WASTE OIL STORAGE

FINAL DRAFT REPORT

by

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EXECUTIVE SUMMARY

The purpose of this study was to evaluate the potential for environmental contamination from waste oil storage systems. The report findings and methodologies used are summarized herein.

Generally, stored waste oil falls into one of two categories: automotive/diesel or industrial. Automotive/diesel waste oils consist primarily of crankcase oils generated by cars, trucks, and other vehicles. Because these oils are usually consistent in composition and levels of contamination, increased contamination as a result of mixing the oils from different sources is not likely. The contaminants that are common in these oils are the metals barium, chromium, and lead. Lead is still the contaminant of greatest concern, despite the fact that the decrease in the use of leaded gasoline has lessened its significance. These waste oils also contain some potentially hazardous polynuclear aromatic compounds (PNA's).

Industrial waste oils, as the name implies, are generated by industry. They include metal working, hydraulic process, electrical, refrigeration, and turbine oils. These waste oils can contain a wide range of potentially hazardous constituents, including halogenated solvents, aromatic solvents, polychlorinated biphenyls (PCB's), and heavy metals (cadmium, chromium, and

zinc). The levels of these contaminants range from very high to essentially zero.

Waste oil is stored in below-ground tanks, above-ground tanks, and 55-gallon drums. Most of the tanks now in use are made of unprotected steel, but this practice is changing, particularly for below-ground tanks. For example, to avoid corrosion problems, the major oil companies are replacing most of their below-ground steel tanks that fail with fiberglass units.

Tank sizes vary widely, but the vast majority of them (both below-ground and above-ground) hold 500 gallons or less. Some facilities, however, have 5,000- to 10,000-gallon tanks, and collector-processors* of waste oil occasionally have tanks that hold a few hundred thousand gallons.

WASTE OIL STORAGE FACILITIES

Waste oil is stored by both generators and collector-processors (Figure I). Automotive/diesel oil is generated by service stations, automotive repair shops, automotive dealers, fleet maintenance garages, and a miscellaneous group classified as "others." This combined group of generators stores an estimated 64 million gallons of waste automotive/diesel oil. Industrial generators store an estimated 41.7 million gallons of waste industrial oil, and collectors† and collector-processors store an estimated 67.8 million gallons of automotive/diesel and industrial waste oil.

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* Collector-processors both collect and process waste oil.

† Collectors collect waste oil, but they do not process it.

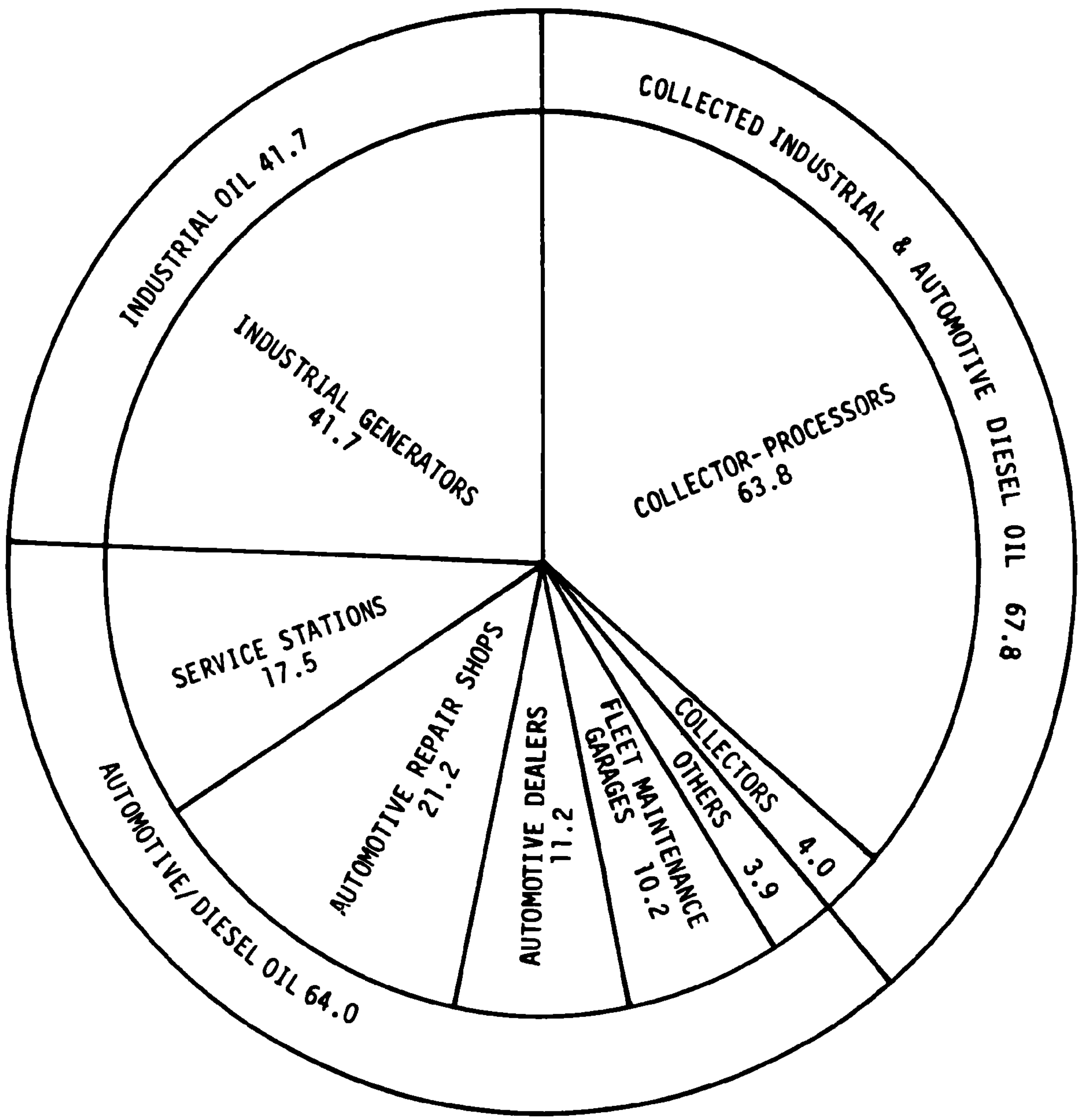

Figure I . Breakdown of waste oil stored by estimated volume of oil (in millions of gallons) at each source.

Because the waste oil stored by collectors and collector-processors includes both industrial oils and automotive/diesel oils, various types of industrial oils may be mixed together and automotive/diesel oils may be mixed with industrial oils. Such mixing increases the potential for a greater variety of contaminants in a given source of collected waste oil. Some collectors and collector-processors segregate their waste oils by source, but most practice some mixing. Cross-contamination can also occur as a result of storing one type of oil in a tank that previously contained a different type.

The proportional relationships between the quantities of stored waste oil and the number of facilities and storage methods vary greatly. Whereas more than 65 percent of the facilities use below-ground tanks, only 49.4 percent of total waste oil is stored in below-ground tanks. On the other hand, only an estimated 7.1 percent of the facilities store waste oil in above-ground tanks, but this group accounts for 43.9 percent of the waste oil stored. For drum storage, the situation is reversed; 27.5 percent of the storage facilities use drums, but drum storage accounts for only 6.7 percent of the waste oil stored. The total amount of waste oil stored is estimated to be 173 million gallons (Table I).

TABLE I . WASTE OIL STORAGE SUMMARY[a]

Type of storage	Average tank sizes, gallons	Number of facilities	Number of tanks and drums	Storage quantity, 10^6 gallons	Storage quantity, % of total
Below-ground tanks	500	269,000	269,000	40.5	23.4
	600	42,000	42,000	7.6	4.4
	5,000	25,000	25,000	37.5	21.6
	10,000	70	70	0.2	0.0
Subtotal		336,070	336,070	85.8	49.4
Above-ground tanks	250	1,500	1,500	0.1	0.0
	500	33,400	33,400	5.0	2.9
	5,000	800	1,600	4.0	2.3
	10,000	570	1,070	3.2	1.9
	50,000	255	2,550	63.8	36.8
Subtotal		36,525	40,120	76.1	43.9
Drums	55	141,490	424,470	11.6	6.7
Total		514,085	800,660	173.5	100.0

[a] Based on numerous contacts with waste oil processors and information developed by Development Planning and Research Associates, Inc., of Manhattan, Kansas.

DETERMINATION OF WASTE OIL LOSSES

Frequency of Losses

Because insufficient data were available to serve as a basis for a direct assessment of the frequency of waste oil losses, alternative methods were used to estimate loss probabilities.

For determination of losses from above-ground tanks and drums, a previously developed "fault-tree" analysis proved to be useful. This analysis provided estimated failure probabilities for the various components in an above-ground storage system. These probabilities were used to estimate above-ground spills from typical above-ground waste oil storage systems.

The results of recently performed research into leakage from below-ground gasoline tanks were used to estimate the frequency of losses in below-ground waste oil tanks. Leaks in below-ground tanks can result from external or internal corrosion, piping failure, tank design and fabrication faults, or improper tank installation, but external corrosion is by far the most common cause. Over three-fourths of all unprotected steel tanks will experience localized external corrosion, which leads to an accelerated rate of failure.

Two approaches were used to estimate the probability of leaks in below-ground waste oil tanks: 1) the use of a mathematical model developed in an American Petroleum Institute (API) study to estimate tank age failure under assumed soil conditions, and 2) the use of recent data compiled by Warren Rogers Associates on the expected age of underground gasoline tanks at time of failure under various soil conditions encountered at automotive service stations. Both approaches were useful only in predicting leaks caused by external corrosion. In each case, a uniform tank age distribution of 0 to 20 years was assumed.

Estimated probabilities and frequencies of waste oil losses from the three modes of storage (below-ground tanks, above-ground tanks, and drums) indicate that the incidence of losses is far greater from below-ground waste oil tanks than from either of the other two storage modes (see Table II). The probability of leakage in a below-ground tank has been conservatively estimated to be between 12 and 14 percent, based on an assumed uniform tank distribution of 0 to 20 years. This percentage translates into 43,500 leaks per year from below-ground tanks.

Considerable evidence indicates that the assumed age range (0 to 20 years) is conservative and that a significant number of waste oil tanks in current use are more than 20 years old. The probability of failure in these older tanks is believed to exceed 50 percent. In areas of the country where below-ground tanks are consistently exposed to moisture-saturated soil, the probability of leakage is much higher than the 12 to 14 percent estimate. Based on engineering judgment, about 25 to 35 percent of the underground waste oil tanks are believed to be leaking in some areas, especially where a large number of tanks over 20 years old are still in service.

TABLE II. ANNUAL WASTE OIL LOSSES

Storage mode	Annual probability of loss, percent	Annual number of loss incidents[a]
Large above-ground tanks	2.9	150
Small above-ground tanks	1.6	550
Total above-ground tanks	1.7	700
Total drums	1.1	4,500
Total below-ground tanks	13.0[b]	43,500[b]

[a] Reflects all estimated incidents of uncontained losses from tanks and drums indicated in Table I. The losses shown for below-ground tanks include ongoing or continuous leaks.

[b] These numbers are the averages of an estimated range.

Magnitude of Losses

Table III presents a summary of losses typically expected from various size tanks. Losses from above-ground tanks are based on the maximum quantities expected to be stored in these tanks. Losses from below-ground tanks are based on the expected maximum quantities received in these tanks over a period of time. It should be noted the maximum expected loss values on this table represent worst-case scenarios.

TABLE III. MAXIMUM EXPECTED WASTE OIL LOSSES FROM DIFFERENT SIZE TANKS

Storage mode	Tank size, gallons	Average loss if tank is emptied, gallons[a]	Maximum expected loss,[b] gallons
Below-ground tanks[c]	500	-	375/month
	5,000	-	3,750/month
Above-ground tanks	250	75/incident	188/incident
	500	150/incident	375/incident
	5,000	2,500/incident	3,750/incident
	10,000	5,000/incident	7,500/incident

[a] Assumes smaller tanks are 30 percent full, on the average, and larger tanks are 50 percent full.

[b] Worst-case scenarios, and losses from widely used tanks without secondary containment.

[c] Losses from below-ground tanks are shown in gallons/month because they usually emanate from slow, continuous leaks.

Nontransportation storage spills reported to the EPA and the Coast Guard between 1974 and 1980 primarily involved losses of less than 250 gallons. Nearly 30 percent involved less than 50 gallons. Only 21 percent of the estimated spills from above-ground waste oil tanks involve the larger tanks (capacities greater than 1000 gallons). The great majority of above-ground waste oil tanks have capacities around 500 gallons and are estimated to be only 30 percent full on the average. Thus, the average total loss from one of these tanks would not be more than 150 gallons. Because many tank spills are probably stopped before the tank is emptied, spills from above-ground waste oil tanks are typically less than the average quantity contained in the tanks.

Based on reported underground gasoline losses, the probability of a waste oil loss of 3750 gallons per month from a below-ground waste oil tank appears to be remote. Some of the largest reported gasoline losses are known to be less than 3750 gallons per month, and these were from larger-capacity tanks. For example, a 30,000-gallon underground gasoline loss in New York is believed to have averaged no more than 2500 gallons per month from two 4000-gallon tanks. Inasmuch as total gasoline storage in service stations is greater than total waste oil storage and tank sizes are generally much larger, the few documented gasoline losses of 3750 gallons or more per month suggest that a waste oil loss of this size would be very unlikely.

ENVIRONMENTAL IMPACT OF WASTE OIL LOSSES

Waste oil that is lost as a result of spills or leaks may contaminate the land, groundwaters, surface waters, and even the air. This report focuses on an evaluation of soil contamination.

Evaluation was limited to the rate or depth of penetration of waste oil into the soil.

A worst-case scenario approach was selected for determination of the environmental impact of losses from waste oil storage systems. This scenario describes the worst conditions for environmental contamination that reasonably can be expected to occur. If environmental contamination is low under these conditions, more typical situations are likely to result in little or no contamination.

Above-Ground Tanks

Environmental contamination from waste oil loss from above-ground tanks can result in seepage of spilled oil from the impounded area around the storage tank or from leaks in the tank bottom. The time required for spilled oil to contaminate a depth of 30.5 centimeters (12 inches) of soil depends on the type of soil present within the secondary containment (impoundment) area, as shown in Table IV. It is predicted that a spill with an average depth of 30.5 centimeters within the secondary containment area will penetrate a typical sandy soil to a depth of 30.5 centimeters in only a few minutes. The amount of oil lost depends on soil porosity, but it will certainly be more than 25 percent. Because cleanup times range from an hour to several days, much of the oil will be lost before it can be cleaned up; thus, a secondary containment system with a sandy soil bottom is virtually useless. The rate of oil seepage is much slower if the soils in the secondary containment area are silt or clay, and expeditious cleanup of spilled oil lessens the loss considerably.

TABLE IV. TIME REQUIRED FOR SPILLED OIL TO CONTAMINATE 30.5 CENTIMETERS (12 INCHES) OF SOIL[a]

Soil type	Time
Clay	37.6 to 772 years
Silt	30.2 to 16.9 days
Sand	9.03 to 13.1 minutes

[a] Calculations assume average soil conditions and an average spill depth of 30.5 centimeters.

TABLE V. OIL MIGRATION TIME FROM AN ABOVE-GROUND TANK WATER TABLE 100 CENTIMETERS (39.4 INCHES) DEEP[a]

Soil type	Time
Clay	286 to 877 years
Silt	12.0 to 17.1 days
Sand	12.3 to 12.8 minutes

[a] Calculations assume average soil conditions and an average oil depth in the tank of 500 centimeters.

Leaks from the bottom of above-ground tanks (Table V) also pose severe problems if the soil under and around the tank is sandy. In the event of a major rupture, oil may reach a shallow (100 centimeters or 39 inches deep) water table in a matter of minutes.* It would take several days for an oil to reach the groundwater table if the tank were placed on a silty soil. Regular monitoring of oil levels within the tank is necessary to assure that a failure does not go undetected.

Below-Ground Tanks

Failure of an underground tank will result in seepage of oil into the surrounding soils. Because leaks are not visible from the surface, they are likely to go undetected for a much longer period than those from above-ground tanks. Failure of a tank placed in an average sandy soil may result in oil migration to a water table 100 centimeters (39 inches) deep in less than an hour (Table VI). An average silty soil may lengthen migration times to 1 or 2 months. Because of the long periods of time that may elapse before detection of oil loss from a below-ground tank, the potential for environmental contamination from a below-ground tank in a silty soil is still significant. Clay is the only type of soil that is believed to be safe for burying below-ground tanks, and this belief may be overly optimistic. Recent research

* Oil that is leaking because of tank bottom failure migrates much more rapidly than spilled oil because of the head exerted by the oil within the storage tank.

indicates that interaction of some organics with clay can greatly increase its permeability.

TABLE VI. OIL MIGRATION TIME FROM A BELOW-GROUND TANK TO A WATER TABLE 100 CENTIMETERS (39.4 INCHES) DEEP[a]

Soil type	Time
Clay	365 to 2598 years
Silt	22.4 to 52.1 days
Sand	34.9 to 39.3 minutes

[a] Calculations assume average soil conditions and an average oil depth in the tank of 120 centimeters.

Containers and Drums

Spills from containers and drums will result in some seepage of oil into soils. Depth of oil penetration was evaluated for both catastrophic spills and sequential small spills. Catastrophic spills tend to spread over a large surface area. Soil penetration varies with soil type and the type of oil spilled. A light oil spilled on a gravel surface results in the deepest oil migration. Sequential small spills do not spread over such a large area, but the repeated spillage usually occurs in the same location. The result is a deeper localized penetration of oil, even though the total volume of oil may be small.

In general, groundwater contamination due to spills from containers and drums should be minimal. Because cleanup of these spills is typically minimized, however, some soil contamination can be expected, and leaching of some oil components from oil-contaminated soil may occur.

SECTION 1

INTRODUCTION

The U.S. Environmental Protection Agency's Office of Solid Waste is funding a study to assess the environmental impact of waste oil as a fuel, waste oil as a dust suppressant, and the storage of waste oil. Three separate reports completed as part of this study characterize each of the practices. This report presents an evaluation of waste oil storage practices in the United States.

Approximately 4.3 billion liters (1.1 billion gallons) of waste oil are generated each year. Regardless of its end use, virtually all waste oil is stored at some time. The composition of waste oil is highly variable, and much of it contains potentially hazardous contaminants. The contaminants in waste oil are highly dependent on its source. Some of those found in waste oil include heavy metals, particularly lead; organic solvents such as benzene, xylene, and toluene; and chlorinated organics such as trichloroethane, trichloroethylene, and polychlorinated biphenyls (PCB's).

The potential for losing waste oil from storage sites (e.g., through leaks, spills, and evaporation) presents the possibility of the release of hazardous materials into the environment. This study is designed to assess the environmental impact of such releases from waste oil storage sites.

The report is divided into two primary parts. The first part (Section 2) presents a technological characterization of waste oil storage in the United States, and the second part (Section 3) examines and summarizes the fate of waste oil that is released into the environment as a result of leaks and spills at storage sites.

The technological characterization includes discussions on the quantity and sources of waste oil, the various types of storage facilities, the composition of stored waste oil, the frequencies and volume of waste oil losses, and the failure mechanisms and their relative importance.

The section addressing environmental impact examines the rate and degree of contamination from typical and worst-case waste oil releases from storage sites. The three mechanisms of oil movement from the storage sites (i.e., evaporation, surface runoff, and seepage into the soil) are discussed. The primary mechanism of spilled oil movement is seepage, which is examined in detail. Mathematical models used to estimate environmental pollution consider the spill conditions, including oil and soil types, distance to the groundwater, and time from spill to detection.

SECTION 2

TECHNOLOGICAL CHARACTERIZATION OF WASTE OIL STORAGE

Included in this section are discussions on the quantity and sources of waste oil, the various types of storage facilities, the composition of stored waste oil, the frequencies and volume of waste oil losses, and the mechanisms and relative importance of storage failures.

This technological characterization of waste oil storage is based on the limited amount of data available. Data on waste oil leaks from underground storage tanks are especially sparse because these leaks usually are not reported to any central agency. The data that do exist generally belong to the private sector and are not available to the public. Also, underground leaks often go undetected (and thus undocumented) for long periods of time. Of necessity, some of the data presented here have been derived from the input of a combination of information sources. We believe these derived data are reasonable, however, and in combination with the other data in the report, will provide a foundation for determining potential environmental effects of waste oil storage.

Generally, stored waste oil falls into one of two categories: automotive/diesel or industrial. Automotive/diesel waste oils consist primarily of crankcase oils generated by cars, trucks, and other vehicles. Industrial waste oils, as the name implies, are generated by industry.

Because automotive/diesel waste oils are usually consistent in composition and levels of contamination, there is little probability of increased contamination as a result of mixing the oils from different sources. These oils are likely to be contaminated with the heavy metals barium, chromium, and lead. Lead is still the contaminant of greatest concern, despite the fact that the decrease in the use of leaded gasoline has lessened its significance. These waste oils also contain some polynuclear aromatic compounds (PNA's), which are potentially hazardous.

Industrial waste oils include metal working, hydraulic process, electrical, refrigeration, and turbine oils. These waste oils can contain a wide range of potentially hazardous constituents, including halogenated solvents, aromatic solvents, polychlorinated biphenyls (PCB's), and heavy metals (cadmium, chromium, and zinc). The levels of these contaminants range from very high to essentially none.

2.1 CHARACTERIZATION OF WASTE OIL STORAGE

Waste oil is stored in below-ground tanks, above-ground tanks, drums, and some surface impoundments. Since the use of surface impoundments (once a major factor in waste oil storage) has been declining rapidly, discussions in this section concern only tank and drum storage.

Estimates have been made of the quantities of waste oil stored in tanks and drums at various facilities (Table 2-1 and

TABLE 2-1. ESTIMATED QUANTITIES OF STORED WASTE OIL BY SOURCE AND TYPE OF STORAGE[a]

Waste storage establishments	Number of facilities	Assumed average tank size, gallons	Assumed average number of units	Quantity of waste oil stored,[b] 10^6 gallons
With below-ground tank storage				
Service stations	113,000	500	1	17.0
Automotive repair shops	93,000	500	1	14.0
Automotive dealers	63,000	500	1	9.5
Fleet maintenance garages	42,000	600	1	7.6
Industrial generators	25,000	5,000	1	37.5
Railroads	70	10,000	1	0.2
Subtotal	336,070			85.8
With above-ground tank storage				
Airplane service facilities	1,500	250	1	0.1
Fleet maintenance garages	2,600	500	1	0.4
Collectors	800	5,000	2	4.0
Collectros/processors	255	50,000	10	63.8
Marine service facilities	500	10,000	2	3.0
Automotive repair shops	30,800	500	1	4.6
Railroads	70	10,000	1	0.2
Subtotal	36,525			76.1
With drum storage				
Service stations	6,000	55	3	0.5
Automotive repair shops	31,900	55	3	2.6
Automotive dealers	21,000	55	3	1.7
Fleet maintenance garages	27,000	55	3	2.2
Collection centers	300	55	3	<0.1
Airplane service facilities	4,000	55	3	0.3
Industrial generators	51,000	55	3	4.2
Railroads	290	55	3	<0.1
Subtotal	141,490			11.6
TOTAL - Tanks and Drums	514,085			173.5

[a] Based on numerous contacts with waste oil processors and information developed by Development Planning and Research Associates, Inc., of Manhattan, Kansas.[1-19]

[b] Assumes tanks 30 percent full on average; for collectors and collectors/processors, tanks assumed to be 50 percent full. Drums assumed to be 50 percent full.

Figure 2-1). Much of this information was compiled by Development Planning and Research Associates, Inc., of Manhattan, Kansas.[1,2] Some was gathered through personal communications with various waste oil processors.[3-19]

An estimated 173 million gallons of waste oil is stored in tanks and drums. Although storage capacity is more than twice this amount, the competitive nature of the waste oil business normally results in the waste oil being collected long before it reaches storage capacity.[12-14] Reported inventories of waste oil processors vary from near capacity to almost none, depending on the processed product and the season of the year.

Less than 7 percent of the estimated total quantity of waste oil is stored in drums. Although many facilities use drums to store waste oil, the quantities produced by these facilities are usually small. Industrial generators tend to use drums only if waste volumes are less than 500 gallons per month.[1]

About half of the total waste oil is stored in below-ground tanks, and nearly two-thirds of the 500,000 facilities that store waste oil use this storage method. Although only 7 percent of these facilities use above-ground tanks from waste oil storage, these tanks account for more than 40 percent of the stored oil. Collector-processors of waste oil use above-ground storage almost exclusively, and the quantities they store are enormous compared with that stored by other establishments.

Stored waste oil generally falls into one of two categories: automotive/diesel oil or industrial oil.[1] About 40 percent of

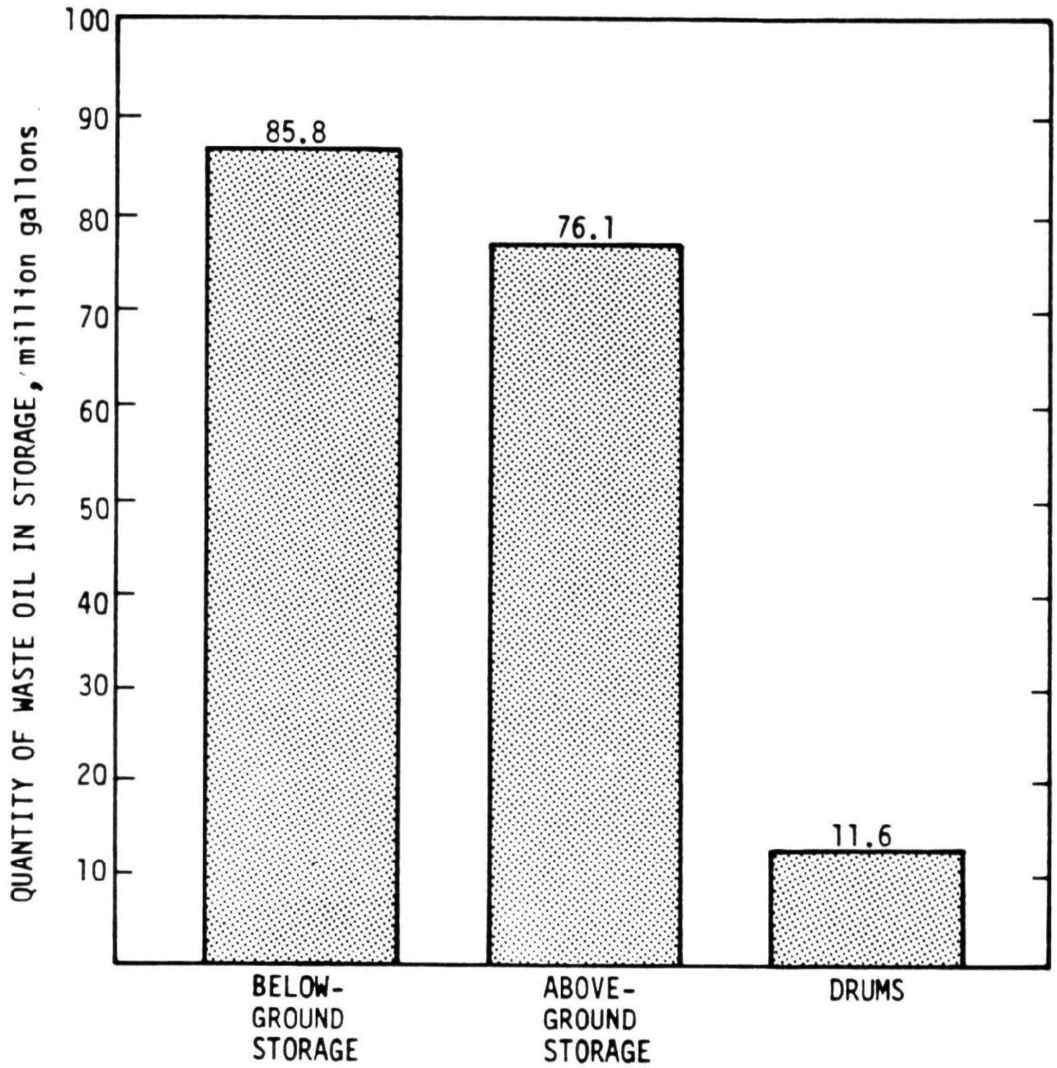

Figure 2-1. Estimated quantity of stored waste oil by type of storage.

the total stored waste oil (excluding that stored by collectors and collector-processors) comes from industrial oil sources; the remaining 60 percent is from automotive/diesel oil establishments. The waste oil stored by collectors and collector-processors represents both categories, and after collection, oils from the two categories are sometimes mixed.

Collector-processors store far more waste oil (63.8 million gallons) than any of the other facilities. Storage is typically in above-ground tanks ranging from 10,000 to more than 250,000 gallons in capacity.[3-13] Based on the information obtained from these references, the average storage capacity per facility is believed to be at least 500,000 gallons.

Industrial generators rank second in the amount of waste oil stored. Most of the total quantity of this industrial waste oil is stored in below-ground tanks, even though a larger proportion of industrial facilities uses drums. Tank sizes vary considerably, but the average capacity is estimated to be 5000 gallons.

Automotive repair shops outnumber any other type of waste oil storage facilities. Most store in below-ground tanks, but some use above-ground tanks or drums. The typical tank size is 500 gallons. Service stations have more below-ground tanks than any other type of waste oil storage facilities, but a few use drums for storage.

With the exception of collectors, collector-processors, and marine service facilities, most sources using tanks to store waste oil have only one tank.

Below-ground waste oil storage tanks with capacities greater than 1000 gallons are used primarily by industrial generators and railroads. Above-ground waste oil storage tanks with capacities greater than 1000 gallons are used primarily by waste oil collectors, collector-processors, marine service facilities, and railroads.

Data gathered on storage of waste oil at marine service facilities are somewhat conflicting. The information presented in Table 2-1 reflects that reported by Development Planning and Research Associates, Inc.[1,2] Discussions with a few identified marine service facilities, however, suggest that they often store waste oil together with large quantities of water.[20-23] Total storage quantities of mixtures of oil and water may be in millions of gallons.

Although the storage quantities of waste oil shown in Table 2-1 are not intended to include substantial amounts of other substances mixed with oil, the quantities for marine service facilities seem questionable, since it is not clear what is included and the storage capacities reported in recent discussions are much higher than indicated.[20-23]

2.1.1 Composition of Stored Waste Oil

The comprehensive data base established as part of this study characterizes the composition of various types of waste oil. Ideally, this data base would be used to predict the most likely composition of the waste oil in each of the storage units for each facility type, and this is done (to some extent) in a supplementary report that deals strictly with waste oil composition issues. This report, however, presents only a general assessment of waste oil composition as it relates to the various sources of oil.

As in the case of its storage, the composition of waste oil falls into two basic categories: automotive/diesel oils and industrial oils. The composition of automotive/diesel oils is fairly consistent; the major variable contaminant is lead, which is directly related to whether the vehicles generating the oil used leaded or unleaded fuel. The composition of industrial oils, on the other hand, varies considerably. Among the several types of industrial oils are metal working, hydraulic process, electric, refrigeration, and turbine oils. Each is used in a unique environment that contributes its own contaminants to the oil. The levels and types of these contaminants differ from industry to industry. All waste oils contain some polynuclear aromatic compounds (PNA's) as part of their basic hydrocarbon makeup. These PNA's also present a hazard potential of some concern.

Both automotive/diesel and industrial oils are stored in one of the three types of storage units already discussed: below-ground tanks, above-ground tanks, or drums. The flow diagram in Figure 2-2 shows the estimated storage for both categories of waste oil. The following subsections discuss qualitatively the composition of the waste oil most likely to be stored in each of these storage units.

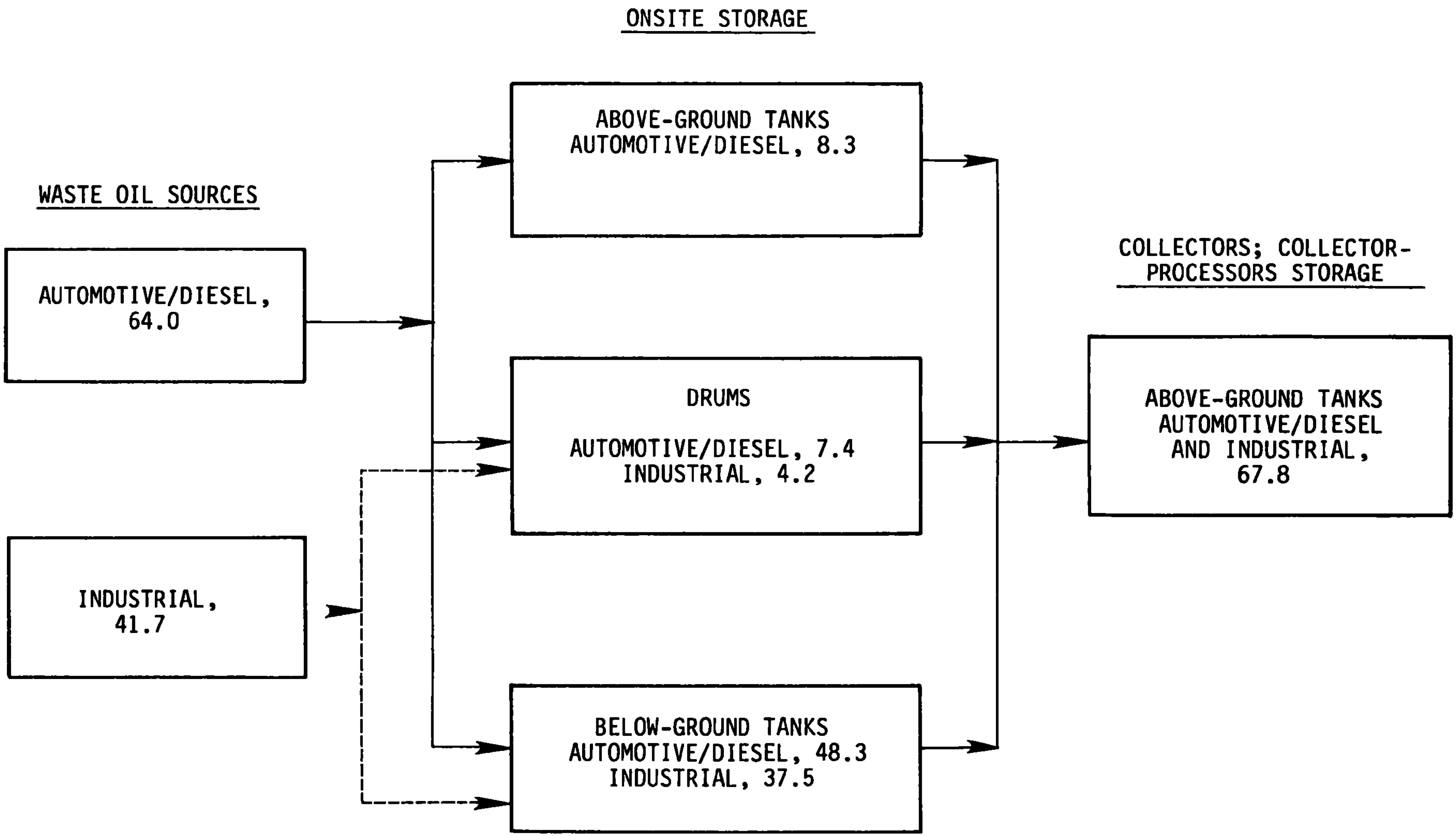

Figure 2-2. Storage practices by source in millions of gallons stored (derived from Table 2-4).

2.1.1.1 Below-Ground Tanks--

This type of storage unit accounts for greater overall quantities of waste oil storage than the other units combined. Most (more than 90 percent) of these units are small-capacity tanks (about 500 to 600 gallons) used to store waste crankcase oil generated at service stations and other automotive repair and service shops. Most of the remaining underground tanks represent the much larger tanks used to store industrial waste oil. Despite their smaller number, these industrial tanks account for nearly half of the waste oil stored underground.

Most of the waste oil stored in below-ground tanks is segregated; that is, each tank usually contains oil generated by a single source. This is particularly true for the crankcase oils, which are relatively consistent with respect to composition and contamination levels. Although crankcase oils stored in below-ground tanks contain some contaminants of concern (primarily heavy metals), they are not likely to be contaminated with other unknown materials (e.g., solvents). Because all waste crankcase oils are usually similar in composition, there also is little probability of contamination resulting from mixing oil from one tank with that from another tank.

Industrial waste oils that are stored underground are far more subject to variability within a single storage tank, from plant to plant, and from industry to industry. Consistency can vary at a single site because more than one oil or oily waste is generated there. Also, the variability in the nature of industrial processes among different industries, or even from plant to plant within a single industry, can produce significant differences in waste oil composition.

Based on an evaluation of approximately 400 composition analyses from various sources, automotive/diesel oils are likely to be contaminated by some heavy metals with potentially hazardous characteristics. Lead is still the primary metal of concern, despite the decrease in its significance as a result of the trend away from leaded gasoline. Other heavy metals of concern are barium and chromium.

Industrial oils can contain a much wider range of potentially hazardous constituents, including heavy metals and organic compounds (such as halogenated solvents, aromatic solvents, and polychlorinated biphenyls). The quality of industrial waste oils ranges from very clean to highly contaminated.

2.1.1.2 Above-Ground Tanks--

Most above-ground storage tanks are located at generator sites, but most of the oil stored in this manner is held by collectors or collector-processors, whose tanks are much larger than those at generator sites. The general discussion of industrial versus automotive/diesel oil quality just presented applies also to segregated oils stored in above-ground tanks at generator or collector-processor sites. One additional type of waste oil is that generated at airplane service facilities. This oil is similar to automotive waste oils, but it is much more likely to be contaminated with chlorinated cleaning solvents used at these sites.

Because of mixing, the composition of waste oil stored by collectors and collector-processors is less predictable than the composition of waste oil stored at the generator sites. Automotive oils may be mixed with industrial oils, and various types of industrial oils may be mixed together. Some collectors and processors segregate their oils according to source, but most of them mix the oils and thereby create a potential for contamination by a wide variety of substances, including heavy metals, halogenated solvents, aromatics, and PCB's.

2.1.1.3 Drums--

Fifty-five gallon drums are used to store waste oils at generator sites. Because of the small capacity of these storage units, the oil in a given drum is likely to be generated from a specific source. Virtually every type of oil is stored in drums, but these units are used somewhat more frequently for crankcase oil storage than for industrial oil storage. The contaminants likely to be present in waste oil stored in drums include the entire range of contaminants identified in all waste oils.

2.1.2 Changes in Composition Resulting From Storage Practices

Switching the material stored in a given tank for inventory purposes or because of product demand is a common industry practice. Such changes affect the composition of the waste oil stored in any type of unit. For example, if a relatively clean automotive waste oil is placed in a storage tank that previously contained oil contaminated with PCB's or some other material, the clean oil will become contaminated if the tank has not been thoroughly cleaned beforehand. This well-documented phenomenon has caused significant problems with regard to misrepresented oil. Such incidents are most likely to occur in the tanks of a collector or a collector-processor, but they also could occur in industrial generator storage tanks.

2.2 CHARACTERIZATION OF WASTE OIL LOSSES

Because waste oil losses may have a significant impact on both health and the environment, it is important to address the frequency and mechanisms of waste oil releases and the magnitude of the resulting losses.

2.2.1 Frequency and Mechanisms of Waste Oil Releases

2.2.1.1 Below-Ground Tanks--

Until very recently almost no data were available on the magnitude of leaks from below-ground storage tanks. A recent study sponsored by the American Petroleum Institute (API), however, focuses on the causes and predictability of leaks in below-ground unprotected steel tanks containing gasoline.[21] This study provides a mathematical model and basic data that are also applicable to failure predictions for other petroleum-filled, below-ground steel tanks. The potential sources of leaks in below-ground tanks are listed as external corrosion, internal corrosion, piping failure, tank design and fabrication, and tank installation.[24]

Although examples of failure resulting from each of these causes have been documented, leaks from external corrosion occur most frequently.[24] External corrosion that is essentially uniform over the entire surface of a steel tank is not usually a concern; tanks with such corrosion are expected to last as long as the rest of a facility. In most (±77 percent) below-ground steel tanks, however, localized external corrosion occurs, which is likely to produce failure in a much shorter time. One or several localized anodes established on the tank surface during installation eventually lead to corrosion perforation(s). The localized anodes may be caused by impurities in the backfill adjacent to the tank surface, physical damage to the tank surface (e.g., scrapes), etc. A mathematical model for predicting the mean age to the outset of leakage from external corrosion was developed in the API study:

$$\text{Age} = 5.75 \times R^{0.05} \times S^{-0.018} \times e^{(0.13\ pH - 0.41M - 0.26\ Su)}$$

where

R = resistivity of soil in ohm-centimeters

S = tank capacity in gallons

pH = soil acidity

e = 2.72

M = 1 if soil saturated with water, 0 otherwise

Su = 1 if sulfides present in soil, 0 otherwise

The model is reported to be very accurate in predicting failures where point-source external corrosion occurs.[24,25,26]

Whereas the average age of a tank to the time of failure can be calculated with the model, the actual age at the time of failure may be less or more than the calculated age. The standard deviation from the calculated mean age is estimated to be 2.5 years.

An effort has been made to estimate the probability and number of failures in below-ground waste oil storage tanks. The probability estimates are based on data from the API study and subsequent data developed and provided by the author of the API study, Warren Rogers Associates.[24,25] These data are considered applicable because the vast majority of below-ground waste oil tanks are unprotected steel tanks subject to essentially the same external soil conditions as gasoline tanks.[25]

Two approaches were used in estimating the probability of leaks in below-ground waste oil tanks. They first utilized a mathematical model from the API study to estimate tank age at failure. The values used in the model were based on two sets of assumed soil conditions and a tank size of 500 gallons. (The assumed soil conditions have a dramatic impact on predicted ages at failure, whereas the tank size is relatively unimportant.) The failure predictions from the mathematical model were applied to an assumed uniform age distribution of 0 to 20 years in below-ground tanks. This permitted determination of the cumulative probability of leaks in tanks equally distributed in this age grouping.

The second approach utilized recent data on the predicted ages at which underground gasoline tanks will fail. These predictions were based on numerous tests of soil conditions at automotive service stations throughout the United States and were applied to an assumed uniform age distribution of 0 to 20 years for below-ground tanks.

Both of these approaches are described in detail in Appendix A. Both are useful in predicting failures caused by external corrosion.

Based on the results of these two approaches, a probability of leaks in below-ground waste oil storage tanks of 12 to 14 percent was calculated. These figures are believed to be overly conservative, however because they consider only external corrosion failures and because evidence indicates that the assumed tank age distribution is probably conservative.[26] Although most of the larger oil companies have begun tank replacement programs in the service stations they control,[25,27,28] at least half of the service stations in the United States are not within their control and generally have no replacement programs. It is also doubtful that below-ground waste oil tanks receive any attention from the numerous other establishments that use them until an obvious problem arises. For these reasons, it seems likely that many of the waste oil tanks in service have been buried for well over 20 years. Indeed, discussions with representatives of oil companies suggest that many of the below-ground tanks currently used in service stations may be 15 to 25 years old.[27,29] One recent study indicates that the age of close to one-third of the 1.2 million below-ground gasoline and fuel oil tanks is 16 years or older.[30] Correspondence received from one major oil company indicated that the age of an estimated 20 percent of their waste oil tanks is 21 years or older.[26]

An estimated 25 to 35 percent of the below-ground waste oil tanks in some areas of the country are believed to be leaking, and nearly all of these tanks are buried in moisture-saturated soil. The higher figure would be expected where the tanks are not only buried in moisture-saturated soil, but many are more than 20 years old.

The use of a 12 to 15 percent leak probability in below-ground waste oil tanks results in an estimate of 40,000 to 47,000 leaking tanks nationwide. Although these figures seem alarmingly high, they may well be conservative. In any case, the number of leaking below-ground waste oil tanks far exceeds the annual number of spills from above-ground waste oil storage in tanks and drums. Also, many of the below-ground tanks have been leaking undetected over a period of many years.

2.2.1.2 Above-Ground Tanks--

Insufficient empirical data are available for direct determination of the frequency and probability of waste oil losses from above-ground tanks. Regulations require that spills of oil and/or hazardous substances affecting U.S. inland surface waters be reported to the EPA. Similarly, spills that could affect navigable waters must be reported to the U.S. Coast Guard. Unfortunately, the spill reports received are not considered a reliable source by which to determine spill probability because the belief is that many spills are not reported.[31] The reported spills are believed to represent only those that could affect surface water.

An attempt was made to estimate how many of these reported spills from 1975 through 1980 were waste oil. It was determined that over 80 percent of the spills reported to the U.S. Coast Guard were petroleum products.[32] Although a similar determination could not be made for spills reported to EPA, 73 percent of the spills reported in Region IV (approximately one-third of the national total) were petroleum products.[31] The Coast Guard data suggested that waste oils were involved in about 11 to 12 percent of the petroleum product spills. These figures lead to an estimate that approximately 360 of the nontransportation storage spills reported to EPA and U.S. Coast Guard were waste oil. This is equivalent to 60 spills of waste oil each year from 1975 through 1980.

Because the amount of directly applicable data is insufficient to serve as the basis for above-ground tank spill probability, JRB Associates (in a study for EPA) developed a "fault-tree" analysis for a reportedly "typical" storage system to examine storage failures.[31] This analysis considers the failure probabilities of the various components of a storage system to arrive at the failure probability of the total system. The analysis is based on combined data from the following sources: a nuclear reactor safety study performed for the U.S. Nuclear Regulatory Commission (published in 1975), a safety study of U.S. deepwater port oil transport systems for the U.S. Department of Transportation (published in 1978), a Sandia Laboratory report on human error probability (published in 1964), an American Petroleum Institute report on fire incidents at bulk plants between 1971 and 1974, and an estimate of the probability of a hose leak (based on the engineering judgment of JRB Associates, the developers).

It should be noted that a fault-tree analysis is only as good as the data used in its development and assumptions relative to a "typical" storage facility.[31] Reported spills have indicated more identified failure causes than those provided in the fault-tree analysis, but the analysis accounts for the major failures identified.[31] Natural disasters (windstorms, floods, earthquakes, etc.) are some of the failure causes not included in the analysis; however, these account for a small percentage of the nontransportation storage spills reported to the EPA and the Coast Guard. Another point to be considered with regard to the analysis is the reliance on the nuclear energy industry for much of the failure probability data. This industry is expected to have higher quality standards than most others. Because the typical storage facility used in the analysis is based on standards developed by the American Petroleum Institute and other associations, the use of the fault-tree analysis probably will lead to conservatively low estimates of failure probability of aboveground storage tanks used for waste oil.

Consideration was given to supplementing the use of the fault-tree analysis in this study with a separate analysis of above-ground tank failures due to external corrosion. Many above-ground waste oil tanks are in contact with the ground surface, and the API study mathematical model used to predict external corrosion in below-ground tanks was judged to have potential here, also. Use of the model for analysis of above-ground tank corrosion was ruled out, however, for several reasons. First, major parameters in the model include the presence (or absence) of moisture-saturated soil in contact with the tank surface and the presence of sulfides in the soil. Although some data are available on which to base estimates of these parameter values for below-ground tanks, similar data for above-ground tanks have not been found. Second, adjustments would have to be made in the model for above-ground tanks to reflect that only a fraction of the tank surface is in contact with the ground surface. Again, data are insufficient for making these adjustments. A final reason for excluding the mathematical model from the above-ground tank analysis is that tank corrosion accounts for a very small percentage of the nontransportation storage spills reported to the EPA and the Coast Guard.

A review of both the fault-tree analysis and the nontransportation storage spill reports submitted to the EPA and Coast Guard provided some insight into failure causes at storage facilities using above-ground tanks. Failure of ancillary equipment (pipes, pumps, valves, etc.) causes the most above-ground tank losses. Failure of the tank itself, vandalism, fire, explosions, and natural disasters are lesser causes. The fact that most above-ground tanks used for waste oil storage are small and simply constructed, however, eliminates much of the probability of failure due to ancillary equipment. Failure in these above-ground tanks is due largely to tank overflow (resulting primarily from operational error).

Surrounding an above-ground storage facility with a secondary containment system (dikes and/or curbing) considerably lessens the probability of pollution from spills. If the surface within such a secondary containment is relatively impermeable or if the potential for damage from percolation of oil into the ground is small, losses within the secondary containment may not be significant. Although the fault-tree analysis includes failure probability of a storage facility with secondary containment, this can be excluded if the storage facility has no secondary containment.

The fault-tree analysis further divides the storage facility failure probability between the storage tank system and the tank filling and discharge system. As shown in Table 2-2, secondary containment has a dramatic impact on the probability of a spill leaving the boundaries of a facility. With secondary containment around both the storage tank system and the fill-discharge system, the probability of facility failure is estimated to be 1.3×10^{-3} percent per year, or roughly just over one chance in 100,000. Conversely, at facilities without secondary containment the failure probability increases by several orders of magnitude, to an estimated 11.6 percent annually. These numbers were arrived at by adding the expected failure probabilities with/without secondary containment from both the storage tank system and the fill-discharge system.

TABLE 2-2. PROBABILITY OF LOSSES FROM ABOVE-GROUND TANK FACILITIES FOR HAZARDOUS LIQUID STORAGE[a]

Category	Failure probability/year, percent
Loss from storage tank system:	
Loss from tank	5.0
Loss from dike (around tank)	2.5×10^{-2}
Combined loss probability	1.3×10^{-3}
Loss from fill-discharge system:	
Loss from plumbing	6.6
Loss from curbing (around plumbing)	1.0×10^{-4}
Combined loss probability	6.6×10^{-6}
Loss from either the storage tank system or fill-discharge system:	
Without secondary containment	11.6
With secondary containment	1.3×10^{-3}

[a] The figures presented are considered applicable to waste oil storage tanks, based upon the sources of supporting data used in developing the JRB Associates fault-tree analysis.[31]

The failure probabilities from the fault-tree analysis were used in this study to estimate the frequency of waste oil losses from above-ground tank storage facilities. (The figures are believed to be applicable, based on the supporting data used in developing the analysis.) The first task was to estimate the number of above-ground storage facilities with secondary containment versus those without such containment. Discussions with collectors, processors, and others in the waste oil business revealed that most facilities with tanks that hold several thousand gallons of waste oil have secondary containment, whereas those with smaller tanks generally do not.[12-19] In some cases, secondary containment is simply natural drainage to a depression (natural or manmade) capable of containing a spill until it can be recovered.

An estimated 5200 above-ground waste oil tanks have capacities larger than 1000 gallons. Assuming 25 percent of these tanks are at facilities that have no secondary containment, and based on the 11.6 percent failure probability from the fault-tree analysis, an estimated 150 noncontained spills could occur annually at these facilities. At storage facilities with secondary containment, the number of noncontained spills each year would be virtually zero.

The smaller above-ground waste oil tanks are believed to number nearly 35,000.[1] The capacities of these tanks are generally 500 gallons or less, and they are located primarily in automotive repair shops and other service establishments. Because of their size, few (if any) are likely to have the fill-discharge system of piping, valves, pumps, etc., that is included in the "typical" facility in the fault-tree analysis. Therefore, it is assumed that only the probability of a loss from the tank and its ancillary equipment should be included in estimating the number of spills from small above-ground tank storage. Since the ancillary equipment would usually consist of a bottom drain with a valve, the probability of a loss from small tank storage is assumed to be the combined probabilities of a tank wall rupture, a bottom drain leak, and tank overflow. These probabilities, which are individually cited in the fault-tree analysis, were simply added together to obtain an estimated combined failure probability.[31] This annual combined failure probability from small tank storage is 2.1 percent. The corresponding annual failure probability in a large tank with more extensive ancillary equipment is estimated to be 5.0 percent.

Based on a conservative assumption that 75 percent of the smaller above-ground tanks are at facilities that have no secondary containment, the estimated annual number of noncontained spills from these facilities would be approximately 550. This figure seems high in comparison with the just over 4000 oil/hazardous waste nontransportation storage spills reported to the EPA and the Coast Guard from 1975 to 1980, of which only about 60 per year were waste oil spills. Part of the discrepancy may be due to the size of the spills. Although many small spills probably go unreported, the fault-tree analysis appears to account for small leaks as well as larger losses. Again, secondary containment reduces the number of noncontained spills dramatically. The installation of secondary containment at all the listed above-ground waste oil storage facilities would reduce the estimated noncontained spills to less than one spill per year.

Table 2-3 presents a summary of nontransportation storage spill incidents (distributed by size and failure causes) reported

TABLE 2-3. STORAGE SPILL PERCENTAGES FROM EPA AND U.S. COAST GUARD DATA BASES[a]
(percent of total in each size category)

	Amount spilled, gallons							
	0-49	50-99	100-249	250-499	500-999	1,000-10,000	>10,000	All spill sizes
Containment devices:								
Tank rupture/leak	4.3	4.3	4.7	3.8	5.1	6.2	10.7	5.1
Tank corrosion	1.4	1.2	3.1	1.4	3.3	3.0	1.6	2.2
Subtotal	5.7	5.5	7.8	5.2	8.4	9.2	12.5	7.3
Operations:								
Tank overflow	16.2	18.5	21.2	19.0	18.2	15.2	8.9	17.1
Other	24.2	22.0	16.2	16.8	15.1	17.9	17.8	19.3
Subtotal	40.4	40.5	37.4	35.8	33.3	33.1	26.7	36.4
Ancillary:								
Pipes	25.5	27.5	32.3	36.8	32.6	28.6	23.0	29.3
Pumps	3.8	4.0	2.9	2.9	3.3	2.5	5.8	3.3
Valves	3.4	9.0	5.4	7.6	10.2	8.9	10.2	6.9
Secondary containment	0.7	-	0.3	-	-	0.4	2.2	0.5
Other	9.8	5.3	4.3	4.3	4.7	5.7	0.9	6.1
Subtotal	43.2	45.8	45.2	51.6	50.8	46.1	42.1	46.1
Other:								
Fire/explosions	3.3	1.0	2.8	0.2	0.4	1.0	4.9	2.0
Weather-related/vandalism/other	7.4	7.2	6.8	7.2	7.1	10.6	13.8	8.2
Subtotal	10.7	8.2	9.6	7.4	7.5	11.6	18.7	10.2
Totals	100%	100%	100%	100%	100%	100%	100%	100%

[a] Derived from PIRS and SPCC nontransportation storage spills reported in Reference 21; represents 1975 to 1980.

to the EPA and the Coast Guard. The distribution of failure causes is by percentage for each spill size category and for all spill sizes. Although ancillary equipment failures and operational errors are clearly the dominating causes of failure in each spill size category, operational errors become progressively less dominant with increasing spill sizes. Containment device failures and failures from other causes are both more significant causes of failure for the larger (greater than 1000 gallons) reported spills.

As noted before, most of the above-ground waste oil tanks hold 500 gallons or less and do not include much ancillary equipment. For this reason, the high percentage of spill failures from ancillary equipment (in Table 2-3) is believed to be considerably overstated for most above-ground tank storage of waste oil. Based on the fault-tree analysis, ancillary equipment failures are estimated to represent less than 15 percent of the above-ground waste oil losses in small tank storage. On the other hand, operational errors appear to account for well over 50 percent of such losses. A rupture or leak in the tank, from whatever cause, accounts for the remaining small tank storage spills.

Causes for failure in the larger above-ground waste oil tanks (5000 gallons and larger) are expected to be related more closely, by percentage distribution, to those shown in Table 2-3; however, most of these larger tanks are believed to be surrounded by secondary containment.

A review of the "Damage Incidents Resulting From Used Oil Mismanagement" (from EPA) provided little additional insight into the causes of spills from above-ground storage. Spills of both oil and other materials are reported, but the causes and quantities are seldom noted. A faulty valve is noted in one tank spill incident, a tank rupture in another, and corrosion from tanks resting in oily water in another. These were the only causes of failure given for failures in above-ground tanks.

2.2.1.3 Drums--

Essentially no data were found on the frequency of waste oil losses from drums, which are used primarily by establishments that generate smaller quantities of waste oil. Industrial generators represent the largest sector using drum storage for waste oil. The general practice is to use drums if waste oil volumes are less than 500 gallons per month and to use below-ground tanks for greater volumes.[1] Establishments using drums to store waste oil are estimated to have an average of three 55-gallon drums each, which equals an average storage capacity of 165 gallons. Some drums are stored inside a building, but secondary containment systems are believed to be rare at drum storage sites. Because they are portable and relatively small, drums could be easily overfilled and overturned. They do not require the piping, pumps, valves, etc., associated with the filling and discharging of large tanks, however, and thus are not subject to the errors attendant with a mechanical fill-discharge system. It also seems reasonable to assume that, on the average, only about 50 percent of the available storage drums actually contain waste oil.

An estimate of drum spills can be made by applying the small tank loss probability (2.1 percent) from the fault-tree analysis to the estimated average number of drums containing waste oil. This produces an estimate of nearly 4500 spills annually, or just over 1 percent of all the drums used for waste oil storage. Whereas the number of spills seems large, a 1 percent probability of a spill of any size does not seem implausible.

It is also important to note that the maximum spill from a single drum is 55 gallons; therefore, although the total number of noncontained waste oil spills from drums may be greater than those from above-ground tanks, the point-source pollution dangers are generally not as great.

2.2.2 Magnitude of Losses

2.2.2.1 Below-Ground Tanks--

The investigation of underground waste oil leaks revealed that much less attention is being given to these leaks than to underground gasoline leaks. Consequently, much of the information on underground waste oil losses has been a byproduct of the attention given to gasoline losses. Some of the more significant reported gasoline leaks and other petroleum leaks from below-ground tanks in recent years are discussed.

In 1979, a loss of 30,000 gallons of gasoline from a service station in East Meadow, New York, was discovered.[27,30] The loss, which occurred over a period just exceeding one year, was from two tanks that held approximately 4000 gallons each. In 1980, a loss in excess of 30,000 gallons of gasoline from a service station in a suburb of Denver, Colorado, was discovered.[30] This loss occurred over a period of 3 to 4 years. A leak discovered in 1978 is speculated to have involved several million gallons of gasoline, fuel oil, and naphtha under Brooklyn, New York.[30] Some years ago a leak of 20,000 gallons of No. 2 oil was discovered under the terminal of a large oil company in the Boston, Massachusetts, area.[30]

The usual volume of gasoline lost in below-ground tanks in service stations is reported to range between 200 and 600 gallons.[33] One source says such losses generally are confined to 1000 gallons or less and that they occur over a period of no more than 3 or 4 months.[27] Nevertheless, it is evident that much larger losses could occur. Leaks often go undetected until the taste or smell of gasoline is noted in the water supply inside homes.

Despite the fact that considerable data exist on gasoline and other petroleum product losses from below-ground tanks, little data are available on waste oil losses. It is known, however, that several of the major oil companies now have tank testing and replacement programs for service stations under their ownership or control and that they test and replace waste oil tanks as well as gasoline tanks.[27,28,29] The gasoline tanks are of much greater concern because a typical station will have four or five such tanks with a total capacity of 20,000 gallons or more, compared with a single waste oil tank with a capacity of 500 gallons. Also, gasoline is much less viscous than oil and spreads through the soil much faster.

One oil company representative estimated that their service stations experience only about six incidents per year in which waste oil leaks migrate beyond the station's property boundaries.[27] He further indicated that most leaks involve only a few gallons per month before being detected. It is a common practice for this company (and others) to replace leaking waste oil tanks (now mostly steel) with new fiberglass units that are not troubled with corrosion problems.

Although the major oil companies have extensive tank replacement programs underway, they apparently control no more than 50 percent of the service stations[27,28,29] and less than 20 percent of all the below-ground waste oil tanks. Also, waste oil tanks used by industrial generators are normally many times larger than those in service stations. It is believed that the large quantity of underground waste oil storage at locations other than service stations receives little attention with respect to leakage until an obvious problem is detected.

Because most below-ground losses result from tank corrosion, leaks are probably very slow in the beginning and grow larger as the perforations caused by corrosion increase in size. The surrounding soil also can slow down the rate of flow from the tank. Some below-ground losses may go undetected for several years, as opposed to losses from above-ground tanks, which are usually more rapid and readily apparent.

More than 90 percent of the below-ground tanks have capacities of a few hundred gallons (typically 500 to 600 gallons). Discussions with waste oil collector-processors indicate that these tanks are usually emptied every 4 to 8 weeks and are never more than three-fourths full. This suggests that no more than 375 gallons of waste oil is placed in a 500-gallon tank each month and that this amount would represent the maximum potential loss. It is also probable that a leak of this magnitude would be readily noticed and reported by the waste oil collector.

Application of this logic to the typical 5000-gallon waste oil tank used by an industrial generator places the upper limit of potential loss at 3750 gallons per month. The probability of an underground waste oil loss of this magnitude seems to be very low compared with the larger gasoline losses listed earlier. The 30,000-gallon gasoline loss in East Meadow, New York, for example, is believed to have averaged no more than 2500 gallons per month, and this loss reportedly occurred from two 4000-gallon tanks.[27]

Although it is not currently possible to estimate the total quantity of waste oil losses from below-ground storage tanks, it is conceivable to assume that individual losses can range from the lower limits of detection (35 to 40 gallons per month) to 375 gallons per month from 500-gallon tanks and 3750 gallons per month from 5000-gallon tanks. Sufficient data are not available for obtaining an average loss, but the enormous number of leaking below-ground waste oil tanks makes underground waste oil losses a matter of utmost concern.

2.2.2.2 Above-Ground Tanks--

Very little documentation of waste oil losses is readily available, and such documentation rarely includes specifics on the magnitude of the losses. Several state agencies with apparently active waste oil regulatory and/or control programs were contacted.[34,35,36] In general, they reported the occurrence of a few oil spills, but indicated that details of these spills were not readily accessible from their files. Two recent spills were reported in Illinois; one (estimated to involve 500 gallons of waste oil) was caused by sabotage at a processor's operation, and the other (quantity unknown) was fire-related.[34] A groundwater contamination inventory in Michigan documents a few cases of apparent waste oil losses, but provides no quantity details.[37] Some of these losses may be from below-ground waste oil storage.

Discussions with collectors and collector-processors of waste oil also yielded relatively little information on waste oil spills.[3-19,38] One reported a spill of 500 gallons at his facility a few years ago. Another indicated a spill at his facility (prior to his ownership) of 10,000 gallons. Sabotage was the reported cause of the latter. Other spills at collector-processor facilities include one (reported by the owner) of 1000 to 1500 gallons and another reported to be between 3000 and 5000 gallons. Because these latter two spills were both contained on site, however, they reflect only potential tank losses.

Though minimal quantitative data were obtained on waste oil losses from above-ground tanks, a review of known waste oil storage characteristics and spills reported to the EPA and the U.S. Coast Guard proved to be useful.

The vast majority of above-ground waste oil storage tanks have capacities of 500 gallons or less, and collectors indicate that the contents of these tanks are usually emptied before the tanks are more than three-fourths full. Thus, maximum losses from 500-gallon tanks generally would be no greater than 375 gallons per incident if the losses were to occur just before scheduled collection of the tank's contents.

An estimated 10 to 15 percent of the above-ground waste oil tanks are much larger (5000 gallons and up). Many collector-processors have tanks that hold 20,000 to 50,000 gallons, and some have tanks that hold 250,000 gallons or more.[12-19] Discussions with selected collector-processors suggest that nearly all of these facilities have secondary containment, which lessens the probability of many offsite waste oil losses.[12-19] On the other hand, some establishments using primarily 5,000- to 10,000-gallon tanks may not have secondary containment. Again, based on the assumption that these tanks are not often filled to capacity, the maximum loss from a 10,000-gallon tank probably would be about 7500 gallons. Such a high loss would be expected only if failure occurred just before a scheduled waste oil collection.

Table 2-4 presents the nontransportation storage spill incidents reported to EPA (3000) and the U.S. Coast Guard (1300) by size and failure and the percentage of total spill incidents within each indicated spill size range. Table 2-5 presents these percentages both separately and in combination for the EPA and U.S. Coast Guard data.

Over 50 percent of the nontransportation storage spills reported to the EPA and the U.S. Coast Guard were under 250 gallons. Of the spills reported to the EPA, exactly 50 percent were less than 250 gallons; of the spills reported to the U.S. Coast Guard, 61 percent were less than this amount. Approximately 25 percent of the combined spills represented 1000 gallons or more. This would undoubtedly be high for waste oil spills because of the predominance of smaller waste oil tanks and the prevalence of secondary containment around the larger tanks. Even if each of the estimated 150 annual spills (losses) previously indicated for larger waste oil tanks amounted to 1000 gallons or more, this would represent only 21 percent of the total estimated spills from above-ground waste oil tanks.

The indicated distribution of spills is probably skewed toward the larger spill sizes because of a tendency for facilities not to report smaller spills of waste oil. Also, the spills reported in Tables 2-4 and 2-5 are judged to be from typically

TABLE 2-4. STORAGE SPILL INCIDENTS FROM EPA AND U.S. COAST GUARD DATA BASES[a]
(percent of total in each size category)

	Amount spilled, gallons							
	0-49	50-99	100-249	250-499	500-999	1,000-10,000	>10,000	Total
Containment devices:								
Tank rupture/leak	51	17	34	16	23	57	24	222
Tank corrosion	17	5	22	6	15	28	4	97
Subtotal	68	22	56	22	38	85	28	319
Operations:								
Tank overflow	194	74	153	79	82	140	20	742
Other	291	88	117	70	68	165	40	839
Subtotal	485	162	270	149	150	305	60	1,581
Ancillary:								
Pipes	306	110	233	153	147	265	52	1,266
Pumps	45	16	21	12	15	23	13	145
Valves	41	36	39	31	46	82	23	298
Secondary containment	9	-	2	-	-	4	5	20
Other	118	21	31	18	21	53	2	264
Subtotal	519	183	326	214	229	427	95	1,993
Other:								
Fire/explosions	39	4	20	1	2	9	11	86
Weather-related/vandalism/ other	89	29	49	30	32	98	31	358
Subtotal	128	33	69	31	34	107	42	444
Totals	1,200	400	721	416	451	924	225	4,337
Percent of Total Spill Incidents	28	9	17	10	10	21	5	100

[a] Based on PIRS and SPCC nontransportation storage spills reported in Reference 31.

TABLE 2-5. SIZE DISTRIBUTION OF SPILLS REPORTED TO EPA (1975-1980) AND U.S. COAST GUARD (1974-1980)

Spill size, gallons	Spills reported to EPA, percent	Spills reported to U.S. Coast Guard, percent	Weighted average,[a] percent
0-49	24	37	28
50-99	9	9	9
100-249	17	15	17
250-499	10	8	10
500-999	12	8	10
1,000-9,999	23	18	21
>10,000	5	5	5
Total	100	100	100

[a] A weighted average is represented to reflect the much greater number of spills reported to EPA.

larger storage facilities than those predominantly used for waste oil storage because of the large number of reported spills resulting from ancillary equipment failures. Thus, it is quite likely that the median waste oil spill from above-ground tanks is considerably below 250 gallons. This is further substantiated by the fact that the typical 500 gallon above-ground waste oil tank is expected to be only about 30 percent full on the average. The loss of the entire contents from a tank that is at 30 percent of capacity would constitute only 150 gallons.

A reasonable estimate of the total quantity of waste oil losses from above-ground tanks is not obtainable from currently available data. Such a determination might be possible if tank size were included in the EPA and Coast Guard spill data. Determination of typical time frames over which losses occur is also impossible without additional data.

2.2.2.3 Drums--

It was previously estimated that 4500 spills (or losses) of waste oil from drums occur annually. The maximum loss from a single typical drum is 55 gallons, but a given incident could, of course, involve more than one drum. On the average, establishments that use drums for waste oil storage are estimated to have three drums each, but some have a much larger number.

The following 11 reported drum spill incidents were documented by EPA[31]:

Amount spilled	Number of spills
0-49 gallons	5
50-99 gallons	2
100-249 gallons	2
500-999 gallons	1
1,000-10,000 gallons	1

Although these reported drum spills are too few in number to serve as a valid indication of the magnitude of most drum spill incidents, they do indicate that such incidents can involve 500 to 1000 gallons or more. If it is assumed that the full 55-gallon capacity of each of the 4500 drums (estimated as spilled annually) is lost, the total waste oil loss from drums would be 247,500 gallons, which is as much as (or possibly more than) the expected annual loss from above-ground oil tanks. It is unrealistic, however, to assume that each drum spill results in the loss of the full 55 gallons it can hold.

Generally, the magnitude of individual drum spill incidents is judged to be less than that of spill incidents involving above-ground tanks. Therefore, there is less potential for severe point-source pollution from drum storage spills.

2.3 SUMMARY

This section has characterized waste oil storage in the United States. The following subsections summarize the information presented in this chapter.

2.3.1 Sources and Composition of Waste Oil

Waste oil can generally be divided into two categories: automotive/diesel and industrial. Automotive/diesel waste oils are primarily crankcase oils generated by cars, trucks, and other vehicles. Contaminants in these oils include barium, chromium, and lead, the contaminant of greatest concern. Polynuclear aromatic compounds (PNA's) are also contained.

Industrial waste oils are generated from industrial sources and include metal working, hydraulic process, electrical, refrigeration, and turbine oils. These waste oils may contain a wide range of contaminants, including halogenated solvents, aromatic solvents, PCB's, and heavy metals (cadmium, chromium, and zinc).

2.3.2 Waste Oil Storage Types and Quantities

Waste oil is stored by the generators and those who collect and process the oil. The total amount of waste oil in storage is estimated to be 173 million gallons. Automotive/diesel oil generators store an estimated 64 million gallons; industrial generators store an estimated 41.7 million gallons; and collectors and collector-processors store an estimated 67.8 million gallons of both waste oil categories.

Waste oil is stored in below-ground tanks, above-ground tanks, and 55-gallon drums. Most storage tanks are made of steel, but major oil companies have recently been replacing steel below-ground tanks with fiberglass tanks. Although tank sizes vary widely, the majority of tanks (both below-ground and above-ground) hold 500 gallons or less. Many industrial waste oil generators, however, use tanks that hold several thousand gallons, and some collector-processors use tanks that hold a few hundred thousand gallons.

Below-ground tanks account for nearly one-half of the stored waste oil, and above-ground tanks for about 44 percent. The remainder is stored in drums.

2.3.3 Waste Oil Losses

Losses of stored waste oil occur far more frequently from below-ground tanks than from above-ground tanks or drums. It is conservatively estimated that 12 to 14 percent of the below-ground tanks containing waste oil (or 43,500 tanks) are leaking, whereas, the estimated annual probability of loss from above-ground waste oil storage facilities is under 2 percent (or 700 loss events annually). The estimated annual probability of loss from drums is just over 1 percent (or 4,500 loss events).

Losses from below-ground waste oil storage tanks are caused primarily by external tank corrosion. Losses from other causes (including internal tank corrosion) are few by comparison. The causes of losses from above-ground waste oil storage tanks are numerous. In general, operational errors account for the majority of failures in above-ground storage facilities with smaller tanks (under 500 gallons each) and drums, whereas failures of ancillary equipment (pumps, valves, pipes, etc.) are the predominant causes in facilities with larger above-ground tanks.

Little information is available on the magnitude of waste oil losses, and realistic estimates cannot be made of typical or average losses. Those who collect waste oil indicate that tanks are seldom more than 75 percent full at the time of collection, which limits the maximum spill from an above-ground tank. The smaller tanks are estimated to be only 30 percent full, on the average, which limits the average spill size. Many spills are probably stopped before a tank is emptied, and others may be stopped before the loss reaches a significant proportion.

Losses from below-ground tanks are different from those from above-ground tanks. Most below-ground losses begin as slow leaks. The size of these leaks increases with time, but the leaks may go undetected for years. Few of these leaks are expected to receive any attention until an obvious problem occurs or the collector observes a noticeable change in the amount collected.

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SECTION 3

ENVIRONMENTAL FATE OF WASTE OIL LOST FROM OIL STORAGE SITES

This section is concerned with the fate of the waste oil that is released into the environment by leaks or spills from storage sites. The rate and degree of contamination from typical and worst-case spills are examined. Losses may be from slow leaks, which go undetected for long periods of time, or from catastrophic spill incidents. The models used to estimate environmental pollution consider the spill conditions, including the oil and soil types, distance to groundwater, and time from spill to detection.

3.1 MECHANISMS OF WASTE OIL MOVEMENT

Waste oil may leave an oil storage site by one or more of three mechanisms: evaporation, surface runoff, and seepage into the soil. The degree of concern for the environment as waste oil and its contaminants leave an oil storage site by one or more of these mechanisms depends on the type and composition of waste oil, type of spill or leak, type of oil storage system, and the climatic conditions.

The processes of evaporation, runoff, and seepage occur simultaneously, and all may be of environmental concern in the event of surface spills. Evaporation and runoff are rarely of concern in subsurface leaks, which occur primarily from below-ground tanks, but sometimes from the bottom of above-ground tanks. Evaporation and seepage are continuous processes following a surface spill, whereas runoff is more intermittent in nature, e.g., rainfall runoff.

Each of the three movement mechanisms is discussed in the following subsections. Because seepage is the primary mechanism for the movement of spill oil, it is examined in more detail than the other two.

3.1.1 Evaporation

Evaporation is the process by which waste oil and contaminants are vaporized, which enables them to leave the oil storage site in gaseous form. The organic vapors from waste oil spills can cause deterioration of air quality.

Ambient air concentrations of organic vapors from oil-covered road surfaces have been modeled in a related study.[1] Both the rate of evaporation of the waste oil components and the distribution and resultant ambient air concentrations were modeled. Environmental contamination levels were calculated for the following components: arsenic, barium, cadmium, chromium, lead, zinc, dichlorodifluoromethane, trichlorotrifluoroethane, trichloroethane, tetrachloroethylene, benzene, toluene, xylene, benzo(a)anthracene, benzo(a)pyrene, naphthalene, and PCB's. Model outputs indicate that ambient levels are not likely to pose a threat to human health.

The mechanism of evaporation from surface spills of waste oil will differ from that of evaporation of waste oil applied to a road surface because of the formation of pools of oil within secondary containment systems. Nevertheless, the overall magnitude of oil evaporation should be similar to or less than evaporation from road surfaces. Because evaporation of spilled waste oil is not likely to pose a threat to human health, it is not considered further within this report.

3.1.2 Rainfall Runoff

Oil and waste oil components that are spilled from aboveground tanks and drums may contaminate surface waters. Rainfall and subsequent surface runoff may carry colloidal oil, dissolved oil components, and oil adsorbed onto soil particles. Oil may be washed from the spill area or it may be carried with water as a surface film or as a colloid. Oil that has seeped into the soil cannot be easily or rapidly washed off by rainfall, but as the rain seeps into the soil, it can displace the oil and cause it to float to the surface, where it can be washed away. Rainfall runoff is generally limited to spills that occur where there is no secondary containment system. Most commonly it will involve small spills from 55-gallon drums. Most large spills are already regulated under the Spill Prevention, Control, and Countermeasures (SPCC) plan. Because this study is concerned with contamination from unregulated oil spills, environmental contamination due to rainfall runoff is not considered further in this report.

3.1.3 Seepage

Seepage of oil (i.e., slow movement of oil through the pore spaces of the soil) from waste oil storage sites is the primary mechanism of oil movement from a waste oil storage site. Seepage is especially important because it is often a gradual process that may go undetected for years and can result in significant environmental contamination.

3.1.3.1 Oil Movement--

Movement of oil through the soil is limited either by the rate of oil loss from the storage system or by the nature of the soil environment. When the rate at which oil enters the soil exceeds the rate at which it can pass through the soil, soil characteristics control the rate of movement. In some situations, however, the rate of oil release may be the variable controlling oil migration rates, e.g., when the leak rates are very low or the soil is highly permeable.

As oil enters the soil environment, it gradually coats available soil surfaces, and if enough oil is present, it fills the pore spaces within the soil. The oil then moves gradually downward or laterally, following the path of least resistance until a boundary is encountered. One such boundary is the groundwater table. When the oil encounters the groundwater, it spreads laterally, floating on the groundwater surface. Although some dissolution of the oil components in water will occur, this is a slow process because of the low solubilities of oil components. The solubility of oil and its contaminants in water is not addressed in this study.

3.1.3.2 Fate of Oil Components--

During oil migration, some interaction can be expected to occur between oil components and soil particles. This process, known as attenuation, usually involves the retention of selected oil components on soil particles while the main body of oil continues to migrate. This results in the reduction of the concentrations of some oil components during soil migration. The extent of such reductions cannot be predicted readily because of the variety of factors that influence the interactions between oil and soil particles. Two major generalizations can be made, however: 1) positively charged ions and some polar organics (e.g., trichloroethylene and most organo-metallic compounds) tend to be adsorbed onto soil particles that have a negatively charged surface (e.g., clay); and 2) nonpolar organic compounds (e.g., benzene or xylene) are more readily attenuated by soils that are high in organic matter. Because organic soils are generally located within a few feet of the surface, attenuation of nonpolar organics should be fairly limited. In the case of clay-type soils (which extend much deeper), metals attenuation and attenuation of some polar organics should continue throughout the oil migration processes.

3.1.3.3 Effect of Organics on Soil Permeability--

Recent research has provided evidence that several organic liquids may have a significant effect on the permeability of clay soil.[2,3,4] Both laboratory and field studies have been undertaken to examine the permeability of compacted clay liners exposed to organic liquids. Initial laboratory tests examined permeability changes when the liners were exposed to a xylene paint solvent waste and a contaminated acetone waste.[4] The three types of clay liners tested consisted of selected clay minerals mixed with sandy loam soil to achieve permeabilities to water normally considered acceptable for waste impoundments ($\leq 10^{-7}$ cm/s). The results of the tests indicated that permeabilities of the clay liners were 2 to 3 orders of magnitude greater for these waste materials than for water; thus the liquids continued to move through the soils at a relatively rapid rate.

Subsequent tests were conducted for several other organic liquids, including diesel fuel and parafin oil.[3,5] All of the liquids have reportedly caused changes in the clay soil. The soil changes that resulted in liner failures may have been caused by reactions that dissolve portions of the soil or by reactions that remove water from the soil and produce changes in soil volume changes.[3] Reactions caused by the organic liquid may increase soil pore openings and/or cracks in the soil and thereby increase the permeability.

The measured permeabilities with parafin oil and diesel fuel were also approximately 2 to 3 orders of magnitude greater than for water.[5] This suggests that oil could flow through a clay liner between 100 and 1000 times faster than water.

The results of this recent research are believed to be of considerable importance to this study with respect to the estimated effectiveness of clay liners in containing waste oil spills.

Whereas the use of equations may indicate that soil liners of only a few inches thickness should contain an oil spill for years (or perhaps even hundreds of years), evidence would seem to indicate the contrary. Actually, it may be optimistic to count on a soil liner to contain a waste oil spill.

Although these experiments[3,5] were not performed on waste oil, they certainly raise important questions about the influence of contaminated waste oil on soil characteristics. The remainder of this analysis is based on the assumption that the use of traditional soil parameters is valid; however, future research may show that this is not the case.

3.1.3.4 Residual Saturation--

As soon as oil is spilled onto a soil surface, it begins to seep into the soil. Once the pool of oil at the surface has been exhausted, saturated flow (i.e., flow in which all the voids are filled with oil) ceases and unsaturated flow begins. Even though all the pores are not filled in the saturated flow mode, oil will continue to migrate downward, coating soil particles as it travels. Some residual oil will remain coated on the particles and some will fill the dead-end spaces. Eventually, oil migration stops completely because all of the oil is coated on soil particles or trapped in pore spaces. The oil that remains after migration has ceased is referred to as residual saturation. In theory, stability occurs when the residual saturation level is reached. Whereas the potential for some soluble components to reach the water table remains, the threat is far less than it would be had the oil reached the groundwater surface. Therefore, reduction to the residual saturation level before reaching the water table removes much of the pollution risk. The amount of residual oil in soil pores varies according to type of oil, soil type, and moisture content, but up to 20 percent of the void space may be occupied by residual oil.

3.2 ABOVE-GROUND TANKS

Oil loss from above-ground tanks may result from surface spills or leaks in the tank bottoms. Surface spills may be uncontrolled or they may be contained within a secondary containment system. Uncontrolled spills are not considered in this report because most are already regulated by SPCC Plans. Seepage is the mechanism of oil movement that is of concern when tank bottom leaks or contained surface spills occur. Evaporation of surface spills will occur, but it is of less concern for reasons described previously.

3.2.1 Surface Spills Within Secondary Containment Systems

Surface spills that occur within a secondary containment system are prevented from leaving the site by a berm (earthen ridge), lagoon, or some other system. The oil generally forms a pool, the deepest part of which is adjacent to the berm or dike wall. In many cases, the bottom of the diked area consists of natural soils, so some seepage can be expected to occur.

Seepage is affected by soil characteristics, oil properties, the nature of the spill, and time until oil cleanup. The Green-Ampt equation[6] can be used to describe the seepage process (Appendix B). The Green-Ampt model, developed in 1911 and normally used for water, approximates the dynamics of the liner infiltration event. In this analysis, the Green-Ampt model has been used to calculate the effectiveness of the secondary containment system in preventing the spilled oil from reaching the groundwater.

Three major soil types are considered: clay, silt, and sand. For each soil type, values of soil parameters (porosity, soil moisture, and relative conductivity) were chosen to simulate low-permeability, high-permeability, and average-permeability soil. Literature agreement is poor regarding the value of one of the parameters of the Green-Ampt equation--capillary force. Capillary force is a surface tension phenomenon that tends to attract liquids to soil and therefore increases the speed of oil propagation. Capillary forces are largest for dry soils. Because of the scatter in the literature data, a range of capillary force values (negative numbers listed in Appendix B) was used in this analysis.

Table 3-1 presents the Green-Ampt calculations in terms of the time it would take for a spill with a liquid depth above the soil of 10, 30.5 , or 50 centimeters to penetrate the soil to a depth of 30.5 centimeters (12 inches). The large variation of times for a specific soil and spill depth is a consequence of the uncertainty in capillary force values. High-permeability soils

TABLE 3-1. TIME REQUIRED FOR PENETRATION OF SPILLED OIL TO A DEPTH OF 30.5 cm (12 inches) FOR VARIOUS SOIL TYPES[a]

Soil type	Spill depth, cm	Low soil permeability		High soil permeability		Average soil permeability	
		Low	High	Low	High	Low	High
		Time, years		Time, years		Time, years	
Clay	10.0	5,700	176,000	8.56	264	38.2	1,180
	30.5	5,620	115,000	8.42	173	37.6	772
	50.0	5,530	87,100	8.29	131	37.0	583
		Time, years		Time, days		Time, days	
Silt	10.0	23.5	202	1.37	11.8	3.24	27.9
	30.5	21.9	122	7.28	7.17	3.02	16.9
	50.0	20.6	89.5	1.20	5.21	2.84	12.3
		Time, days		Time, min		Time, min	
Sand	10.0	2.23	3.98	7.55	13.5	12.5	22.3
	30.5	1.61	2.34	5.46	7.92	9.03	13.1
	50.0	1.28	1.69	4.32	5.73	7.16	9.48

[a] Calculations based on soil seepage factors listed in Table B-4 of Appendix B.

represent the worst-case scenarios, and the highly negative values for capillary force result in the fastest rates of oil penetration into the soil. Worst-case times for clays indicate a minimum of 8 years to reach a 12-inch (30.5-cm) soil depth, whereas times for sand are as low as 6 minutes, and for silt, are generally measured in days.

3.2.2 Tank Bottom Leaks

Above-ground tanks may develop leaks anywhere on their surfaces, but visible leaks should be detected and repaired quite rapidly. Leaks that occur on the tank bottoms, however, may go undetected for long periods of time. Seepage of oil as it leaves the tank bottom can be described by use of the Green-Ampt equation. The ranges of soil and oil characteristics are the same as described for above-ground spills (Section 3.2.1), but the head within the tank greatly exceeds that which could occur in a secondary containment system. Ranges of typical tank sizes and levels of contained oil are given in Table 3-2. These values have been used to determine probable times of migration to the groundwater table for depths of 100 and 1000 centimeters (Tables 3-3 and 3-4). The range in times listed for a given type of soil results from using a range of capillary force values, as described in the previous section.

Leak rates from the tanks have not been estimated for this part of the calculations because it has been assumed that soil characteristics will control the rate of oil flow under worst-case conditions.

TABLE 3-2. ABOVE-GROUND TANK SIZES AND TYPICAL OIL LEVELS

	Tank size, gallons	Typical configuration, height:diameter	Typical height, meters	Typical oil level, meters
Vertical tank	10,000	3:1	9	6
	25,000	2:1	8	5
	50,000	1.5:1	8	5
	200,000	1:1	6	4
Horizontal tank	10,000	1:3	3	2
	25,000	1:2	4	2.5

TABLE 3-3. OIL MIGRATION TIME FROM AN ABOVE-GROUND TANK TO A WATER TABLE 100 CENTIMETERS DEEP[a]

Soil type	Tank head, cm	Low soil permeability		High soil permeability		Average soil permeability	
		Low	High	Low	High	Low	High
		Time, years		Time, years		Time, years	
Clay	200	51,500	274,000	77.2	411	344	1,830
	500	42,700	131,000	64.1	196	286	877
	750	37,400	91,300	56.2	137	251	611
		Time, years		Time, days		Time, days	
Silt	200	137	264	8.02	15.7	18.9	36.4
	500	86.7	124	5.07	7.25	12.0	17.1
	750	66.4	86.3	3.88	5.04	9.16	11.9
		Time, days		Time, min		Time, min	
Sand	200	4.49	4.88	15.2	16.5	25.2	27.4
	500	2.20	2.29	7.46	7.76	12.3	12.8
	750	1.54	1.59	5.24	5.38	8.67	8.91

[a] Calculations based on soil seepage factors listed in Table B-4 of Appendix B.

TABLE 3-4. OIL MIGRATION TIME FROM AN ABOVE-GROUND TANK TO A WATER TABLE 1,000 CENTIMETERS DEEP[a]

Soil type	Tank head, cm	Low soil permeability		High soil permeability		Average soil permeability	
		Low	High	Low	High	Low	High
		Time, years		Time, years		Time, years	
Clay	200	3,710,000	9,530,000	5,560	14,300	24,800	63,800
	500	3,220,000	6,730,000	4,840	10,100	21,600	45,100
	750	2,910,000	5,460,000	4,366	8,190	19,500	36,600
		Time, years		Time, days		Time, days	
Silt	200	6,700	9,030	391	527	2.53	3.41
	500	5,160	6,360	301	371	1.95	2.40
	750	4,340	5,140	254	300	1.64	1.94
		Time, days		Time, min		Time, min	
Sand	200	161	166	9.08	9.39	15.0	15.5
	500	114	117	6.46	6.60	10.7	10.9
	750	93.0	94.6	5.25	5.34	8.70	8.85

[a] Calculations based on soil seepage factors listed in Table B-4 of Appendix B.

Migration times are strongly influenced by both soil type and permeability. The longest migration calculated times are for clay soils, followed by silt. Migration of oil through sand is the most rapid. In general, low soil permeabilities result in much longer migration time. Factors that reduce the permeability of soils to oil are high moisture content, low porosity, and low relative conductivity.

There is a nonlinear relationship between the water table depth and the time to reach the water table. Tables 3-3 and 3-4 show that it takes much more than 10 times longer for oil to migrate 1000 centimeters than to migrate 100 centimeters. Actually, it usually takes almost 100 times as long. This nonlinearity results from the fact that the hydraulic gradient (rate of change of head with depth below the surface) varies in a nonlinear fashion.

3.3 BELOW-GROUND TANKS

Storage tanks that are located underground are subject to develop leaks. The rate at which oil leaves the tank is determined by the head of oil within the tank, the size of the leak, and soil characteristics. For the purposes of this analysis, it has been assumed that soil characteristics rather than leak size are the primary factors controlling the rate of oil migration. Once again, the Green-Ampt equation (Appendix B) is used to describe oil movement through the soil environment. The range of soil and oil characteristics is the same as used in previous analyses (Table 3-5).

TABLE 3-5. OIL MIGRATION FROM A BELOW-GROUND TANK TO A WATER TABLE 100 CENTIMETERS DEEP[a]

Soil type	Tank head, cm	Low soil permeability		High soil permeability		Average soil permeability	
		Low	High	Low	High	Low	High
		Time, years		Time, years		Time, years	
Clay	60	56,900	568,000	85.4	851	381	3,800
	120	54,500	388,000	81.7	582	365	2,598
	180	52,200	296,000	78.3	443	350	1,980
		Time, years		Time, days		Time, days	
Silt	60	189	338	11.0	32.9	26.0	77.7
	120	163	227	9.49	22.0	22.4	52.1
	180	143	171	8.34	16.6	19.7	39.3
		Time, days		Time, min		Time, min	
Sand	160	8.81	10.7	29.9	35.6	49.4	59.0
	120	6.22	7.09	21.1	23.8	34.9	39.3
	180	4.82	5.32	16.3	17.9	27.1	29.6

[a] Calculations based on soil seepage factors listed in Table B-4 of Appendix B.

Results are very similar to those for above-ground tanks, as would be expected. Once again, soil permeability is the major factor influencing migration rates. The differences between predicted migration times for above- and below-ground tanks are the result of differences in the head or oil depth typically found in the two tank types. Above-ground tanks are taller, and the increased head results in slightly faster migration times than those predicted for below-ground tanks.

3.4 SPILLS FROM CONTAINERS AND DRUMS

This analysis evaluates the extent of soil contamination resulting from spills or leaks from establishments that store waste oil in drums and have no secondary containment systems. Approximately 12 million gallons of waste oil is stored in drums (primarily 55-gallon drums) at more than 141,000 sites. The contaminated soil volume and depth of oil penetration resulting from spills are calculated.

Two spill scenarios are considered: 1) a catastrophic spill resulting in a sudden loss of waste oil stored on the site, and 2) the cumulative effect of a number of sequential spills such as might occur during a drum-filling operation.

3.4.1 Catastrophic Spills

The average number of waste oil drums per site is three, although some have as many as 10. Thus the maximum amount of oil that could be spilled in a single incident (e.g., vandalism or fire) is 550 gallons. A typical drum storage quantity is considered to be four drums (220 gallons), and that is the amount used in the models described in this section.

When a spill occurs at a site that has no secondary containment, oil will flow in the direction of the slope of the land. It will spread and form a thin layer over the surface; the area covered will depend on the type of land surface and the viscosity of the oil. The model used for this analysis is a simple one that was developed for Arctic regions based on data from spills in Canada.[7]

$$A_s = 53.5\ V_s^{0.89} \qquad \text{(Eq. 1)}$$

where

A_s is the spill area in square meters.

V_s is the spill volume in cubic meters

In the more temperate regions of the continental United States, the spill area may be considerably larger because of the warm weather and the resulting lower oil viscosity. When the spill area from Equation 1 is used, a worst case for oil penetration into the soil may be approximated, because as the soil area decreases with a constant volume, the depth of penetration increases. The spill area (as calculated from Equation 1) for spills up to 550 gallons is shown in Figure 3-1 as a function of spill volume. Typical spill areas range from 13 square meters (140 square feet) for a 55-gallon spill to 45 square meters (490 square feet) for a 220-gallon spill. These areas result in an average spill depth of 1.6 cm (0.63 in.) for a 55-gallon spill and 1.8 cm (0.71 in.) for a 220-gallon spill. The model assumes

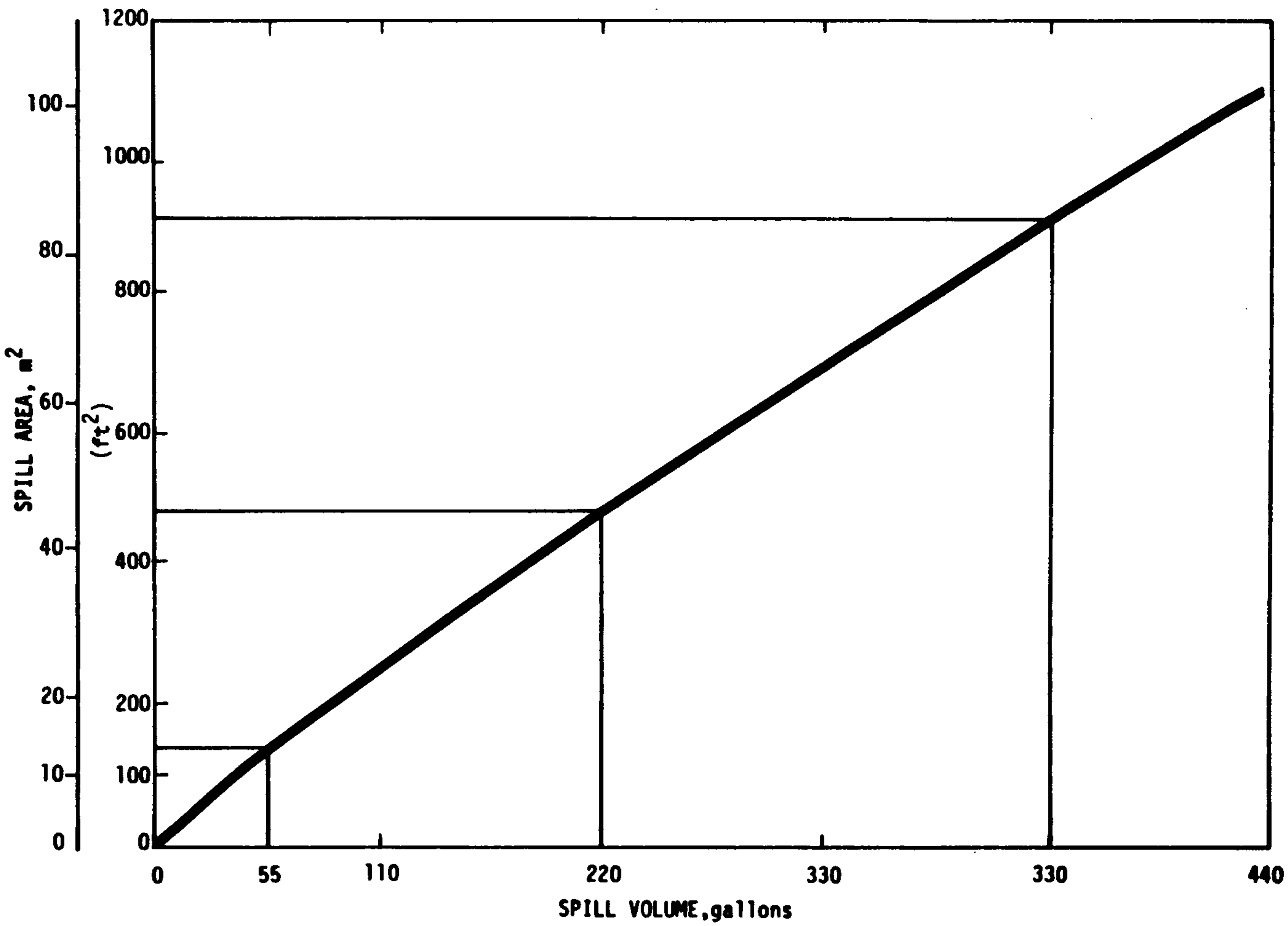

Figure 3-1. Spill area versus spill volume for oil spills without secondary containment.

that the spill is so abrupt that the liquid spreads out before significant quantities penetrate the soil.

The movement of oil through soil has been described by Van Dam,[8] Schwille,[9] and Dietz.[10] The Green-Ampt equation is not used for noncontained spills because the liquid head above the surface is continuously changing and is equal to zero soon after the spill. After the spilled oil enters the soil, it begins to seep vertically downward under the influence of gravity (with some lateral movement) until saturated flow conditions are met. When all of the spilled oil has entered the soil, the oil will continue to move downward under unsaturated flow conditions, and some of the oil will be left behind as it passes through the soil. Oil movement will eventually cease, and coated soil with part of the pore spaces filled will be left behind. Residual saturation levels for oil in soil have been measured for several oil types.[10] These levels, which are expressed as a fraction of total spaces in the soil that are filled with oil, are 0.2 for lube oil and heavy fuel oil; 0.15 for diesel and light fuel oil; and 0.10 for light oil or gasoline.

Assuming the spilled oil has completely soaked into the soil and that the groundwater level is deeper than the soil penetration depth, the volume of oil-contaminated soil depends on the soil porosity and the residual saturation according to the following relationship:

$$V\ soil = \frac{V_s}{nS_r} \qquad \text{(Eq. 2)}$$

where

V_{soil} = Volume of oil-contaminated soil, m^3

V_s = Spill volume, m^3

n = Soil porosity or ratio of void space to total soil volume after correction for moisture content

S_r = Residual saturation

In Figure 3-2, the volume of contaminated soil is plotted as a function of spill volume for soil porosity of 50 percent (typical for clay) and residual saturations of 0.2, 0.15, and 0.1. The worst case for volume of contaminated soil occurs with light oil because the residual saturation of this oil is the lowest. Typical volumes for light oil range from 4.2 cubic meters (148 cubic feet) for a 55-gallon spill to 16.7 cubic meters (590 cubic feet) for a 220-gallon spill.

The volume of contamination is a function of the type of soil, in that a more porous soil holds more oil and, therefore, less total volume of soil is contaminated as a result of a spill of a given size.

Table 3-6 lists representative porosity ranges for dry gravel, sand, silt, and clay. The effective porosity for the purposes of calculating saturated soil volume is obtained by subtracting the soil moisture content from the porosity of the dry soil.

The effect of porosity of contaminated soil volume is shown in Figure 3-3. A spill volume of 220 gallons was assumed for this analysis. Over 33 cubic meters (1165 cubic feet) of low-porosity sand or gravel may be contaminated with a 220-gallon

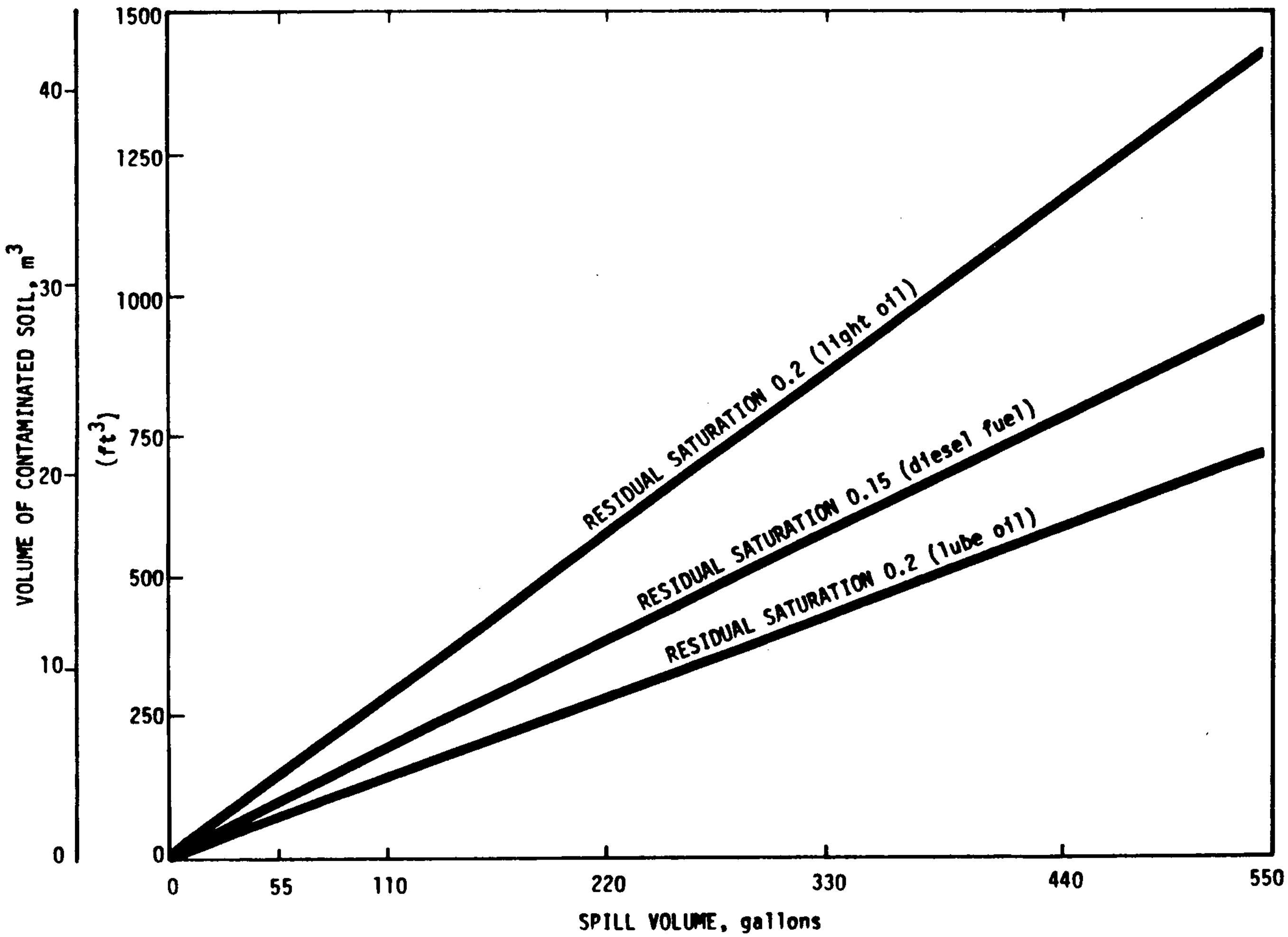

Figure 3-2. Volume of saturated soil versus spill volume for a soil porosity of 50 percent.

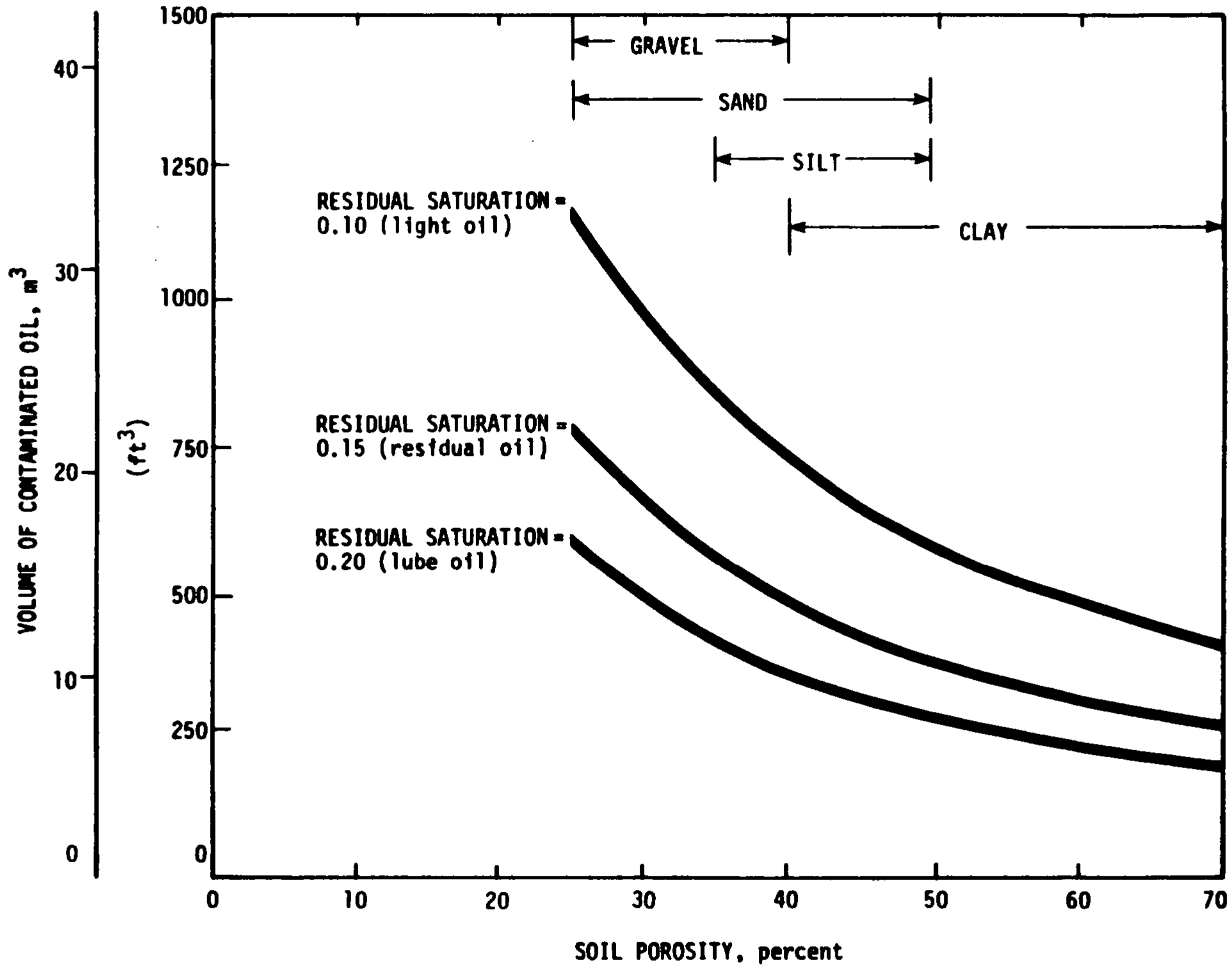

Figure 3-3. Volume of contaminated soil versus soil porosity for a spill volume of 220 gallons.

catastrophic spill of light oil or gasoline. On the other hand, if the spill is on a highly porous clay, the contaminated soil volume would be only 12 cubic meters (424 cubic feet). The range for a lube oil spill of 220 gallons is from 16.7 cubic meters (590 cubic feet) for a low-porosity sand to 6 cubic meters (212 cubic feet) for a porous clay.

TABLE 3-6. RANGE OF VALUES OF POROSITY[a]

Soil type	Porosity, %
Gravel	25-40
Sand	25-50
Silt	35-50
Clay	40-70

[a] Source: Reference 11, p. 37.

The maximum depth reached by the spilled oil is obtained by assuming there is no lateral flow and that the groundwater level is too deep to be reached by the oil. In this case, the contaminated soil volume can be approximated by a cylinder. Because the volume of a cylinder is equal to the area of its base times its height, Equation 2 can be rewritten as follows to determine the depth:

$$d_s = \frac{V_{soil}}{A_s} = \frac{V_s}{nS_rA_s} \qquad \text{(Eq. 3)}$$

where

d_s = Spill penetration depth, m

V_{soil} = Volume of oil-contaminated soil, m^3

V_s = Spill volume, m^3

n = Soil porosity corrected for moisture

S_r = Residual saturation

A_s = Area of the oil spill, m^2

The depth of penetration for a 220-gallon spill is shown as a function of soil porosity in Figure 3-4 for residual saturations of 0.1, 0.15, and 0.20. Typical porosity ranges for gravel, sand, silt, and clay are indicated on the figure. The maximum penetration depth is obtained when light oil is spilled on a low-porosity sand or gravel, where the depth of penetration is 0.73 meter (2.4 feet). At the other extreme, a spill of lube oil on a porous clay results in a penetration depth of 0.26 meter (0.86 foot).

In most oil spills some horizontal spreading will occur as a result of capillary forces and produce a coning effect; therefore, penetrations will be shallower than shown in Figure 3-4. The angle of the resulting cone of contaminated soil depends on soil characteristics. Low-permeability soils (such as clay and some silts) generally result in more horizontal spreading. Quantitative experimental data are limited, but laboratory model experiments by Schwille[9] have demonstrated that minor differences in permeabilities laterally or vertically can produce strong distortions in the shape of the oil migration zone. Undisturbed soils may exhibit permeabilities 10 or more times greater in one direction than the other. In general, fluvial deposits (deposits laid down by physical processes in river channels or floodplains) have

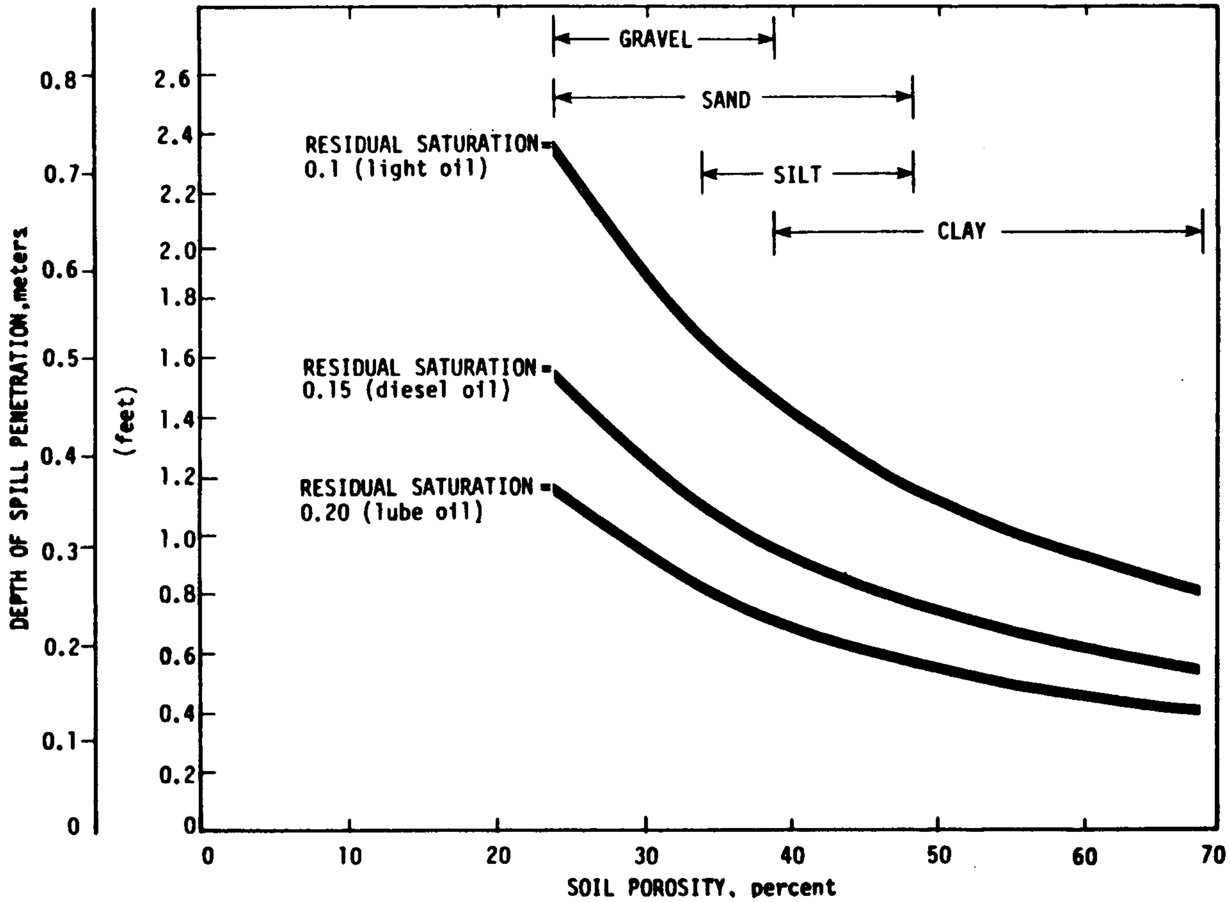

Figure 3-4. Depth of spill penetration versus soil porosity for a catastrophic spill of 220 gallons. Spill area is 45 square meters (489 square feet).

higher horizontal permeabilities and aeolian deposits (materials that are transported and deposted by wind) have higher vertical permeabilities.[11] The shape of the contaminated soil volume in an aeolian soil can be closely approximated by a cylinder. In a homogeneous, isotropic soil, a cone angle of approximately 45 degrees, with a rounding of the leading front, may be expected. Of course, fractures, root channels, and animal burrows can cause a secondary permeability in the vertical direction that would result in even much greater depths than those calculated by assuming a cylindrically shaped zone.

The sensitivity of penetration depth to cone angle can be calculated by the following equation:

$$d_s = \left[\frac{3V_{soil}}{\pi \tan^2\phi} + \frac{r^3}{\tan^3\phi}\right]^{1/3} - \frac{r}{\tan \phi} \qquad \text{(Eq. 4)}$$

where

d_s = depth of spill penetration, m

V_{soil} = volume of oil-contaminated soil, m^3

ϕ = 1/2 angle of the cone (see Figure 3-5)

r = spill radius on the surface, m (see Figure 3-5)

A derivation of Equation 4 is based on the cone as shown in Figure 3-5. See Appendix C for the derivation.

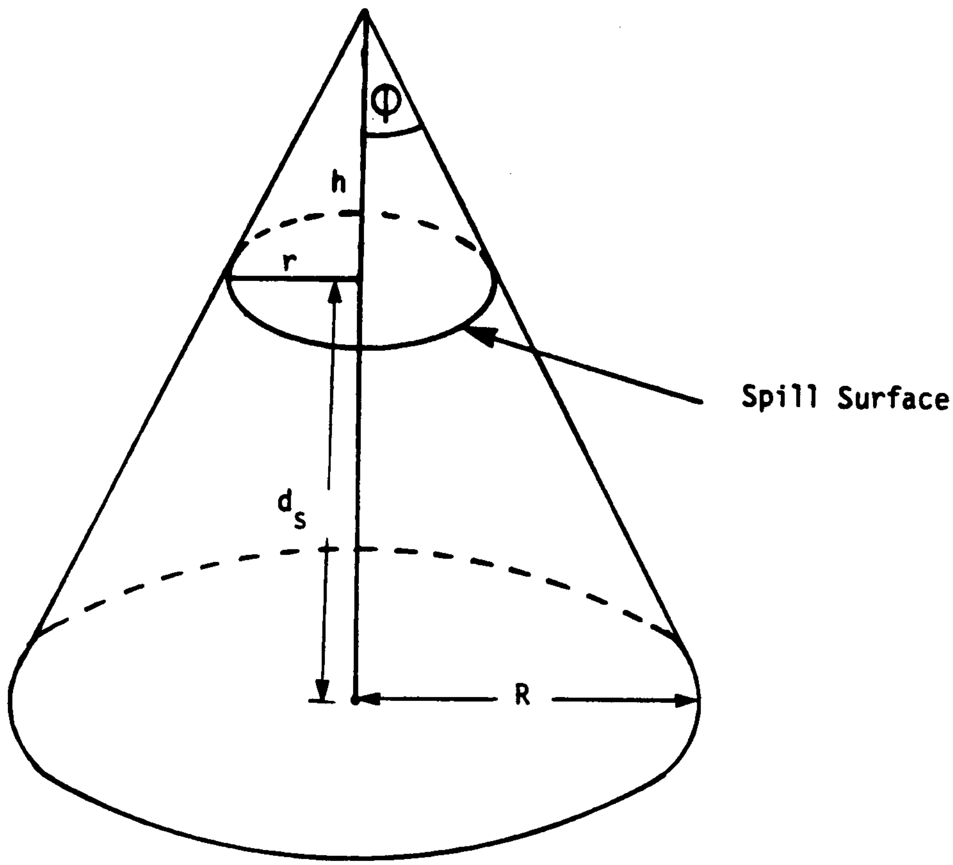

Figure 3-5. Geometry of cone assumed for calculating penetration depths.

Figure 3-6 shows how the depth of spill penetration varies with cone angle for a residual saturation of 0.1 (typical for light oil or gasoline). For the rather shallow depths under these conditions (less than 1 meter), a cone angle up to 45 degrees affects the maximum depth by less than 20 percent.

Based on the analysis above, a single catastrophic spill from a waste oil drums storage location should not result in groundwater contamination. A worst-case spill, where four 55-gallon drums are spilled on low-porosity sand or gravel, results in a large area of surface spread, but even without lateral

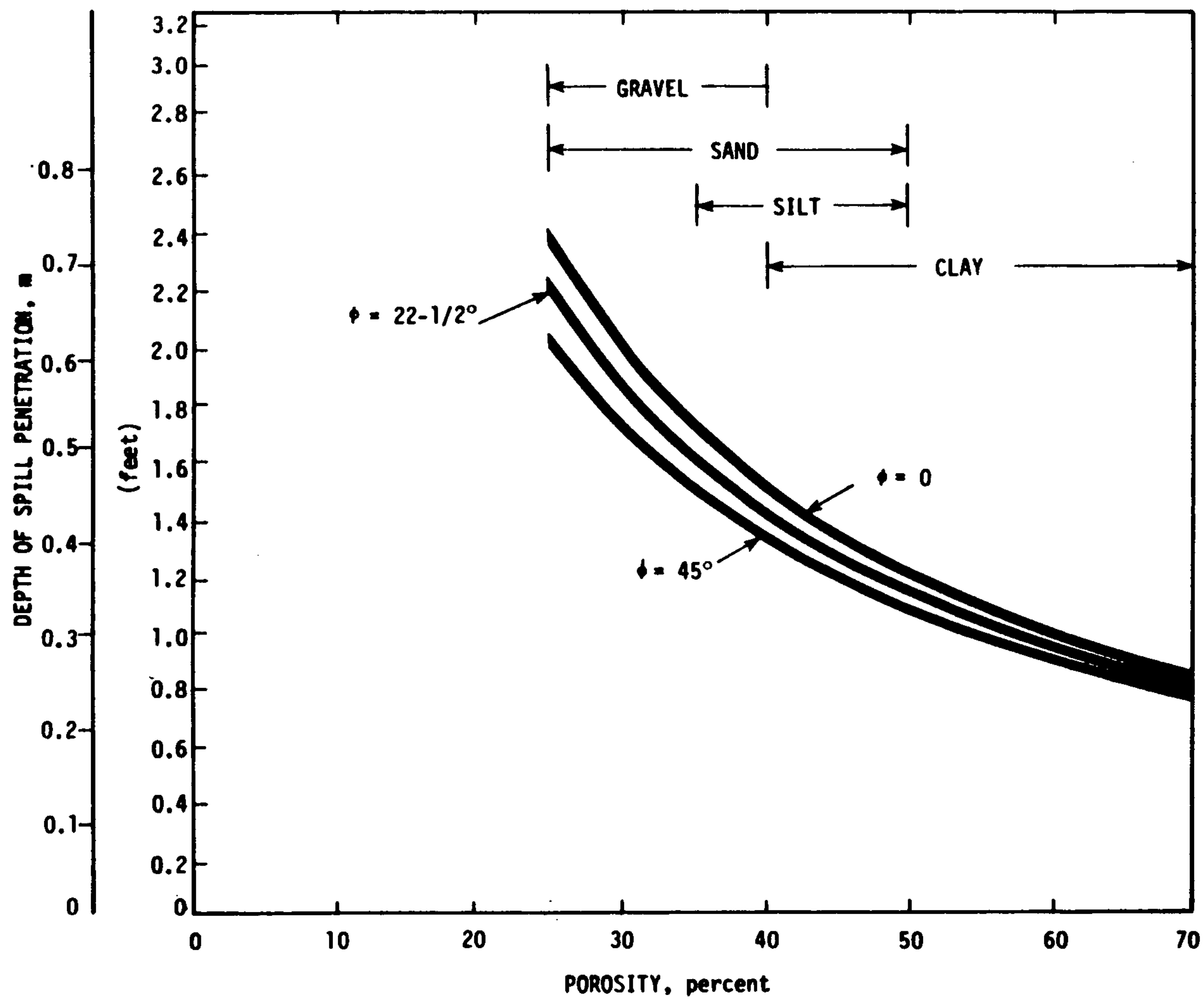

Figure 3-6. Depth of spill penetration versus soil porosity for three cone angles for residual saturation of 0.1. Assumes a catastrophic spill of 220 gallons and spill area of 45 meters (489 square feet).

spreading after entering the oil, the penetration depth would be less than 1 meter.

3.4.2 Sequential Spills

If a site generates 220 gallons of waste oil per month and places the oil in drums (typical for a service station) in 5-gallon increments, oil would be added to the drums 44 times per month. If the fill operation is a careless one, as much as 1/2 gallon of oil could be spilled without being cleaned up (although 1 pint or less would be more typical. Thus, the monthly quantity of spilled oil could vary from 5 to 22 gallons.

Each of the small spills would be unlikely to occur at exactly the same spot; instead they probably would occur at all four drum locations (four drums are assumed for this analysis). Thus, according to Equation 1, the spill area covered by the 44 small spills would be four times the area calculated for a single spill. The calculated spill areas from a series of one-pint or half-gallon spills are as follows:

	Spill area, m^2	
Spill volume	Single spill	Four locations
1 pint	0.059	0.235
1/2 gallon	0.202	0.807

The volume of contaminated soil from sequential spills is calculated by using Equation 2 in the same manner as for the catastrophic spills, where the spill volume is the cumulative volume of oil spilled. For example, a series of 44 one-pint spills of light oil in a month could contaminate about 0.42 m^3 (14.7 ft^3) of clay soil with a 50 percent porosity. If the spills occurred in half-gallon increments, the contaminated soil volume would be 1.66 m^3 (58.8 ft^3). Spills of heavier oils would result in less contaminated soil.

The depth of soil penetration from a month-long accumulation of spills can be calculated by using Equation 3 (cylindrically shaped contaminated soil volume) and Equation 4 (cone-shaped volume). The spill volume (V_s) in Equation 3 represents the month's accumulation of spills, and the spill area is an area equal to four times the area calculated from a single small spill (four drum locations).

Figure 3-7 shows the maximum depth of spill penetration versus soil porosity for a total spill volume of 22 gallons, where the spill area is based on four half-gallon spills. This should represent a worst-case month for a very careless four-drum service station operation.

The maximum depth of 4.1 meters (13.5 feet) is obtained if light oil is spilled on gravel or sand of low porosity. Lube oil spilled on the same gravel or sand would penetrate only to a depth of about 2.1 meters (6.8 feet). A spill on a high-porosity clay would range from a depth of 1.5 meters (4.8 feet) for light oil to a depth of 0.75 meter (2.4 feet) for heavy lube oil.

Figure 3-8 shows the sensitivity of the penetration depth to the spreading cone angle for light oil (deepest penetration in Figure 3-7). This graph shows that a cone angle of 45 degrees,

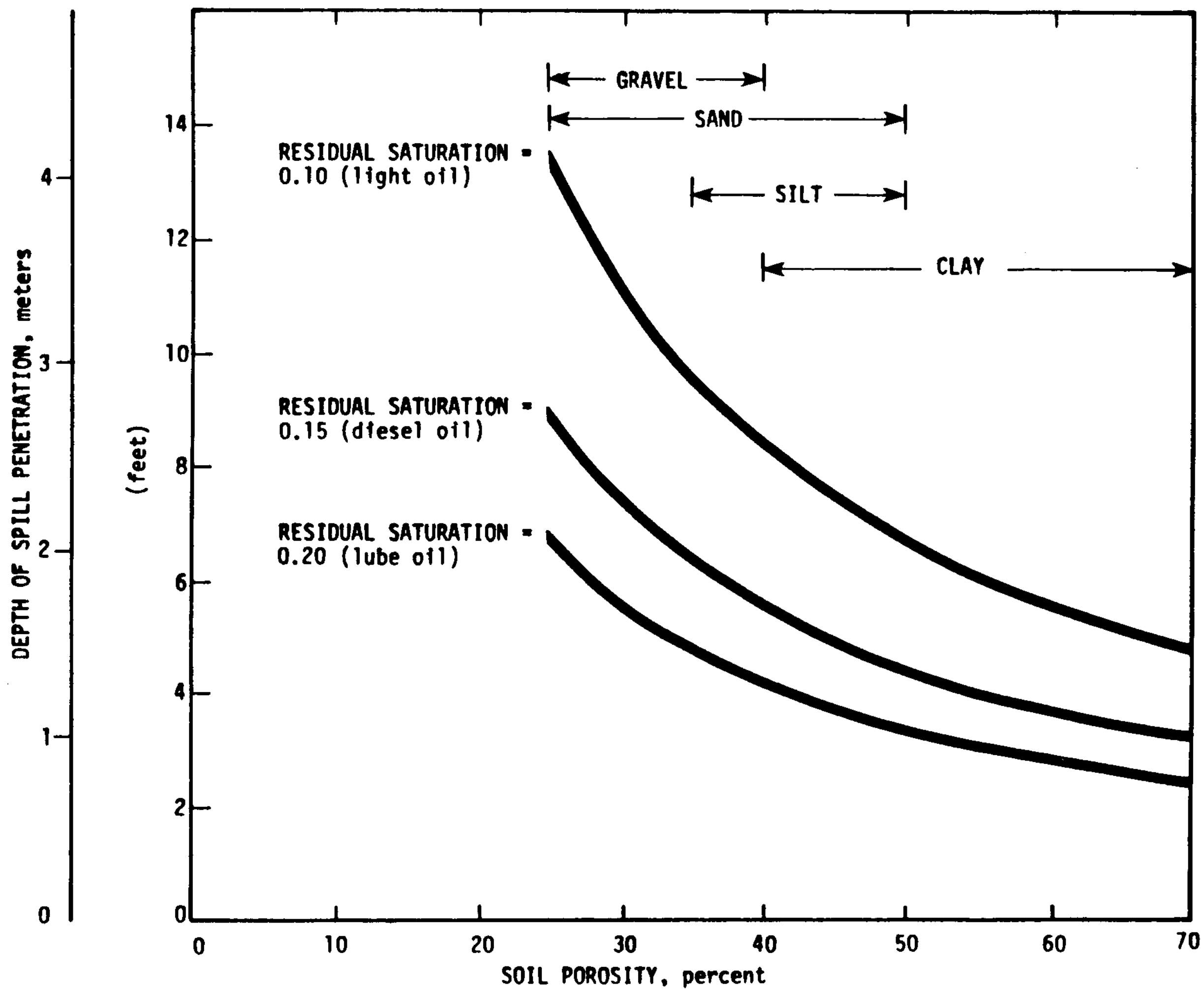

Figure 3-7. Depth of spill penetration versus soil porosity for periodic spills of one-half gallon each. Assumes 44 spills per month at four spill areas - total spill area is 0.81 square meters (8.69 square feet). Total spill volume is 22 gallons.

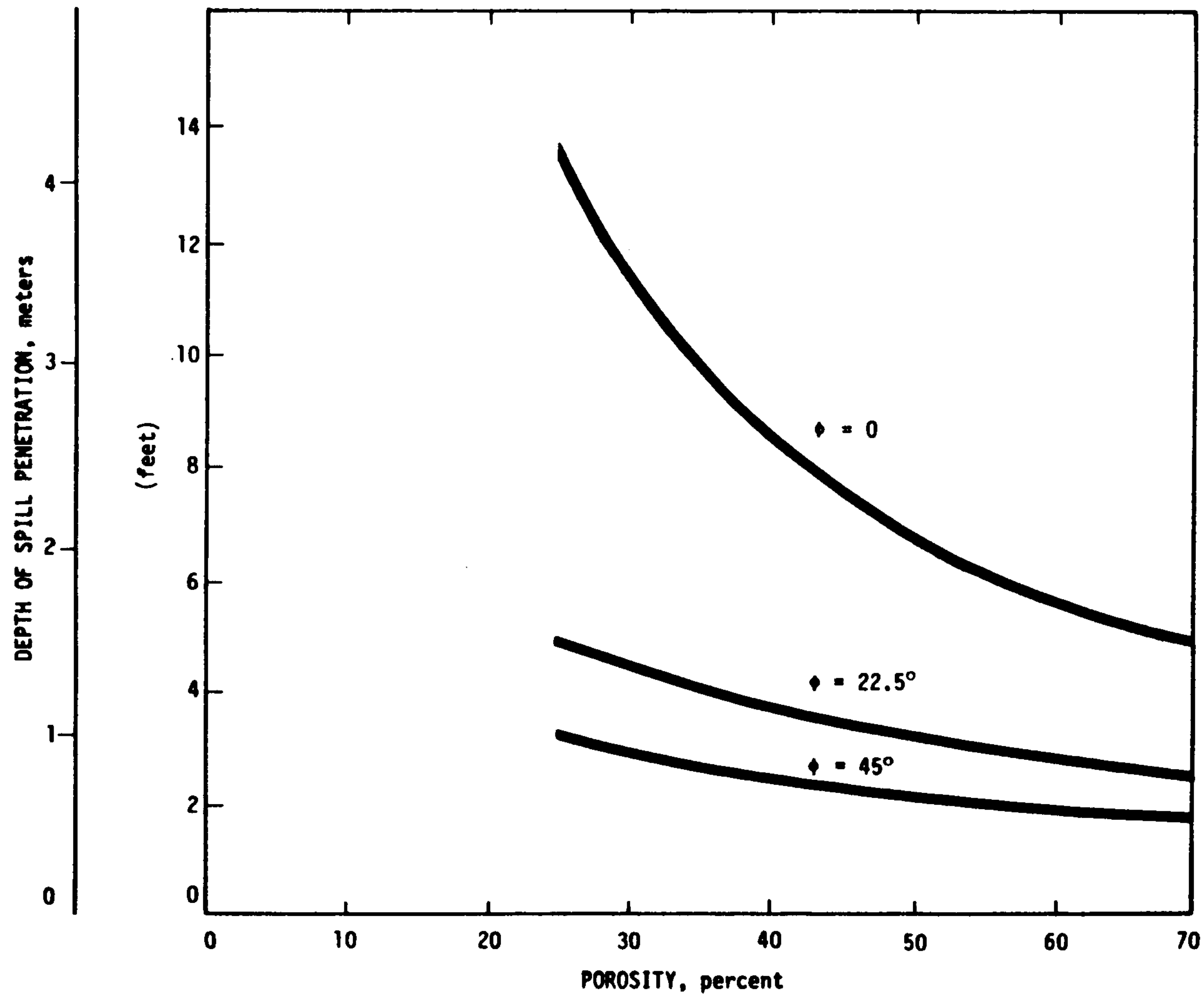

Figure 3-8. Depth of spill penetration of soil porosity for three cone angles for residual saturation of 0.1 (light oil). Assumes 44 sequential spills of one-half gallon each at four locations. Total spill area is 0.81 square meters (8.69 square feet). Total spill volume is 22 gallons.

which may be representative of a homogeneous isotropic soil, would reduce the penetration depth by a factor of 2 to 4, with the greatest reduction in depth occurring for the low-porosity soils.

Figure 3-9 shows spill penetration depth versus oil porosity for a typical service station with 44 one-pint spills in a month. This size spill is expected to be more typical for a four-drum service station operation than the half-gallon spills. It should be noted that although the quantity of oil spilled at each occurrence and the total oil spilled per month are reduced by a factor of 4, the penetration depth is reduced by only 14 percent. The reduction in penetration depth is much less than the reduction in spill volume because a smaller spill area results from the one-pint spills.

Figure 3-10 shows the sensitivity of penetration depth to the spreading cone angle for 44 one-pint spills of light oil. This graph, which is similar to the graph in Figure 3-8, shows that a spreading angle of 45 degrees would reduce the penetration depth by a factor of 2 to 4, with the greatest reduction in depth occurring for the low-porosity soils.

This analysis represents typical spills over a month's time. If the spills are chronic and continue over a long period of time, the depths can be significantly greater than those shown, and groundwater is likely to be contaminated eventually. According to the model assumed, after the residual saturation level of the soil has been reached, any new spilled oil simply flows

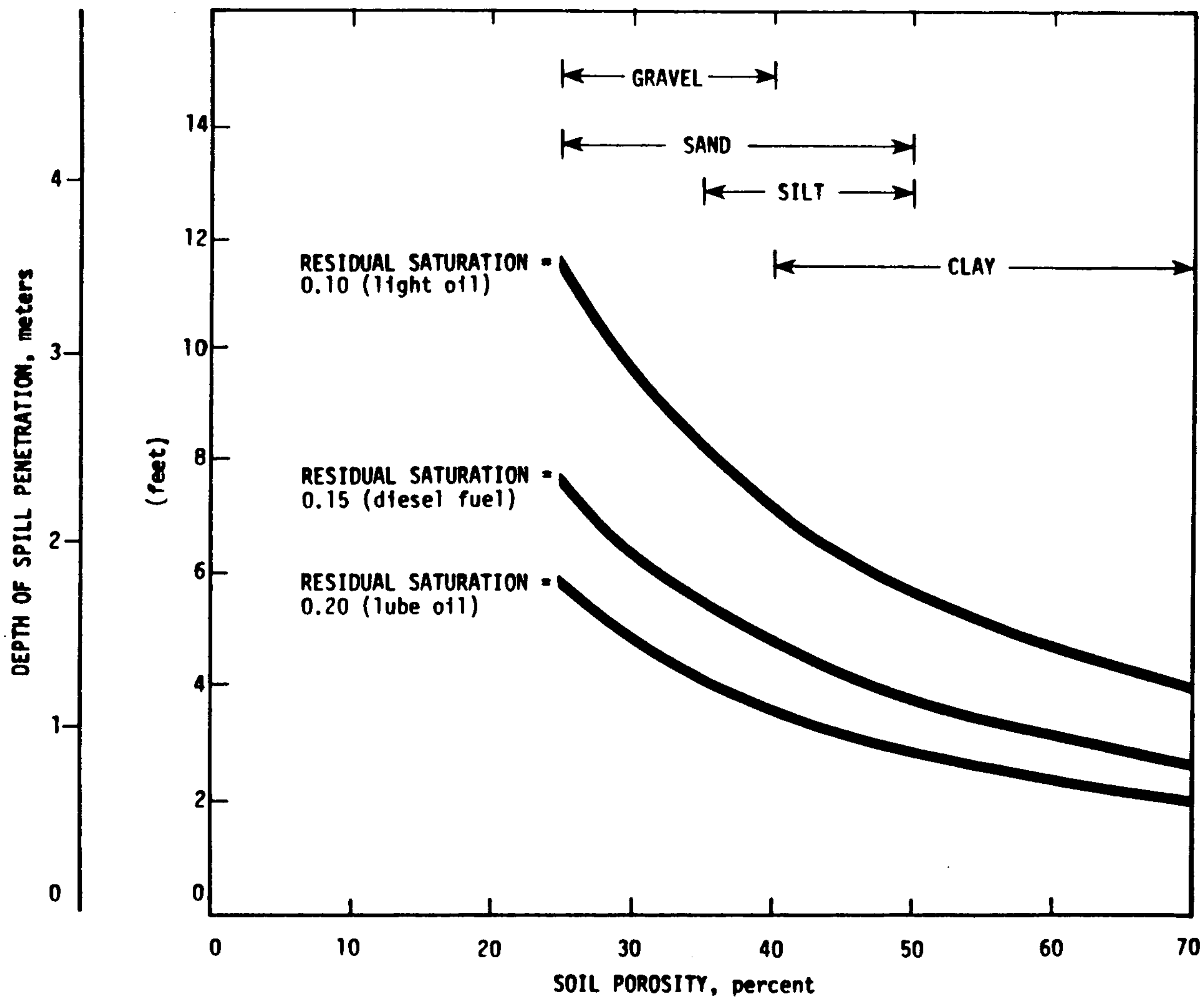

Figure 3-9. Depth of spill penetration versus soil porosity for periodic spills of one pint each in four spill areas. Assumes 44 spills per month. Total spill area is 0.24 square meters (2.53 square feet). Total spill volume is 5.5 gallons.

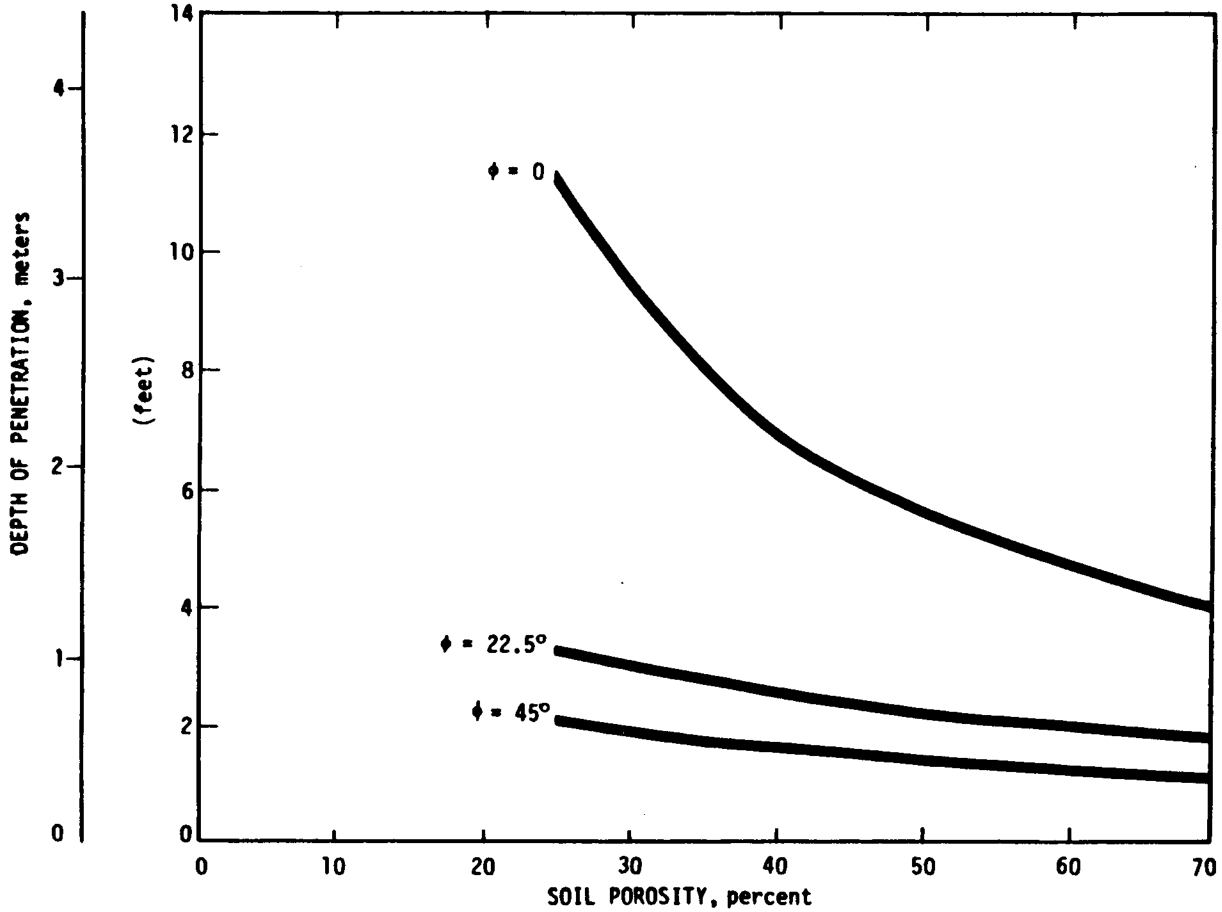

Figure 3-10. Depth of spill penetration versus soil porosity for three cone angles for a residual saturation of 0.1 (typical for light oil). Assumes 44 spills of one pint each in four spill areas. Total spill volume is 5.5 gallons.

through the already contaminated soil and the penetration depth continues to increase until the groundwater table or some other boundary is reached. Once the groundwater has been reached, each pint of soil spilled at the surface results in a pint of oil being introduced into (or on top of) the groundwater.

The calculations of penetration depths shown in this section are conservative and represent worst-case conditions. At least three factors can limit the depth of contamination: 1) evaporation of oil from near the surface, 2) decomposition (by bacterial action) of the oil over a period of time, and 3) soil compaction. The evaporation rate is temperature-dependent, and can be significant for the lighter oils. Significant quantities of oil can be decomposed by bacterial action, but decomposition requires several months and depends on ground temperature, soil moisture content, and type of oil. Under ideal conditions, such as at land disposal sites where the soil is periodically mixed, the rate of decomposition can be as high as 60 pounds of oil per cubic foot of soil per month.[12] At waste storage sites, however, natural biodegradation is expected to be extremely slow, primarily because of the lack of oxygen. With regard to soil compaction, the upper layer of soil will be compacted if the spill area is heavily traveled, and the oil will spread out further before it enters the soil. This causes the oil to stay near the surface, where rates of evaporation and biodegradation are the highest.

Thus, in some cases, sequentially spilled oil will be mitigated and will not reach groundwater, but in a large number of cases, these mitigative factors will not be significant, and small amounts of oil will reach groundwater.

3.5 SUMMARY

In this section, the fate of waste oil that has entered the environment through spills or leaks from oil storage containers has been examined. Such entrance of waste oil components into the environment has been evaluated according to storage container type, spill or leak processes, soil characteristics, and other hydrogeological factors. This evaluation indicates that seepage of oil into the subsurface environment is the area of greatest concern. The following subsections summarize the findings that were discussed in detail in this chapter.

3.5.1 Storage Tanks

Spills from storage tanks can be classified into two main groups: slow leaks and contained surface spills. The rate of contamination of the subsurface environment from leaks and contained surface spills depends primarily on soil and hydrogeological characteristics. The greater the soil permeability, the higher will be the oil migration rates for spilled oil and leaks from above- and below-ground tanks. Predictions based on the Green-Ampt equation (Appendix B) indicate that oil penetrates sand and some silts very rapidly, but its movement through clay is much slower. It is assumed that passage of oil through the soil does not alter its permeability. This assumption was necessary because, even though recent research indicates that some permeability increase may occur, quantification of this effect is not possible based on current knowledge. Green-Ampt predictions for clay are especially likely to be much too high.

3.5.1.1 Above-ground Tanks--

Oil can escape from an above-ground tank through a leak in the tank bottom or as a result of an above-ground spill. A tank bottom leak or rupture that goes undetected could result in severe groundwater contamination. If an above-ground tank is placed on a sand bed, groundwater could become contaminated in a matter of minutes. If placed on silt, contamination could occur within a few weeks. A clay bed affords a significant degree of protection if the soil structure has not been altered by interaction with the oil.

A surface spill of oil from an above-ground storage tank can result in rapid oil loss if the soil within the containment area is not low in permeability. Even with immediate detection and efficient cleanup, oil is likely to remain within the berm area for several hours, during which time significant soil contamination can be expected to occur if the surrounding soil is sand; some contamination can be expected if the soil is silt. If the soil is not removed following cleanup of the pooled oil, groundwater contamination may occur from the leaching of oil components. Clay is the only soil with a slow enough rate of oil penetration to allow for safe oil cleanup without soil removal. Also, short exposure of the clay bed to oil is not likely to cause the permeability changes some researchers have observed to occur during prolonged exposure.

3.5.1.2 Below-ground Tanks--

Leaks in storage tanks located underground will go unnoticed until they are large enough to be detected visually or by a monitoring system (if one is used). A severe tank failure or rupture can result in rapid groundwater contamination. A leaking below-ground tank could cause groundwater contamination in less than an hour in sandy soil and in just over a week in a silty soil. It is predicted that it could take more than 75 years for such contamination to occur in clay soil, but this prediction does not consider the increases in soil permeabilities that can result from long-term exposure to organics.

Because below-ground tanks are more likely to develop leaks than above-ground tanks are, and because these leaks are likely to go undetected for longer periods of time, storage of waste oil in below-ground tanks presents a greater risk to the environment.

3.5.2 Containers and Drums

Two types of spills that may be expected to occur at waste oil drum storage facilities were analyzed: the catastrophic spill and sequential small spills. In the catastrophic spill, which represents one extreme, all the oil stored at a particular site is spilled in a single incident. This type of spill results in the spread of oil over a large surface, but usually results in relatively shallow penetration. A single spill of 220 gallons or less would not be likely to contaminate the groundwater. On the other hand, a series of small sequential spills will spread over a much smaller area than the single catastrophic spill (even if the same total quantity of oil is spilled over a month's time), but the depth of oil penetration under these circumstances can be quite high. Over a long period of time, the oil from small spills at one location (such as a service station) can be expected to reach the groundwater; however, the volume of oil that reaches the groundwater will probably be too small to cause significant water quality deterioration. Cleanup also may be more difficult and expensive for the small sequential spills than for a sudden quickly recognized spill.

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APPENDIX A

DERIVATION OF ESTIMATED FAILURE PROBABILITIES IN BELOW-GROUND WASTE OIL STORAGE TANKS

The first of the two approaches used to estimate failure (or leak) probabilities in below-ground waste oil tanks was based on applications of the API study mathematical model.[1] The model was used in conjunction with assumed conditions relevant to its application and an estimation of failure probabilities in the total system of below-ground waste oil tanks. The mathematical model predicts the mean age to failure from external corrosion as follows:

$$Age = 5.75 \times R^{0.05} \times S^{-0.018} \times e^{(0.13\ pH - 0.41M - 0.26\ Su)}$$

where

R = resistivity of soil in ohm-centimeters

S = tank capacity in gallons

pH = soil acidity

e = 2.72

M = 1 if soil saturated with water, 0 otherwise

Su = 1 if sulfides present in soil, 0 otherwise

The data in Table A-1 show estimated failure probabilities for 500-gallon underground steel tanks subject to localized corrosion based on two sets of soil conditions. The first set of soil conditions is judged to be typical of those encountered around below-ground waste oil tanks. A moisture-saturated soil condition is assumed, however, whereas such soil conditions are estimated to occur in only about 50 percent of the cases.[2] The presence of moisture-saturated soil is highly important in predictions of failures due to corrosion. The second set of soil conditions, which is supposed to represent the

TABLE A-1. ESTIMATED FAILURE PROBABILITIES FOR 500-GALLON BELOW-GROUND STORAGE TANKS SUBJECT TO LOCALIZED EXTERNAL CORROSION[a]

Years	Probability under typical soil conditions,[b] percent	Cumulative probability under typical soil conditions,[b,c] percent	Probability under optimum soil conditions,[d] percent	Cumulative probability under optimum soil conditions,[c,d] percent
0-1	0.0	0.0	0.0	0.0
1-2	0.0	0.0	0.0	0.0
2-3	0.0	0.0	0.0	0.0
3-4	0.0	0.0	0.0	0.0
4-5	0.0	0.0	0.0	0.0
5-6	0.1	0.0	0.0	0.0
6-7	0.2	0.0	0.0	0.0
7-8	0.7	0.1	0.0	0.0
8-9	2.0	0.3	0.0	0.0
9-10	4.9	0.8	0.0	0.0
10-11	10.4	1.7	0.0	0.0
11-12	19.5	3.2	0.0	0.0
12-13	32.3	5.4	0.0	0.0
13-14	47.6	8.4	0.0	0.0
14-15	63.3	12.1	0.0	0.0
15-16	77.0	16.1	0.0	0.0
16-17	87.3	20.3	0.0	0.0
17-18	93.8	24.4	0.1	0.0
18-19	97.4	28.2	0.1	0.0
19-20	99.0	31.8	0.5	0.0

[a] Based on Warren Rogers Associates model applied to various soil properties. (Reference 1).

[b] Assumes the following values for parameters used in Warren Rogers Associates model: soil resistivity = 4,000 ohm-centimeters; pH = 7.5; moisture = saturated; sulfides = none; calculated mean age failure = 13.66 years.

[c] Assumes equal tank age distribution.

[d] Assumes the following values for parameters used in Warren Rogers Associates model: soil resistivity = 30,000 ohm-centimeters; pH = 8.5; moisture = nonsaturated; sulfides = none; calculated mean age to failure = 25.[illegible] years

optimum for preventing corrosion, assumes that soil is not saturated with moisture. The mean age of a tank to the outset of a leak was calculated for each of the two assumed soil conditions by using the mathematical model developed in the API study. Under the first set of soil conditions, the mean age of a tank at the time of failure was calculated to be 13.66 years; under the second set of soil conditions, the mean age was 25.93 years.

The probability of external corrosion failures (Table A-1) for unprotected steel tanks of various ages was based on three mean ages to failure, as calculated by the mathematical model and the application of tables of the standard normal distribution (with the use of the estimated 2.5 years standard deviation) to compute failure probabilities at each age.

The probabilities of failure for tanks up to 20 years of age under both soil conditions are shown in Table A-1. A comparison of the corresponding probabilities of failure under these two soil conditions reveals the enormous impact of soil conditions on tank failures from corrosion. Under the first set of soil conditions, an underground storage tank with localized corrosion is expected to fail within 20 years. Under the second set of soil conditions, there is a less than 1 percent probability of failure within 20 years.

Estimated cumulative probabilities of below-ground tank failures from external corrosion are based on an assumed equal number of tanks in all age categories up to 20 years. Thus, for the first set of soil conditions, it is estimated that 31.8 percent of a given number of tanks (with localized corrosion), uniformly distributed between 0 and 20 years of age, are leaking, whereas essentially none of these tanks would be leaking under the second set of soil conditions.

If it is assumed that an average of the figures derived under the two sets of soil conditions is a reasonable expectation, the cumulative probability of failure is about 16 percent. The API study estimates that 77 percent of the below-ground unprotected steel tanks experience localized corrosion. Application of this figure results in an expectation that at least 12 percent of the tanks uniformly distributed between the ages of 0 and 20 years are leaking. This is believed to be a conservative estimate for several reasons. First, the 12 percent only covers expected failures from external corrosion; failures due to leaks from other causes are not included. Second, soil conditions generally encountered are believed to be closer to those assumed in the first set used. Third, the age distribution of below-ground waste oil tanks is believed to be very conservative (on the average these tanks are believed to be older than indicated).[2,3] Finally, the capacity of many of the below-ground waste oil tanks is larger than 500 gallons; these larger tanks would be expected to fail slightly earlier from external corrosion.

Another approach used to estimate the probability of leaks in below-ground waste oil tanks involved the use of recent data compiled by Warren Rogers Associates on predicted national mean tank ages to predict the occurrence of leaks in underground gasoline tanks at service stations (Figure A-1). The expected average age of tanks at the time of failure due to external corrosion is from 8 to 24 years. A marked number of tank failures occur between the ages of 10 and 15 years and 19 and 23 years. The earlier predicted failures are reported to be due to moisture-saturated soil[2]; failures in dry soil occur later. Nearly all such tanks are expected to have failed by 24 years of age or shortly thereafter.

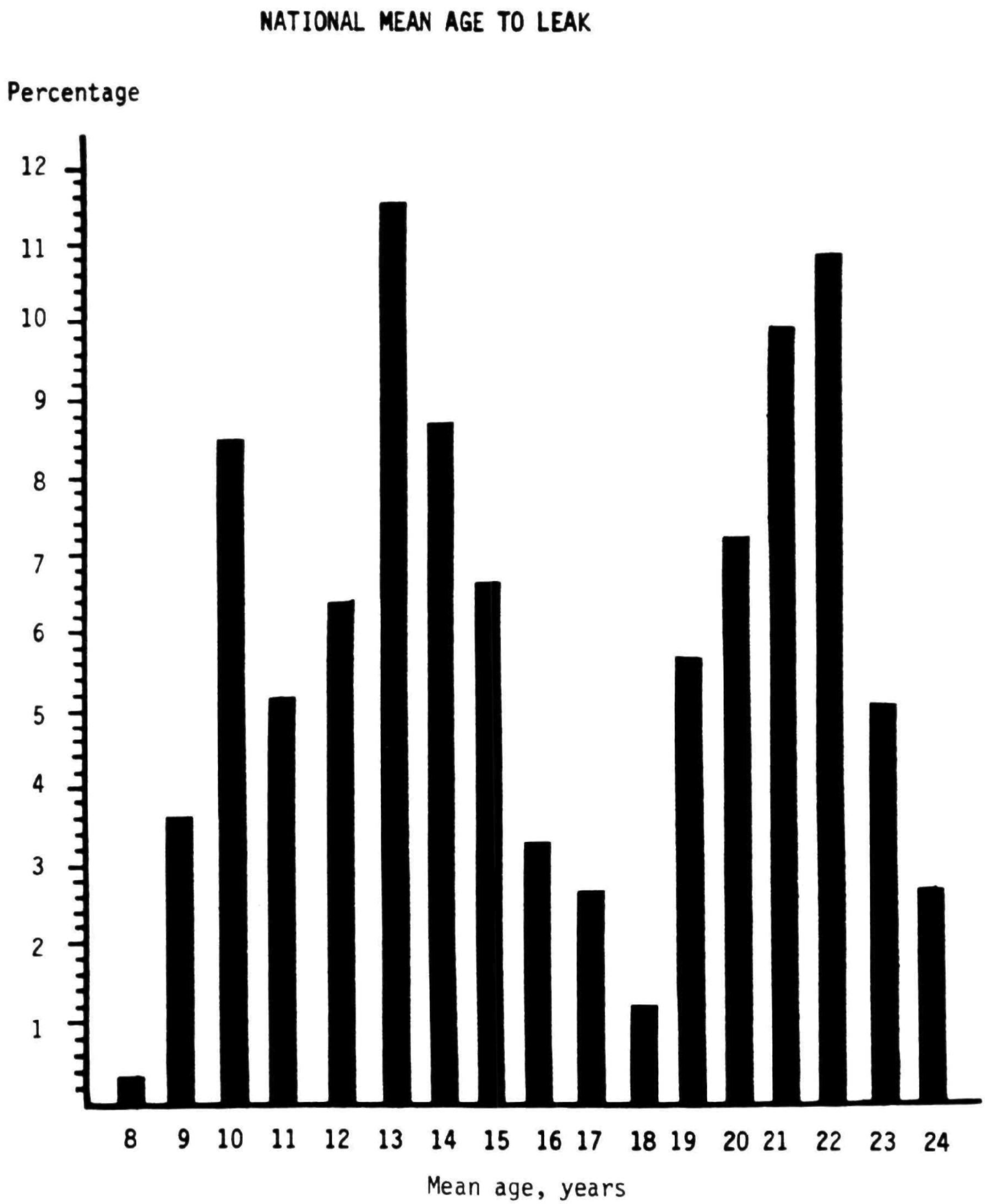

Figure A-1. National mean age to leak.[1]

The data in Figure A-1 were used to estimate failure probability for below-ground unprotected steel tanks experiencing localized corrosion, as shown in Table A-2. The figures in Column 2 represent the probability of failure for tanks of different ages. For example, the probability of leak(s) for the tanks between 19 and 20 years old is shown at just over 60 percent. This assumes that all below-ground tanks remain in service for a full 20 years even though they have begun to leak earlier.

As a point of clarification, the distinction between Figure A-1 and Column 2 in Table A-2 is as follows. The data in Figure A-1 represent the mean (average) ages at which a leak (resulting from external corrosion) is expected to begin. The probabilities of a mean age to leak occurrence are shown for each age category. The probability figures in Column 2 of Table A-2 are based on the information from Figure A-1. For example, the probability that a below-ground tank 15 years old is leaking is based on the cumulative probability of a leak beginning during each previous year. This cumulative probability may be determined from the data in Figure A-1 and the application of a normal distribution with a 2.5-year standard deviation.

The estimated cumulative probabilities of below-ground tank failures from external corrosion shown in Table A-2 are based on the probabilities by age group. The estimates are based on the assumption that there is an equal number of tanks in all age categories up to 20 years. Thus, it is estimated that more than 18 percent of the tanks with localized corrosion (uniformly distributed between 0 and 20 years of age) are leaking. If the tanks that do not have localized corrosion are included, 14 percent of below-ground unprotected steel tanks of these ages are estimated to be leaking.

TABLE A-2. ESTIMATED FAILURE PROBABILITIES FOR UNDERGROUND STORAGE TANKS SUBJECT TO LOCALIZED EXTERNAL CORROSION[a]

Tank age, years	Probability based on nationally determined ages to leak occurrence, percent	Cumulative probability based on nationally determined ages to leak occurrence,[b] percent
0-1	0.0	0.0
1-2	0.0	0.0
2-3	0.0	0.0
3-4	0.0	0.0
4-5	0.0	0.0
5-6	0.0	0.0
6-7	0.0	0.0
7-8	0.0	0.0
8-9	0.2	0.0
9-10	2.3	0.3
10-11	7.8	0.9
11-12	12.5	1.9
12-13	18.2	3.2
13-14	27.3	4.9
14-15	35.7	6.9
15-16	43.3	9.2
16-17	48.5	11.5
17-18	52.7	13.8
18-19	55.6	16.0
19-20	60.2	18.2

[a] Based on application of Warren Rogers Associates national mean age to leak data.

[b] Assumes equal tank age distribution.

Although these figures are based on data generated to predict failure in below-ground gasoline tanks, they are judged to be almost equally applicable to waste oil tanks. Two factors that could result in some differences are the relatively smaller sizes of the waste oil tanks and their generally shallower placement underground. Comparison of predicted mean age to failure arrived at by the API study mathematical model shows little difference between a typical waste oil tank size and a typical gasoline tank size. Further, soil conditions around the waste oil tanks in service stations are reportedly not substantially different from those around the larger gasoline tanks.[1]

The probability of leaks in below-ground waste oil storage tanks is estimated at 12 to 14 percent, based on the two estimation approaches described. For reasons already cited, these figures are believed to be conservative.

APPENDIX A

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3. Correspondence from Shell Oil Company, Houston, Texas, December 8, 1982.

APPENDIX B

OIL INFILTRATION INTO SOIL USING GREEN-AMPT MODEL

Green and Ampt derived a simple model of infiltration in 1911. This model describes the infiltration of soil moisture as a square wave moving down the soil column (Figure B-1). Above the wetting front, the soil is completely saturated, but below the wetting front, soil moisture remains at its original level. The time required for water to penetrate a given depth of the soil column can be calculated from Equation B-1.[1]

$$t = \frac{n - \theta_i}{K} \left[d - (h-\psi) \ln \left(\frac{h+d-\psi}{h-\psi} \right) \right] \qquad \text{(Eq. B-1)}$$

where

t = time

θ_i = initial solid moisture content

n = porosity

d = depth of fluid (head) above the soil surface

ψ = capillary pressure

K = hydraulic conductivity

The Green-Ampt wetting front model can be used for estimating oil infiltration by simply using the appropriate hydraulic conductivity (K) and capillary pressure (ψ) values for oil. The oil hydraulic conductivity can be determined for a three-phase system of oil, water, and air by modifying hydraulic conductivity values for a one-phase oil system by using the diagram in Figure B-2.[2]

Each point within the triangle corresponds to a different degree of saturation for air, oil, and water, as indicated on the scales along the sides

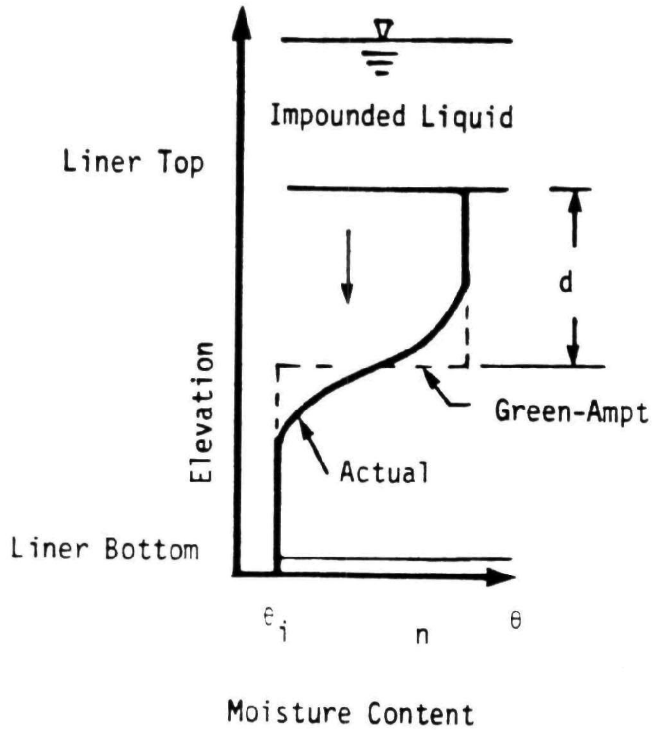

Figure B-1. Green-Ampt infiltration model.

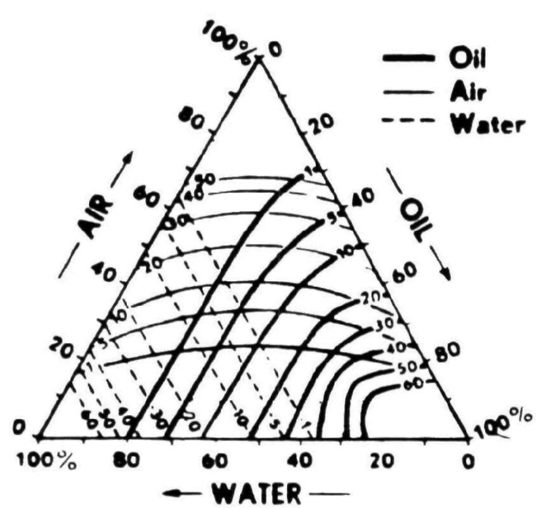

Figure B-2. Relative permeabilities of three-phase flow.[2]

of the triangle. The heavy solid lines, light solid lines, and dashed lines labeled oil, air, and water, respectively, represent relative permeabilities for each of the three phases.

For example, consider the determination of oil hydraulic conductivity for a highly porous sand with the pore spaces filled with oil (70 percent), water (15 percent), and air (15 percent). The phase diagram in Figure B-2 can be used to determine that the hydraulic conductivity (permeability) of oil is reduced to approximately 55 percent (heavy line labeled oil) of the value with no water or air present. As shown in Table B-1, for a highly porous sand, oil hydraulic conductivity would be about 1.4 E-2 cm/s, with no soil moisture and 55 percent of that value, or 7.7 E-3, for a soil with a 15 percent soil moisture and 15 percent air content.

TABLE B-1. SEEPAGE FACTORS FOR OIL AND WATER IN VARIOUS SOILS[a]

	Hydraulic conductivity (K)[b]			Intrinsic permeability (K) cm^2
	Porosity	Oil, cm/s	Water, cm/s	
Clay	0.40 to 0.70	1.4 E-12 to 1.4 E-9	E-10 to E-7	E-15 to E-12
Silt	0.25 to 0.35	1.4 E-9 to 1.4 E-5	E-7 to E-3	E-12 to E-8
Sand	0.25 to 0.50	1.4 E-5 to 1.4 E-2	E-3 to 1	E-8 to E-5
Gravel	0.25 to 0.40	1.4 E-3 to 1.4	E-1 to E+2	E-6 to E-3

[a] Reference 3.

[b] K = 100 Kg ÷ μ, where K = hydraulic conductivity (cm/s), k = intrinsic permeability (cm^2), g = acceleration due to gravity (9.8 m/s^2), μ = kinematic viscosity (0.71 cm^2/s for oil and 0.01 cm^2/s for water).

The Green-Ampt model is particularly sensitive to values used for capillary pressure. Since the capillary forces attract the liquid molecules to the soil particles, their effect is mathematically that of a negative pressure. Capillary forces vary according to soil type and the amount of moisture initially present in the soil. The lower the initial soil moisture, the larger the capillary forces.

The literature values show poor agreement for the negative capillary pressure for water in various soils.[1,4,5] Values to -80 atmospheres (-1,200 psi) have been reported.[1] More recent reports, however, indicate that these extremely negative values are probably not valid.[4,5] Values for the various soil types have recently been calculated by Rawls et al.[4] to be in the range of 5 to 50 centimeters (Table B-2).

Capillary pressures for oil in soil are not readily available in the literature. For this analysis, estimates for oil capillary pressures have been made based on the data for water and the ratio of oil surface tension to water surface tension. Use of this ratio should give a reasonably good estimate of capillary pressures in a soil environment.

The effect of soil moisture on oil capillary forces is uncertain. It is known that at low moistures, water remains preferentially adsorbed to soil particles as oil passes through the soil-water system. In this situation, oil will interact with both soil and water surfaces and the capillary forces exerted will be influenced by these interactions.

Because of the uncertainty in capillary pressures, a range of values was used for this analysis. The values used for water range from the low values in Table B-2 to the high values in a range of textbook values (Table B-3). Values for oil were derived from these data and adjusted by the ratio of surface tension. The high values should represent a worst case for infiltration times.

TABLE B-2. GREEN AND AMPT PARAMETERS ACCORDING TO SOIL TEXTURE CLASSES AND HORIZONS[a,b]

Soil texture class	Horizon	Total porosity	Effective porosity	Wetted front capillary pressure, centimeters	Hydraulic conductivity, centimeters per hour
Sand		0.437 (0.374-0.500)	0.417 (0.354-0.480)	4.95 (0.97-25.36)	11.78
	A	0.452 (0.396-0.508)	0.431 (0.375-0.487)	5.34 (1.24-23.06)	
	B	0.440 (0.385-0.495)	0.421 (0.365-0.477)	6.38 (1.31-31.06)	
	C	0.424 (0.385-0.436)	0.408 (0.365-0.451)	2.07 (0.32-13.26)	
Loamy sand		0.437 (0.363-0.506)	0.401 (0.329-0.473)	6.13 (1.35-27.94)	2.99
	A	0.457 (0.385-0.529)	0.424 (0.347-0.501)	6.01 (1.56-22.87)	
	B	0.447 (0.379-0.515)	0.412 (0.334-0.490)	4.21 (1.03-17.24)	
	C	0.424 (0.372-0.476)	0.385 (0.323-0.447)	5.16 (0.76-34.85)	
Sandy loam		0.453 (0.351-0.555)	).412 (0.283-0.541)	11.01 (2.67-45.47)	1.09
	A	0.505 (0.399-0.611)	0.469 (0.330-0.608)	15.24 (5.56-41.76)	
	B	0.466 (0.352-0.580)	0.428 (0.271-0.585)	8.89 (2.02-39.06)	
	C	0.418 (0.352-0.484)	0.389 (0.310-0.468)	6.79 (1.16-39.65)	
Loam		0.463 (0.375-0.551)	0.434 (0.334-0.534)	8.89 (1.33-59.38)	0.34
	A	0.512 (0.427-0.597)	0.476 (0.376-0.576)	10.01 (2.14-46.81)	
	B	0.512 (0.406-0.616)	0.498 (0.382-0.614)	6.40 (1.01-40.49)	
	C	0.412 (0.350-0.474)	0.382 (0.305-0.459)	9.27 (0.87-99.29)	
Silt loam		0.501 (0.420-0.582)	0.486 (0.394-0.578)	16.66 (2.92-95.39)	0.65
	A	0.527 (0.444-0.610)	0.514 (0.425-0.603)	10.91 (1.89-63.05)	
	B	0.533 (0.430-0.636)	0.515 (0.387-0.643)	7.21 (0.86-60.82)	
	C	0.470 (0.409-0.531)	0.460 (0.396-0.524)	12.62 (3.94-40.45)	
Sandy clay loam		0.398 (0.332-0.464)	0.330 (0.235-0.425)	21.85 (4.42-108.0)	0.15
	A	- [c] -	- -	- -	
	B	0.393 (0 310-0.476)	0.330 (0.223-0.437)	26.10 (4.79-142.30)	
	C	0.407 (0.359-0.455)	0.332 (0.251-0.413)	23.90 (5.51-103.75)	
Clay loam		0.464 (0.409-0.519)	0.309 (0.279-0.501)	20.88 (4.79-91.10)	0.10
	A	0.497 (0.434-0.560)	0.430 (0.328-0.532)	27.00 (6.13-118.9)	
	B	0.451 (0.401-0.501)	0.397 (0.228-0.530)	18.52 (4.36-78.73)	
	C	0.452 (0.412-0.492)	0.400 (0.320-0.480)	15.21 (3.79-61.01)	
Silty clay loam		0.471 (0.418-0.524)	0.432 (0.347-0.517)	27.30 (5.67-131.50)	0.10
	A	0.509 (0.449-0.569)	0.477 (0.410-0.544)	13.97 (4.20-46.53)	
	B	0.469 (0.423-0.515)	0.441 (0.374-0.508)	18.56 (4.08-84.44)	
	C	0.475 (0.436-0.514)	0.451 (0.386-0.516)	21.54 (4.56-101.7)	
Sandy clay		0.430 (0.370-0.490)	0.321 (0.207-0.435)	23.90 (4.06-140.2)	0.06
	A	- -	- -	- -	
	B	0.435 (0.371-0.499)	0.335 (0.220-0.450)	36.74 (8.33-162.1)	
	C	- -	- -	- -	
Silty clay		0.479 (0.425-0.533)	0.423 (0.334-0.512)	29.22 (6.13-139.4)	0.05
	A	- -	- -	- -	
	B	0.476 (0.465-0.507)	0.424 (0.345-0.503)	30.66 (7.15-131.5)	
	C	0.464 (0.430-0.498)	0.416 (0.346-0.486)	45.65 (18.27-114.1)	
Clay		0.475 (0.427-0.523)	0.385 (0.269-0.501)	31.63 (6.39-156.5)	0.03
	A	- -	- -	- -	
	B	0.470 (0.426-0.514)	0.412 (0.309-0.515)	27.72 (6.21-123.7)	
	C	0.483 (0.441-0.525)	0.419 (0.294-0.544)	54.65 (10.59-282.0)	

[a] Reference 4.

[b] Numbers in (), + one standard deviation.

[c] Insufficient sample to determine parameters.

TABLE B-3. CAPILLARY PRESSURES FOR WATER IN VARIOUS SOILS[a]

Soil	Size of particles and of openings, mm	Capillary pressures, cm
Sand:		
Coarse	2.0-0.025	1.5-12
Fine	0.025-0.05	12-61
Silt	0.05-0.005	61-610
Clay	0.005-0.001	610-3,050
Colloids	0.01 and finer	3,050 and more

[a] Reference 5.

Other parameters in the Green-Ampt equation that affect infiltration rate include: porosity (n), initial moisture (ϕ_1), and liquid head (h). Porosity is a measure of the volume of void space in a given soil.

For oil infiltration calculations, the soil moisture is subtracted from the total porosity to obtain a measure of the void space available for the oil to occupy.

The liquid head (h), which is the depth of standing liquid from the spill or leaking tank, is a parameter in the Green-Ampt equation because the standing liquid exerts some pressure on the migrating oil front, which results in an increasing rate of movement with increasing head.

A list of values used for parameters in the Green-Ampt equation to calculate the time required for penetration of spilled oil in Section 4 of this report is shown in Table B-4.

TABLE B-4. GREEN-AMPT PARAMETER VALUES FOR WASTE OIL

Soil type	Soil variables	Low soil permeability	High soil permeability	Average soil permeability
Clay	Total porosity [a]	0.4	0.7	0.45
	Relative conductivity (cm/sec) [b,c]	4.2 E-13	4.2 E-10	6.9 E-11
	Soil moisture [d]	0.2	0.4	0.23
	Capillary force (cm) [e]	-1,200 to -11	-1,200 to -11	-1,200 to -11
Silt	Total porosity [f]	0.35	0.5	0.4
	Relative conductivity (cm/sec) [b]	5.6 E-10	4.2 E-6 [c]	1.6 E-6
	Soil moisture [g]	0.1	0.2	0.13
	Capillary force (cm) [e]	-250 to -4	-250 to -4	-250 to -4
Sand	Total porosity [a]	0.25	0.5	0.35
	Relative conductivity (cm/sec) [b]	9.8 E-6	7.0 E-3	3.2 E-3
	Soil moisture [h]	0.03	0.13	0.07
	Capillary force (cm) [e]	-25 to -2	-25 to -2	-25 to -2

[a] Range of values from Reference 3. Average value from Reference 6.

[b] From Table B-1 and Figure B-2; all values assume 10% of voids filled with trapped air.

[c] Assumes relative permeability for oil (Figure B-2) cannot be below 0.3, which is value below which Figure B-2 shows water mobility also.

[d] Estimated by FAL. Value equals soil saturation multiplied by total porosity.

[e] Derived from literature values for water multiplied by ratio of surface tension of oil to surface tension of water. Ratio used = 0.383 (References 7 and 9). Range of water values taken from high values of Table B-3 and low values in Table B-2.

[f] Range of values from Reference 3. Average estimated by FAL.

[g] Range estimated by FAL. Average based on residual saturation of 0.33 (Reference 7).

[h] Low and high numbers based on residual saturations of 0.10 and 0.25 respectively (Reference 8). Average number based on residual saturation of 0.20 (Reference 7).

APPENDIX B

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APPENDIX C

DERIVATION OF SPILL PENETRATION DEPTH EQUATION

The purpose of this appendix is to show the derivation of the equation for calculating the spill penetration depth (d_s), given the spill area and the volume of saturated soil. The spill area is related to the spill volume according to a simple model developed from spill data in Canada.

$$A_s = 53.5\ V_s^{0.89} \quad \text{(C-1)}$$

The volume of saturated soil is directly proportional to the spill volume and inversely proportional to the soil porosity and the residual saturation level:

$$V_{soil} = \frac{V_s}{nS_r} \quad \text{(C-2)}$$

In these two equations:

V_s = volume of oil spilled (cubic meters)

V_{soil} = volume of saturated soil (cubic meters)

n = soil porosity or ratio of void volume to total soil volume,

S_r = residual saturation

A_s = spill area (square meters)

It is assumed in this analysis that the oil spill does not reach the groundwater.

Two shapes for the contaminated soil volume are considered in this analysis. If the shape is that of a cylinder, then the depth of penetration (d_s) is equal to the contaminated soil volume divided by the surface area:

$$d_s = \frac{V_{soil}}{A_s} = \frac{V_s}{nS_rA_s} \quad \text{(C-3)}$$

If there is lateral movement of the oil as it moves through the soil, then the shape of the contaminated soil volume may be approximated by a truncated cone as shown in Figure C-1.

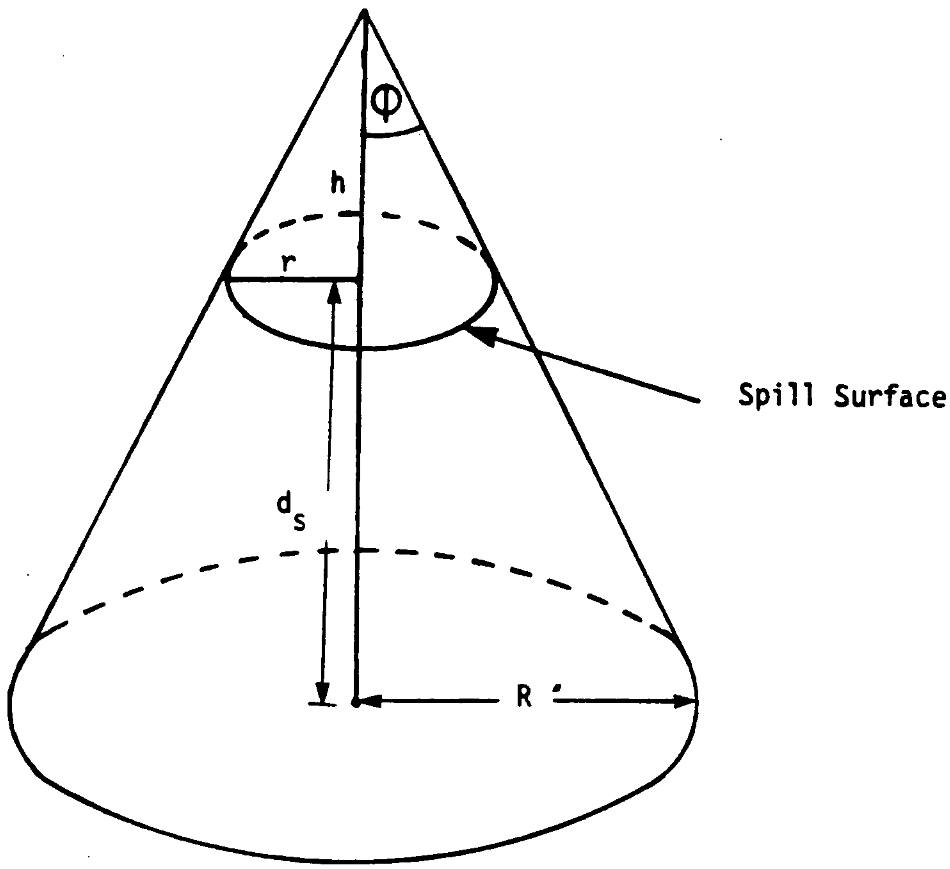

Figure C-1. Geometry of contaminated soil volume, with lateral movement.

The volume of a cone is given by:

$$V_t = \frac{\pi}{3} R^2 H \text{, where R is the radius of the base of the cone} \quad \text{(C-4)}$$

and H is the cone height. From the geometry in Figure C-1,

$$R = \frac{Hr}{h} \text{, or } R^2 = \frac{H^2 r^2}{h^2} \quad \text{(C-5)}$$

Therefore, by substitution, equation 4 becomes:

$$V_t = \frac{\pi}{3} \frac{H^3 r^2}{h^2} \text{, which after} \quad \text{(C-6)}$$

solving for H, can be written as:

$$H = \left[\frac{3Vth^2}{\pi r^2}\right]^{1/3} \quad \text{(C-7)}$$

Since Vt is equal to the sum of the cone volume below the surface (V_{soil}) and the imaginary cone volume above the surface, i.e.,

$$V = V_{soil} + \pi/3 r^2 h \text{, which can be written as:} \quad \text{(C-8)}$$

$$V = V_{soil} + \pi/3 \frac{r^3}{\tan \theta} \quad \text{(C-9)}$$

then Equation 7 can be rewritten as:

$$H = \left[\frac{3h^2}{\pi r^2} \quad V_{soil} + \pi/3 \frac{r^3}{\tan \theta}\right]^{1/3} \quad \text{(C-10)}$$

From Figure C-1, the spill depth can be written as:

$$d_s = H-h, \quad \text{(C-11)}$$

and h, the height of the imaginary cone above the surface, can be written as:

$$h = \frac{r}{\tan \theta} \quad \text{(C-12)}$$

Therefore, combining Equations 10, 11, and 12, the expression for the spill penetration (d_s) can be written as:

$$d_s = \left[\frac{3h^2}{\pi r^2} \; V_{soil} + \pi/3 \, \frac{r^3}{\tan\,\theta} \right]^{1/3} - \frac{r}{\tan\,\theta} \qquad \text{(C-13)}$$

or $$d_s = \left[\frac{3}{\pi \tan^2 \theta} \; V_{soil} + \pi/3 \, \frac{r^3}{\tan\,\theta} \right]^{1/3} - \frac{r}{\tan\,\theta} \qquad \text{(C-14)}$$

Rearranging, we have

$$d_s = \left[\frac{3V_{soil}}{\pi \tan^2 \theta} + \frac{r^3}{\tan^3 \theta} \right]^{1/3} - \frac{r}{\tan\theta} \qquad \text{(C-15)}$$