoustic properties. for lines which are used intermittently this technique can be used during downtime when the level of disturbing noise is low.

14. LEAKPROOF CONTROL OF PIPELINES, GAS PIPING, TANKS AND TECHNOLOGICAL INSTALLATIONS USING RADIOACTIVE TRACERS

14.1 General Consideration

The tracer can be added to the pressurizing fluid for detection of small leaks. The leak is detected by patrolling the pipeline with a detector which is sensitive to the tracer or by visual observation of a visible tracer.

The method of isotopic tracers can be used as a complementary technique to the hydraulic and pneumatic pressure tests. The method shows many advantages. It is sensitive, easy to apply. The test and preliminary works are not time consuming. In addition the isotopic test can be carried out at low pressure (0.2-0.4 MPa) without excessive effort of construction materials. It should be mentioned that hydraulic tests cannot be applied to some object despite the fact that such tests are necessary.

The method is based on the phenomenon of migration of the isotopic tracer in the direction of the leak, its penetration to the surrounding medium, adsorption of the tracer in this medium and measurement of gamma radiation emitted by the tracer. Methyl bromide labeled with radioisotope ^{82}Br is the best tracer.

The chemical reaction:

$$\mathbf{2K\,^{82}Br + /CH_3\,/2\,SO_4 \xrightarrow[70°C]{H_2SO_4} 2\,CH_3\,^{82}Br + K_2SO_4}$$

Is carried out in a special generator (Fig. 22) constructed for this purpose. Depending on the type of the generator activities up to 10 Ci (370 G Bq) can be handled. For transportation of the gaseous radioactive tracer to the dispensing point special containers are used. The radiotracer is sucked off from the generator to the container. The containers vary in size depending on the activity of the tracer to be transported.

The detection and localization of leaks is carried out by recording changes of radiation intensity (resulting from adsorption of the radioactive tracer in the insulating material) with the aid of portable radiometers with scintillation detectors.

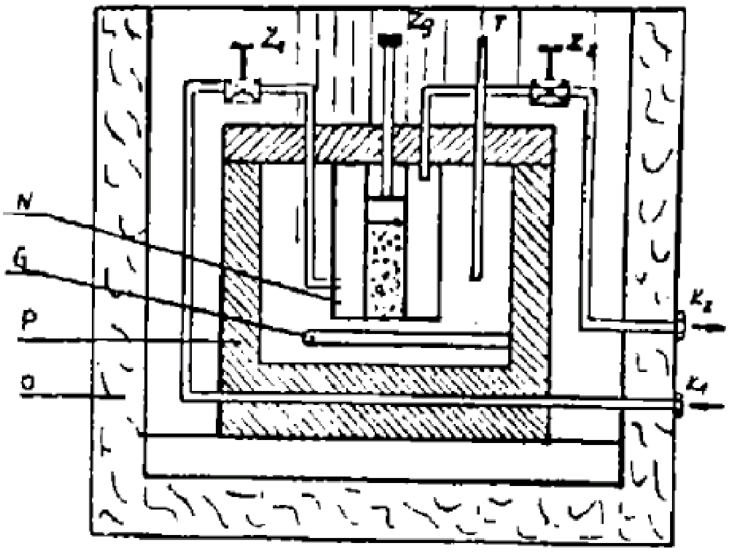


Fig. 22

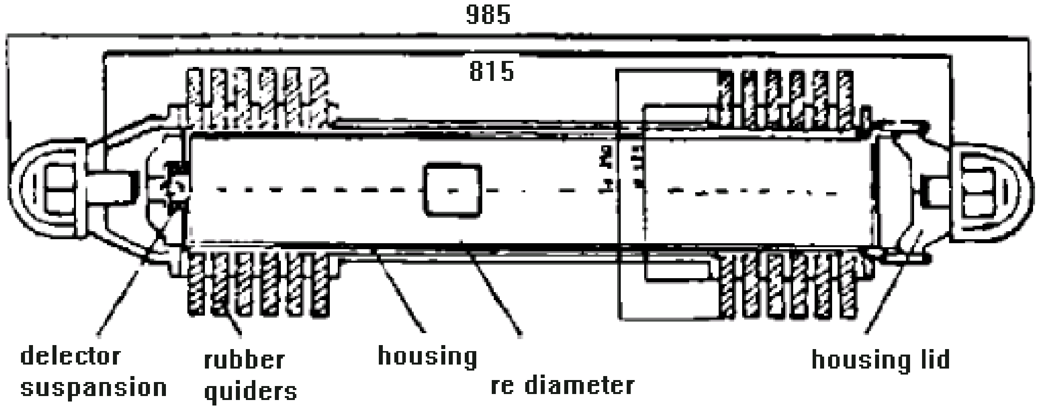
A diagram of the radio tracer generator:

Z_1	Inlet cut-off valve;
Z_2	Outlet cut-off valve;
Z_g	Squeezer for crushing ampoules;
T	Contact thermometer;
K_1/K_2	Connector pipes;
G	Electric heater (24 V);
N	Reaction vessel;
P	Shielding container;
O	Wooden casing.

The measurement of the dose rate on the surface of the generator container and the determination of the boundaries of the controlled area is carried out with the aid of Geiger-Muller counters. When simultaneous measurements are carried out at many points highly sensitive multichannel radiometers are used.

14.2 Leak Detection in Pipelines for Liquids

In methyl bromide (and in the case of water-potassium bromide) labeled with radioactive ^{82}Br should be introduced to the liquid in the pipeline and detected with the aid of a special gamma-ray detector, placed in a pressure proof pig (Fig. 23) moving with the medium through the pipeline. The detector is introduced to the pipeline after the tracer has passed. It continuously measures the natural radiation in the pipeline and also the peaks of gamma radiation of ^{82}Br (if present). The minimum activity which must be present in the leak in order to be detected is 1-10 µCi (37-370 kBq)



PIPELINE PIG FOR RADIATION DETECTOR

Fig. 23

The signals recorded on the tape are called "general localization" of the leak and supply information as to the position of the leak with an accuracy of several to several tens of meters depending on the distance between the distance markers (^{60}Co sources placed on the outer walls of the pipeline) and on the rate of tape winding of the recorder. Exact localization of the leak is carried out by searching the radiation of the ground above the pipeline in the area delineated as described above. In the case of pipelines of very small diameters, to which radiometers can not be introduced, only accurate localization is carried out. In such cases the detection is based on the measurement of tracer radiation, that penetrated through the leak to upper layers of the ground, by means of a detector moved just above the surface of the ground. In this method it is necessary to stop the operation of the pipeline for some time in order to follow the movement of the added tracer. The total applied activity should be 20 Ci (740 G Bq). The minimum leak detected shall be in the range of 30-1000 cm^3/h. With the detectors introduced into the pipeline it is possible to examine pipelines with diameters 200-800 mm.

14.3 Leak in Gas Pipelines Detection

The choice of the method of examination on the size of the leak, the length of the section of the gas pipeline to be examined and on the pipe diameter. This factors affect the rate of movement of the tracer on the way from the point of its introduction to upper layers of the soil in the leak zone, where the tracer is detected by means of a gamma-ray detector.

Leak testing with the aid of radioactive tracers can be carried out before, during and after the pressure tests for strength. The choice of the variant of the method depends on the pressure decrease in the conventional pressure test.

14.3.1 The method of labeling total volume of the gas pipeline

The method can be applied to short pipelines and small leaks. The medium and the tracer should be pumped in to the pipeline at one or more points in such a way as to evenly distribute the tracer in the whole volume of the line.

For the detection, apply high test pressure as much as possible. When a definite pressure is attained the pumping is interrupted. After several hours (this time is necessary to allow the labeled gas to pass through the smallest leaks to the upper layers of the ground) the radiation of the tracer in the leak is recorded. In this method it is possible to simultaneously detect all leaks without the necessity of following the movement of the tracer i.e. without digging up the pipeline when locating leaks.

14.3.2 Methods of single injection of the tracer

The method is used for testing short sections. The gas should be pumped up to a definite pressure. The pumping is then interrupted and the radioactive tracer should be introduced into the middle section of the gas piping.

Introduction of the tracer into the middle section of the gas piping permits to reduce the time of localization of the leaks. Radiometers located on pipe on both sides of the point of injection of the tracer permit to determine the direction of movement of the tracer i.e. the part in which the leak occurs.

14.3.3 Method of injection of the tracer at several points of the gas pipeline

The method is used in the case of examination of long sections of gas pipeline. The leak is localized by following the movement of the radioisotope with the aid of radiometers located on both sides of the injection point. In this method very small portions of the tracer are used (the radioactivity of each is about 1 mCi). The last portion of the tracer injected in the close vicinity of the leak is sufficiently high to be measured above the leak zone.

14.3.4 Method of tracer injection under constant pressure of the inspection medium

The method can be applied to gas pipelines of any length with large leaks. It should be noted that the single pumping may not be sufficient to transport the tracer to the leak zone the gas is continuously pumped under a constant pressure. Continuous pumping of the gas shows advantages in the case of small leaks since it permits to reduce the time of their localization. It is necessary to continuously maintain definite supply of the gas in order to compensate for the losses through the leaks. The localization can be carried out at any place and the minimum detectable leakage rate is less than 30 cm^3/h.