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RAPID ASSESSMENT OF EXPOSURE TO PARTICULATE EMISSIONS FROM SURFACE CONTAMINATION SITES

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FOREWORD

The Exposure Assessment Group (EAG) of EPA's Office of Research and Development has three main functions: (1) to conduct exposure assessments; (2) to review assessments and related documents; and (3) to develop guidelines for Agency exposure assessments. The activities under each of these functions are supported by and respond to the needs of the various EPA program offices. In relation to the third function, EAG sponsors projects aimed at developing or refining techniques used in exposure assessments. This study is one of these projects and was done for the Office of Emergency and Remedial Response.

The Comprehensive Environmental Response, Compensation, and Liability Act of 1980 established a national fund for the purpose of cleaning up spills and abandoned sites containing hazardous substances. When these sites are discovered EPA must decide quickly if an urgent threat exists requiring immediate action. This project is intended to aid the Agency in making these decisions by providing a method for rapidly evaluating the human health and environmental threat caused by particulate emissions from land contamination sites.

Spills, waste disposal, and various waste industrial operations can result in the contamination of land surfaces with toxic chemicals. Soil particles from these areas can be entrained into the air, transported off-site via the wind, and result in human exposure by direct inhalation. Indirect exposure could result if particulates are deposited in agricultural fields, pastures, or waterways and enter the human food chain. This exposure route is enhanced by the facts that many of the environmentally troublesome compounds are tightly bound to particles and that many surface contaminated sites have conditions favoring wind erosion, such as sparse vegetation cover and high levels of activity which disturb the surface.

James W. Falco, Director
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ABSTRACT

Emergency response actions at chemical spills and abandoned hazardous waste sites often require rapid assessment of (a) the potential for atmospheric contamination by the chemical or waste compound and (b) the inhalation exposure of people living in the vicinity of a surface contamination site. This manual provides a methodology for rapid assessment of inhalation exposure to respirable particulate emissions from surface contamination sites. Respirable particulate matter is defined as airborne particles equal to or smaller than 10 μm aerodynamic diameter. The methodology consists of a site survey procedure, particulate emission factor equations for wind and mechanical entrainment processes, procedures for mapping atmospheric contaminant concentration distributions by scaling the output of pre-solved computer models of regional atmospheric dispersion, and an equation for calculation of inhalation exposure. In addition to the components of the methodology, this manual discusses critical contaminant and site characteristics, describes assumptions and limitations of the procedures, and presents example applications.

The quantitative procedures for estimating atmospheric contaminant concentrations are based on a number of simplifying assumptions related to the contaminated surface and the atmospheric environment, to conform to the data, time, and resource limitations expected during an emergency response. Consequently, the assessment methodology provides order-of-magnitude estimates of atmospheric contaminant concentrations as a function of averaging time and downwind location. The user should carefully review all the assumptions and limitations, and make specific judgments as to their validity for the specific site, contaminant(s), and emergency situation being analyzed. Familiarity and prior training in the use of this manual is highly recommended for efficient use during an emergency response situation.

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SECTION 1

INTRODUCTION

The purpose of this manual is to provide a rapid assessment methodology for estimating potential atmospheric contamination and resulting inhalation exposure of people living in areas surrounding an abandoned hazardous waste or toxic chemical spill site. Only respirable particulate emissions, defined as particles equal to or smaller than 10 μm aerodynamic diameter (denoted by the symbol PM_{10}) are considered in this assessment methodology. PM_{10} is the anticipated size fraction for the impending revision to the primary (health-related) national ambient air quality standard (Federal Register, 1984).

Specifically, this manual is designed for use by field personnel to quickly estimate how breathing-height concentrations of contaminated respirable particulate matter might change with distance and direction from an emergency response site, under annual average and worst-case 24-hr conditions. The procedures include evaluation of critical contaminant and site characteristics as input to an assessment methodology for analyzing the entrainment and atmospheric dispersion of chemicals or contaminated surface material. A modeling technique has been developed for determining the spatial distribution of atmospheric contaminant concentration resulting from wind and/or mechanical entrainment processes, taking into account regional differences in meteorology. Guidelines for evaluating critical contaminant and site characteristics are provided to allow estimation of needed input parameters.

1.1 SCOPE AND LIMITATIONS OF THIS MANUAL

The phrase EMERGENCY RESPONSE is emphasized throughout this manual because it has been the overriding criterion (and constraint) for selection, evaluation, and development of pollutant transport assessment methods and parameter evaluation techniques included herein. Emergency response situations require assessments of potential atmospheric contamination to be completed in less than 24 hr. Consequently, extensive field sampling, laboratory analyses, data search and collection, and sophisticated computer analyses are generally impractical during this limited time frame. Although these extensive sampling and analysis activities may be initiated during the emergency response period, the results cannot be expected to be available for use in an emergency assessment. The assessment procedures in this manual are designed to allow emergency response personnel to make a first-cut, order-of-magnitude estimate of the potential extent of atmospheric contamination and exposure resulting from a waste site or chemical spill, within the 24-hr emergency response time frame.

The primary goal of this manual is to provide the basis for determining the need for emergency actions, such as emergency sampling, containment/stabilization or removal, in order to minimize human exposure to atmospheric contamination by respirable particulate matter in the vicinity of an emergency response site. Two specific emergency response situations are envisioned where the assessment procedures in this manual would be applied:

1. Discovery of an abandoned hazardous waste site where an assessment of the potential extent of the atmospheric contamination is needed within the emergency response time frame.

2. Spill (or leakage) of a toxic waste or chemical where the potential for atmospheric contamination and/or the extent of contamination must be assessed within the emergency response time frame.

Time and resource limitations expected during an emergency response have required a number of simplifying assumptions in the assessment procedures; additional simplifications may be needed by the user due to limited data and information available at a particular emergency response site. The most fundamental assumptions incorporated into the assessment procedures in this manual are as follows:

1. Uniform contamination of a symmetrical land area is assumed, with the concentration in respirable particulate emissions matching the bulk contaminant concentration in the surface material.

2. Emission rates associated with wind and mechanical entrainment processes are modeled as continuous and steady.

A variety of other assumptions and limitations in the procedures are further discussed in Section 4.4. The user should carefully review all the assumptions and limitations, and make specific judgments as to their validity for the specific site, contaminant(s), and emergency situation being analyzed.

Perhaps the most critical aspect of an emergency response situation will be the ability of the user to adequately characterize, within the 24-hr time frame, the surface media (e.g., erodibility, suspendible particle content, level and extent of surface contamination) from which the contaminants are emitted. Consequently, access to and/or availability of data, expertise, and familiarity with local, site-specific surface conditions is critical to the successful application of the assessment procedures in this manual. If the emergency response situation consists of a long-term surface contamination problem with no apparent change in intensity, it may be reasonable to extend the response time frame beyond 24 hr.

1.2 REQUIRED USER BACKGROUND, TRAINING, AND PREPARATION

Effective use of this manual requires a general understanding of a mix of disciplines, such as climatology, soil science, chemistry, on the part of the intended user, and sufficient familiarity or training with the techniques, procedures, and auxiliary sources of information described herein.

This manual is not intended to be a primer on pollutant release and transport through the atmosphere; a variety of excellent introductory textbooks and reports in these areas are available to the potential user to provide the needed background.

Ideally, advanced academic training in physical science supplemented with pertinent work experience and job training, (e.g., short course attendance) provides a profile of the recommended background for a user. Alternatively, an engineering or science undergraduate degree with appropriate training is acceptable as long as a basic understanding in the following areas is included:

1. The mechanisms of wind and mechanical entrainment of surface particulate matter.

2. Meteorological concepts, processes, and terminology related to atmospheric transport.

3. Soil science concepts related to surface soil processes.

4. Chemical processes, parameters, and terminology.

5. Mathematical capabilities and skills in the use of scientific hand calculators.

6. Map reading techniques.

In many emergency response situations, the user will have access to experts in the above disciplines to provide guidance in parameter evaluation. Thus, it is important that the user comprehend the fundamental concepts of each discipline in order to take full advantage of available expertise.

User training and preparation is needed to develop familiarity with the assessment procedures described in this manual. Training and/or familiarity with the specific procedures described herein is absolutely essential to effectively use this manual. Without prior study, users cannot expect to use this manual for assessing potential atmospheric contamination within a 24-hr period. Every effort has been made to simplify the procedures and parameter evaluation guidelines; however prior study is needed to become familiar with the assumptions/limitations, the step-by-step calculations, the application of the graphs, the parameter evaluation guidelines, and the auxiliary sources of information.

Since site characterization may require the greatest effort during an emergency assessment, preparation of a regional or local data base on meteorology, soils properties, and local experts (i.e., contacts and phone numbers) could considerably shorten the time needed to obtain data and improve the resulting parameter estimates. A similar, regional data base for the characteristics of wastes and chemicals produced in, or transported through, the region would be extremely valuable. Recommendations for the contents and format of such a regional data base have been developed for EPA (Battelle PNL, 1982).

1.3 FORMAT OF THE MANUAL

The format of this manual is similar to that used in the companion manual on the rapid assessment of potential groundwater contamination. (Donigian et al., 1983). In this section as well as Section 2, much of the wording was taken directly from the companion manual whenever the subject matter was common to both manuals.

Section 2 describes the types of hazardous waste and spill situations for which the assessment procedures are designed, and provides a methodology flowchart to guide an application. An overview of critical compound and site characteristics is provided along with a discussion of recommended sources of information. Section 3 provides technical guidelines for conducting a contamination site survey.

Section 4 provides a detailed description of the assessment methodology, making use of information gathered from the site. Guidelines are presented for estimating the other input parameters for the assessment. Emphasis is placed on obtaining local site and contaminant specific data in order to obtain realistic parameter estimates. Section 4 also discusses the assumptions and limitations of the assessment procedures; these should be carefully reviewed and understood by the user.

Section 5 presents example applications for the assessment. Section 6 includes cited references. Appendix A contains photographs of ground surfaces of varying erodibility. Appendix B describes the evaluation of the integral needed for calculation of wind erosion emission rates. Appendix C presents a general discussion of atmospheric dispersion models and their applicability to the assessment; Appendix C also describes the process by which meteorological input to the assessment procedures was developed. Appendix D provides the tabulated dispersion modeling output needed for implementation of the assessment procedure. Appendix E provides particulate emission factors for several mechanical entrainment processes other than vehicle traffic. Appendix F is a glossary of terms. Finally, Appendix G contains graphics needed to create the map overlays for use in the assessment process.

1.4 CAVEAT

Although all efforts have been made to insure the accuracy and reliability of the methods and data included in this manual, the ultimate responsibility for accuracy of the final predictions must rest with the user. Since parameter estimates can range within wide limits, especially under the resource and time constraints of an emergency response, the user should assess the effect of methodology assumptions and parameter variability on predicted concentrations for the specific site. The methodology predictions must be evaluated with common sense, engineering judgment, and fundamental principles of soil science, meteorology, and chemistry. Accordingly, neither the authors nor Midwest Research Institute (MRI) assume liability from use of the methods and/or data described in this manual.

SECTION 2

OVERVIEW OF RAPID ASSESSMENT METHODOLOGY

An emergency response to releases of hazardous substances is generally comprised of three steps--characterization, assessment, mitigation--defined as follows (Battelle PNL, 1982):

- Characterization - The acquisition, compilation, and processing of data to describe the scene so that a valid assessment of alternative actions can be made.

- Assessment - An analysis of the severity of an incident; the evaluation of possible response actions for effectiveness and environmental impact.

- Mitigation - The implementation of the best response action and followup activities.

This manual addresses the first and second steps relative to potential for atmospheric contamination and resulting exposure.

The assessment procedures for potential atmospheric contamination in this manual draw upon data and information developed in the characterization phase in order to provide a tool for performing parts of the assessment phase when atmospheric contamination is suspect. The EPA Field Guide for Scientific Support Activities Associated with Superfund Emergency Response (Battelle PNL, 1982) provides an excellent framework within which to view these procedures as part of the arsenal of the emergency response team for assessments of hazardous substance releases. This field guide identifies the calculation of transport rates of hazardous materials as an important element in the assessment phase. When entrainment and atmospheric transport of hazardous substances is important at an emergency response site, these calculations can be made with the procedures described herein based on the methodology assumptions and data expected to be available within the emergency response time frame.

2.1 APPLICATION SCENARIOS

Surface contamination by hazardous materials may result from surface spills; seepage from waste injection operations, waste storage/burial sites; and upward migration from leaks in underground containers (i.e., waste or storage) or pipelines. The rapid assessment procedures are designed for application in two typical scenarios, or cases, based on the temporal nature of the release:

- A typical hazardous waste site or chemical/waste storage facility where the depth of surface contamination provides a relatively continuous and constant potential for emissions over an extended period of time (e.g., years).

- A typical spill incident where the contaminant is highly exposed in a relatively thin surface layer such that emissions can be expected to decay significantly over a relatively short period of time (e.g., weeks or months).

The assumption of a constant release either on a continuous or intermittent basis is necessary for the analytical solutions which have been developed for application within the emergency response time frame. Consequently, although actual releases may be time decaying, the user will need to approximate the actual release as a constant over a given exposure period. However, the constant can be adjusted to reflect the decrease in release rate as the surface contamination is depleted.

Superimposed on the temporal nature of the release is the averaging time of concern for the assessment of resulting atmospheric contamination. The averaging time may represent either long-term (monthly, annual) conditions or short-term (24-hr) "worst-case" conditions. Thus, the time period of concern and the temporal nature of the release jointly determine the appropriate type of analysis (i.e., annual average versus worst-case) and parameter estimates for the driving force behind contaminant transport.

2.2 METHODOLOGY FLOWCHART

The overall flowchart for the rapid assessment methdology is shown in Figure 2-1. Prior to initiating application of these procedures, the On-Scene Coordinator (OSC) at the emergency response site must determine that (a) the potential for atmospheric contamination exists, and (b) an assessment of the potential or current extent of contamination must be made within the 24-hr emergency response time frame. These decisions will be based on the results of the characterization phase of the emergency response effort and will depend on current conditions (e.g., extent of contamination of surface material, weather forecasts), contaminant characteristics (e.g., toxicity, solubility, sorption, volatility), and site characteristics (e.g., soil characteristics, distance to populated areas). If no emergency assessment is deemed necessary, the procedures in this manual should not be used, except as preliminary guidance for subsequent detailed sampling, analysis, and investigations. If an emergency assessment is deemed necessary, the steps in Figure 2-1 should be followed.

The rapid assessment methodology is directed to estimation of respirable particulate inhalation exposure of people living in the vicinity of a surface contamination site. The assessment methodology consists of three sequential estimating procedures as described in the following subsections.

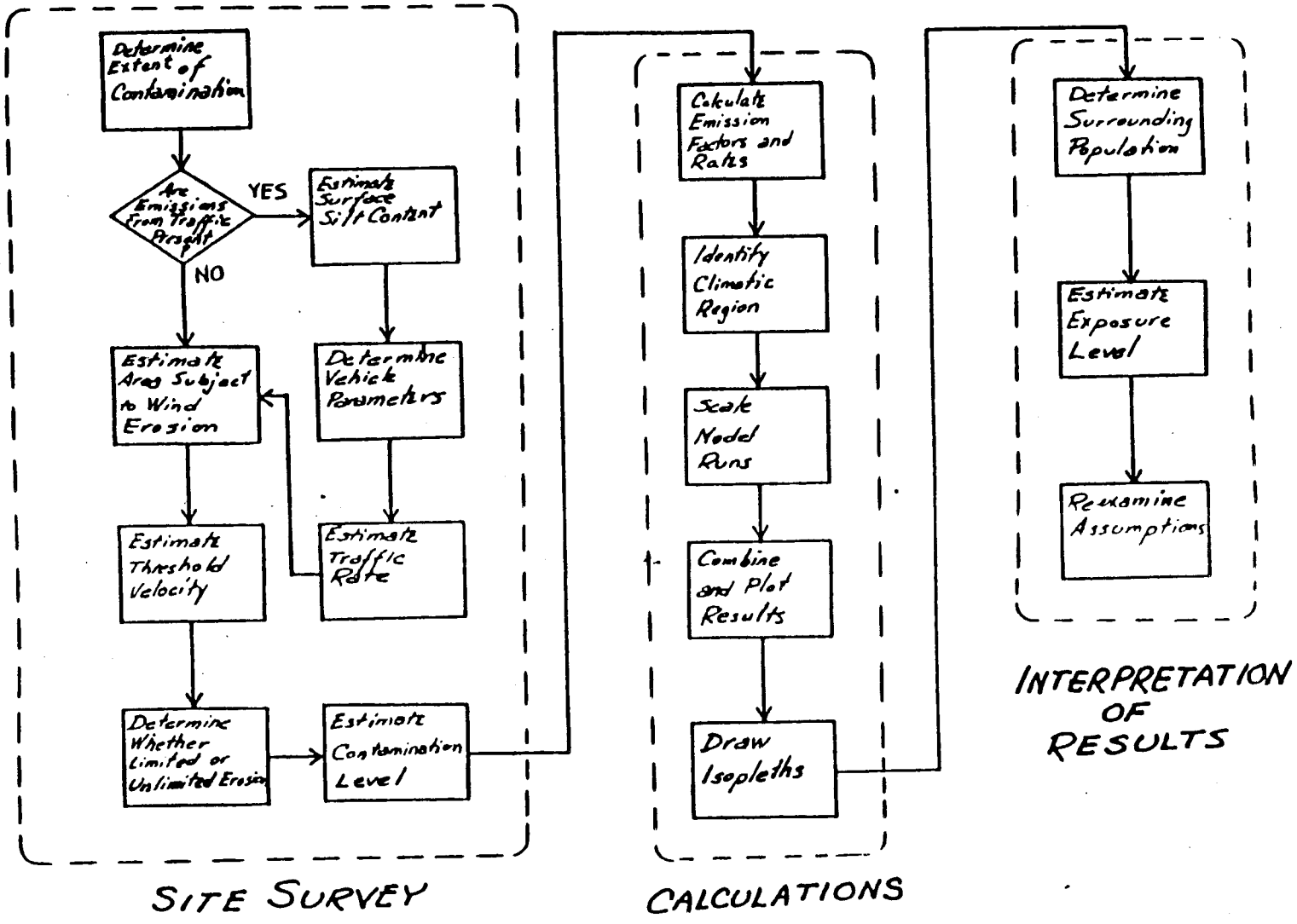


Figure 2-1. Diagram of Assessment Procedure

Step 1 - Estimation of Emissions

The technical approach for estimating respirable (PM_{10}) emissions from surface contamination sites is consistent with the technique used in air pollution assessments. It is based on the following equation:

$$R_{10} = \alpha E_{10} A \qquad (2\text{-}1)$$

where R_{10} = emission rate of contaminant as PM_{10} (mass/time)

α = fraction of contaminant in PM_{10} emissions (mass/mass)

E_{10} = PM_{10} emission factor (mass/source extent)

A = source extent (source-dependent units)

The emission factor is simply the ratio of uncontrolled emissions per unit of source extent. For wind erosion, the source extent is the area of erodible surface. In the case of emissions generated by mechanical disturbance, source extent is also the area (or volume) of the material from which the emissions emanate. Normally, the "uncontrolled" emission factor incorporates the effects of natural mitigation (e.g., rainfall). If anthropogenic control measures (e.g., treating the surface with a chemical binder which forms an artificial crust) are applied to the source, the uncontrolled emission factor must be reduced to reflect the resulting fractional control.

The first step in the estimation of atmospheric particulate emissions from a surface contamination site is to decide whether potential emissions are limited to those generated by wind erosion. If traffic over the site occurs, it is likely that the traffic emissions (or emissions from other forms of mechanical disturbance) substantially exceed emissions from wind erosion. This is because, for most parts of the country, vehicle traffic is an intensive entrainment mechanism in comparison with wind erosion.

For estimation of emissions from traffic on unpaved surfaces, a predictive emission factor equation is recommended in Section 4. This equation, developed from regression analysis of field test data, explains much of the observed variance in road dust emission factor values on the basis of variances in specific road surface and traffic parameters. Thus it provides more reliable estimates of source emissions on a site specific basis than does a single-valued average emission factor. The appropriate measure of source extent for this emission factor is obtained by converting traffic counts and road segment lengths into the total vehicle-distance traveled; in effect this represents the cumulative road surface area from which the emissions are released.

For estimating emissions from wind erosion, either of two emission factor equations are recommended in Section 4 depending on the erodibility of the surface material. In both cases, the appropriate measure of source

extent is the contaminated area of the site. The contaminated surface must be placed in one of two erodibility classes described below. The division between these classes is best defined in terms of the threshold wind speed for the onset of wind erosion.

Nonhomogeneous surfaces impregnated with nonerodible elements (stones, clumps of vegetation, etc.) are characterized by the finite availability ("limited reservoir") of erodible material. Such surfaces have high threshold wind speeds for wind erosion, and particulate emission rates tend to decay rapidly during an erosion event. An emission factor equation developed from wind tunnel data on coarse textured aggregate materials is suitable for this application. It relates the rapidly occurring fine particle loss from the surface to wind speed maxima during periods between mechanical disturbance of the surface.

Bare surfaces of finely divided material such as sandy agricultural soil are characterized by a large number ("unlimited reservoir") of erodible particles. Such surfaces have low threshold wind speeds for wind erosion, and particulate emission rates are relatively time independent at a given wind speed. An emission factor equation based on fine particle emission measurements performed during agricultural wind erosion events is suitable for this application. For either class of erodible surface, the source extent is simply the area contaminated.

As noted in Eq. (2-1), estimation of contaminant emissions requires knowledge of the contaminant levels in the erodible surface material. It is presumed that the surface contamination data which triggered the emergency response will be available. In the case of spills, the estimated level of contamination can be based on the amount of material spilled and the volume of receiving material penetrated by the spill.

Contaminants in particulate form may be present either as discrete solid particles or adsorbed onto soil or other surface aggregate materials. This depends on the physical and chemical interaction between the contaminant species and the surface aggregate. For adsorbed contaminants, there is usually an enrichment of contamination in the finer particle sizes because of larger surface-to-volume ratio. However, in the absence of data on the contamination level of PM_{10} particles in the surface material, it will be assumed that the level of contamination (denoted throughout by the symbol α) in the respirable particulate emissions matches that measured in the bulk surface material.

Step 2 - Estimation of Ambient Concentrations

The primary purpose of this assessment is to provide the user with first-order estimates of atmospheric concentrations and exposures caused by respirable particulate emissions from a surface contamination site. Using the emissions estimates developed in Step 1, the assessment procedure employs atmospheric dispersion models to estimate pollutant transport and dilution under annual average and worst-case 24 hour meteorological conditions. An introduction to air quality dispersion models and the rationale for selection of specific models for this assessment are provided as Appendix C.

Numerous "off-the-shelf" computer models for atmospheric dispersion have been developed in the past. The most common air quality models are contained in the EPA's User's Network for Applied Modeling of Air Pollution (UNAMAP). The applicability of such models within the emergency response time frame, however, is severely constrained by the amount of time required to collect and prepare input data in a suitable format and by the constraint of having immediate access to an implemented model.

It is also possible to develop hand calculation algorithms for use in the assessment process (Versar, 1983; Dynamac, 1983; EPA, 1981). However, this approach requires either restrictive assumptions about the site's meteorology or excessive time to extract information from wind data (which may not be available for the site). Other complications in these hand calculation schemes would involve using a point to represent a source with a definite non-zero areal extent and assuming that the directional distribution of the high-speed winds is identical to that observed over all wind speeds. Both of these complications would result in distortion of the concentration field.

Thus, although computerized models are capable of modeling area sources with emission rates that are functions of wind speed, their direct use is limited by time constraints and accessibility. Hand calculation algorithms are readily implemented but either require restrictive simplification or become unwieldly in terms of application.

The approach adopted in this manual attempts to combine the best features of both options. The manual user scales tabulated output from two relatively sophisticated UNAMAP computer models as a basis for assessing the impact of the site in question. This approach allows the analyst to obtain concentration estimates of a quality comparable to that for computer models while performing calculations that are algebraically simpler than those required for the hand calculation algorithms.

Step 3 - Estimation of Exposure

Human exposure resulting from the air transport of particulate emissions from surface contamination sites is the final aspect of the emergency response assessment procedure. The primary interest of this manual is direct exposure due to inhalation of the airborne contaminant. Although not addressed in this manual, the assessment of acute risk focuses on the worst-case 24-hr exposure, while chronic risk is associated with annual average exposure levels.

When the dispersion modeling is completed, the user will have maps showing the spatial variation of atmospheric contaminant concentrations at breathing height. These maps are overlaid onto a map of the site and surrounding area, and the number of people residing within areas bounded by certain respirable particulate concentration isopleths is then estimated. Thus, the analyst is presented with information about the number of people exposed to specified levels of respirable concentrations of the contaminant.

Indirect exposure resulting from spreading of the surface contamination is also possible. Spreading of the surface contamination can be attributed to settling of airborne emissions from the original site. Such surface spreading can constitute an exposure risk, especially to field workers or children at play. In addition, particulate settling may result in contamination entering the food chain. The treatment of indirect exposure, however, is beyond the scope of this manual.

2.3 CRITICAL CONTAMINANT AND SITE CHARACTERISTICS

The EPA has compiled a list of 271 hazardous chemicals that are abundant and dangerous enough to be singled out for special attention (Federal Register, 1981). This list provides a good starting point for considering the properties such as solubility, physical state, viscosity, size distribution, chemical reactivity, etc., which allows one to divide the chemicals into groups for which similar fates in the soil would be expected. For example, a study by Wentsel et al. (1981) on land restoration recommends physical removal for 98 of the 271 hazardous chemicals. Of these 98 chemicals, 18 are insoluble (Table 2-1) and may offer a long-term air pollution hazard because they will not be removed from the soil surface by rainfall. Thus, transport by wind to populations vulnerable to the chemical contaminant exposure may be possible for long periods following the contamination.

TABLE 2-1. EXAMPLE INSOLUBLE HAZARDOUS CHEMICALS FOR THE RECOMMENDED CLEANUP PROCEDURE IS PHYSICAL REMOVAL

Common name	Synonyms
Aldrin	Octalene, HHDN
Arsenic trioxide	Arsenious acid, arsenious oxides, white arsenic
Arsenic trisulfide	Arsenious sulfide, yellow arsenic sulfide
Calcium arsenate	Tricalcium orthoarsenate
Chlordane	Toxichlor, chlorodan
Dichlone	Phygon, dichoronaphtoquinone
Dieldrin	Alvit
Diuron	DCMU, DMU
Endosultan	Thiodan
Endrin	Mendrin, Compound 269
Kelthane	Di(p-chlorophenyl)-trichloromethycarbonol, DTMC, dicofol
Lead arsenate	
Lead sulfate	
Lead sulfide	Galena
Lindane	Gamma-BHC, Gamma-benzene hexachloride
Polychlorinated biphenyls	PCB, Arochor, polychlorinated diphenyls
Tetraethyl lead	Lead tetraethyl, TEL
Toxaphene	Camphechlor

The extent of contaminant transport following releases to the land surface and subsequent entrainment to the atmosphere depends upon a variety of critical contaminant and site characteristics. This section briefly describes the important contaminant and site characteristics. It provides the user with an understanding of the types of information needed to perform a valid assessment. Guidelines for translating these characteristics into required specific parameter values required by the assessment procedures are provided in Section 4.

2.3.1 Critical Contaminant Characteristics

To assess the potential for atmospheric contamination in an emergency response situation, several properties of the compound or waste must first be determined, especially in the case of chemical spills. Much of this information may be difficult to accurately quantify within a 24-hr time frame, but it is likely that an applicable range of values will be estimated. Some properties are used directly in the assessment or to estimate parameters, while others are needed to interpret the results. Those characteristics deemed crucial to an informed assessment are discussed below:

1. Contaminant identity - The identities of the contaminants must be known to determine those physical/chemical properties necessary for assessing pollutant fate and migration. The physical state of the contaminant (liquid or solid) should be assessed as part of the identification process. Within the emergency response time frame, it may be possible to identify only general classes of chemicals rather than specific compounds. In such instances, parameter estimation will be especially difficult.

2. Extent of the contamination - The extent of the surface contamination must be defined to determine the source term used in estimating transport into the atmosphere. This assessment should provide an estimate of the mass fraction of the contaminant in the surface material. Ideally, the level of contamination in the PM_{10} fraction of the surface material is needed. In addition, the total ground area contaminated by the spill or the disposal operation should be ascertained. In the case of a spill it is necessary to account for contaminant losses by volatilization into the air, runoff, and containment or removal measures on the land surface in estimating the extent of residual contamination. Information on the volatility and reactivity of the waste may be required in making this assessment.

3. Volatility - The volatility of an organic liquid affects its loss to the atmosphere as a vapor. This is especially important in the case of spills where a high degree of atmosphere exposure is typical. As with most other critical contaminant properties, volatility is strongly temperature dependent.

4. Solubility - The solubility of a compound affects its mobility in the soil. The spreading of the contaminant from a surface spill is usually controlled by its tendency to dissolve in the water moving through the soil.

A material's solubility may also affect the ease with which it can adsorb on soil particles, with less soluble wastes being more easily adsorbed. The existence of solvents other than water should also be determined since it can affect the compound's miscibility with soil water.

5. Adsorption - Adsorption can be a significant means of retarding contaminant movement through the soil. It is a property dependent upon both the nature of the compound and the soil. Adsorption capabilities for organic, nonionic compounds are often described in terms of adsorption (or partition) coefficients for a particular compound/soil combination. These coefficients are often estimated from the organic carbon (or organic matter) content of the soil and the organic carbon partition coefficient (which in turn can be estimated from compound characteristics such as the octanol/water partition coefficient). Adsorption of ionic compounds is also a function of ion exchange capacities and clay type and content. This is especially important for soils or media with low organic matter.

6. Degradation - Degradation by both chemical and biological mechanisms is important because it can reduce levels of contaminants in the surface material. Common degradation mechanisms in the environment are hydrolysis, photolysis, biodegradation, chemical oxidation, and radioactive decay. Hydrolysis and chemical oxidation are important primarily for contaminants in soils. Photolysis can occur only on the surface of the soil. Biodegradation is most important in the top few feet of soil where bacterial concentrations are high. Radioactive decay occurs in all environments under all conditions.

6. Toxicity - To assess the hazard of any predicted or observed atmospheric contamination, the toxicity of the pollutants must be determined. Since nearly all chemicals are toxic at very high concentrations, the concern in this assessment is for materials that are moderately to severely toxic or are carcinogenic, mutagenic, or teratogenic to humans and other organisms.

7. Density, viscosity and surface tension - These compound parameters are important in evaluating the penetration characteristics of the contaminant into the soil and the potential for particle reentrainment into the atmosphere.

2.3.2 Critical Site Characteristics

To assess potential atmospheric contamination at a hazardous waste or spill site, a number of site characteristics are important in addition to the contaminant characteristics discussed above. The discussions below are intended to provide an overview of the information needed to characterize an emergency response site in appropriate detail to estimate contaminant release to and transport in the air environment; specific guidelines on parameter estimation are presented in Sections 3 and 4.

Emissions from open dust sources associated with contaminated land areas exhibit a high degree of variability from one site to another, and emissions at any one site tend to fluctuate widely. The site characteristics which

cause these variations may be grouped into two categories: measures of energy expended by wind or machinery interacting with the contaminated surface (for example, the wind speed or the speed of a vehicle traveling over the surface); and properties of the contaminated surface material (for example, the content of suspendable fines in the surface material and its moisture content or, for a crusted surface, the strength of the crust).

1. Surface material texture - The dry particle size distribution of the exposed soil or surface material determines its susceptibiliy to wind erosion and mechanical entrainment. Wind forces move soil by three transport modes: saltation, surface creep, and suspension. Saltation describes particles, ranging in diameter from about 75 to 500 μm that jump or bounce within a layer close to the air-surface interface. Particles transported by surface creep range in diameter from about 500 to 1,000 μm. These surface creep particles move very close to the ground propelled by wind stress and the impact of smaller particles transported in saltation. Particles smaller than about 75 μm in diameter move by suspension and tend to follow air motions. The upper size limit of silt particles (75 μm in diameter) is roughly the smallest particle size for which size analysis by dry sieving is practical, and this particle size is also a reasonable upper limit for particulates which can become suspended. The threshold wind speed for the onset of saltation, which drives the wind erosion process, is also dependent on soil texture, with 100 to 150 μm particles having the lowest threshold speed.

2. Surface material moisture - Dust emissions are known to be strongly dependent on the moisture level of the emitting material. Water acts as a dust suppressant by forming cohesive moisture films among the discrete grains of surface material. In turn, the moisture level depends on the moisture added by natural precipitation and on the moisture removed by evaporation and moisture movement beneath the surface. The evaporation rate depends on the degree of air movement over the surface soil texture, clay minerology and crust presence. The moisture holding capacity of the air is also important, and it correlates strongly with the surface temperature. Vehicle traffic intensifies the drying process primarily by increasing air movement over the surface.

3. Nonerodible elements - Nonerodible elements such as clumps of grass or stones (larger than about 1 cm in diameter) on the surface, consume part of the shear stress of the wind which otherwise would be transferred to erodible soil. Surfaces impregnated with a large density of nonerodible elements behave as having a "limited reservoir" of erodible particles, even if the material protected by nonerodible elements is of itself highly erodible. Wind-generated emissions from such surfaces decay sharply with time, as the particle reservoir is depleted. Surfaces covered by unbroken grass are virtually nonerodible.

4. Crust formation - Following the wetting of a soil or other surface material, fine particles will move to form a surface crust. The surface crust acts to hold in soil moisture and resist erosion. The degree of protection that is afforded by a soil crust to the underlying soil may be measured by the modulus of rupture and thickness of the crust. This modulus

of rupture is roughly a measure of hardness of the crust. A soil which lacks a surface crust (for example a disturbed soil or a very sandy soil) is much more susceptible to wind erosion.

5. Frequency of mechanical disturbance - Emissions generated by wind erosion are also dependent on the frequency of disturbance of the erodible surface. A disturbance is defined as an action which results in the exposure of fresh surface material. This would occur whenever aggregate material is either added to or removed from the old surface. A disturbance of an exposed area may also result from the turning of surface material to a depth exceeding the size of the largest pieces of material present. Each time that a surface is disturbed, its erosion potential is increased by destroying the mitigative effects of crusts, vegetation and friable non-erodible elements and by exposing new surface fines. Although vehicular traffic alters the surface by pulverizing surface material, this effect probably does not restore the full erosion potential, except for surfaces that crust before substanital wind erosion occurs. In that case, breaking of the crust over the area of the tire/surface contact once again exposes the erodible material beneath.

6. Wind speed - Agricultural scientists have established that total soil loss by continuous wind erosion is dependent on the cube of wind speed. More recent work has shown that the loss of particles in suspension mode follows the same dependence. Soils protected by non-erodible elements or crusts exhibit a weaker dependence of suspended particulate emissions on wind speed. In fact, mean atmospheric wind speeds in many areas of the country are not sufficient to initiate wind erosion from "limited reservoir" surfaces. However, wind gusts may quickly deplete a substantial portion of the erosion potential of surfaces having a "limited reservoir" of erodible particles. In addition, because erosion potential (mass of particles constituting the "limited reservior") increases rapidly with increasing wind speed, estimated emissions should be related to the gusts of highest magnitude.

The routinely measured meteorological variable which best reflects the magnitude of wind gusts is the fastest mile. The quantity represents the wind speed corresponding to the whole mile of wind movement which has passed by the 1-mile contact anemometer in the least amount of time. Daily measurements of the fastest mile are presented in the monthly Local Climatological Data (LCD) summaries. The duration of the fastest mile, typically about 1-2 min (for fastest miles of 30-60 mph, respectively), matches well with the half-life (i.e., the time required to remove one-half the erodible particles on the surface) of the erosion process. It should be noted, however, that peak wind speeds can significantly exceed the daily fastest mile.

SECTION 3

SITE SURVEY AND DATA GATHERING

3.1 ASSESSMENT OF EXTENT OF SURFACE CONTAMINATION

As stated in Section 2.1, it is presumed that surface contamination data will be available for the spill site or the abandoned waste disposal site being assessed. Ideally, the surface contaminant levels will have been determined for that fraction of the surface material which has the potential to become airborne, i.e., the silt fraction (defined in this manual as particles passing a 200 mesh screen on dry sieving). In any case, unless data can be obtained on the fine particle enrichment of contamination for classes of compounds which are readily adsorbed onto soil particles, the analyst should assume that the level of contamination in the particulate emissions matches that measured in the bulk surface material.

As an alternative to contamination measurements for chemical spills, it may be possible to estimate the level of contamination based on the amount of material spilled and the volume of receiving material penetrated by the spill. Although the size of the surface affected by the spill may be easily determined, the depth of penetration depends on several factors such as viscosity and surface tension of the chemical and the porosity of the receiving surface. For volatile chemicals, that portion of the spill which evaporates must also be accounted for.

Unless the level of contamination in the surface material is uniform over the full extent of the contaminated area, it is desirable to know the spatial distribution of surface contamination. Also, it is implied that there are well defined boundaries to the contaminated area. Generally, except for spills, such will not be the case because of the spreading of contamination over a period of time by successive entrainment/deposition processes.

If no data are available on the distribution of contamination and its boundaries, the emergency response team must estimate the size of the contaminated area based on historical data on the typical size ranges of contaminated areas of various types. Also, surface features (cover, topography, surface texture, etc.) can be used to delineate site boundaries. A worksheet has been prepared for use in conducting a site survey and is shown in Figure 3-1. An expanded version of the site survey decision flowchart is given in Figure 3-2.

SITE SURVEY WORKSHEET

By _____ Date _____ Reviewed by _____ on _____

I GENERAL

DATE OF { INCIDENT _____ / DISCOVERY _____ }

SITE _____

LOCATION _____ COMPOUND _____

LAT/LONG _____ CONTAM. LEVEL (α) _____ (units)

SKETCH OF SITE (Indicate north, landmarks, approximate dimensions

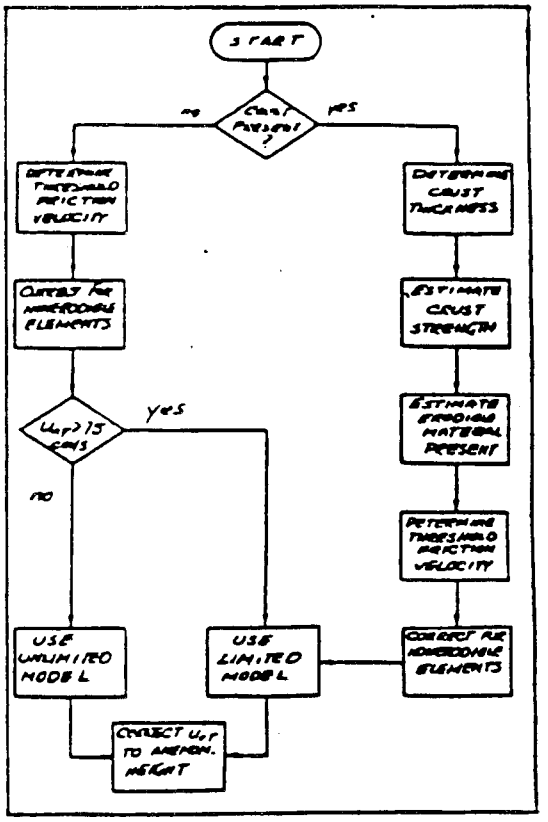
II. MECHANICAL RESUSPENSION (Omit if no evidence of traffic is found)

PARAMETER	VALUE	DATA SOURCE/COMMENTS
SILT	%	
AVG. VEH. SPEED	kph	
AVG. VEH. WEIGHT	Mg	
AVG. NO. WHEELS PER VEHICLE		
AVG. DAILY TRAFFIC	veh/day	
CONTAMINATED TRAVEL LENGTH	km	

Figure 3-1. Site Survey Worksheet

III. WIND EROSION

The site must be classified as either of limited or unlimited erosion potential. To make this decision, first look for evidence of crusting, and then follow the steps in the flowchart to right. Also, refer to Section 3.0 of the manual for guidance in the estimation processes.



COMPLETE APPROPRIATE SECTION BELOW

PARAMETER	VALUE	DATA SOURCE/COMMENTS
LIMITED		
THRESHOLD SPEED	m/s	
FREQ. OF DISTURBANCE	/mo	
FRACTION OF VEGETATIVE COVER		
UNLIMITED:		
THRESHOLD SPEED	m/s	
FRACTION OF VEGETATIVE COVER		

Figure 3-1. (concluded)

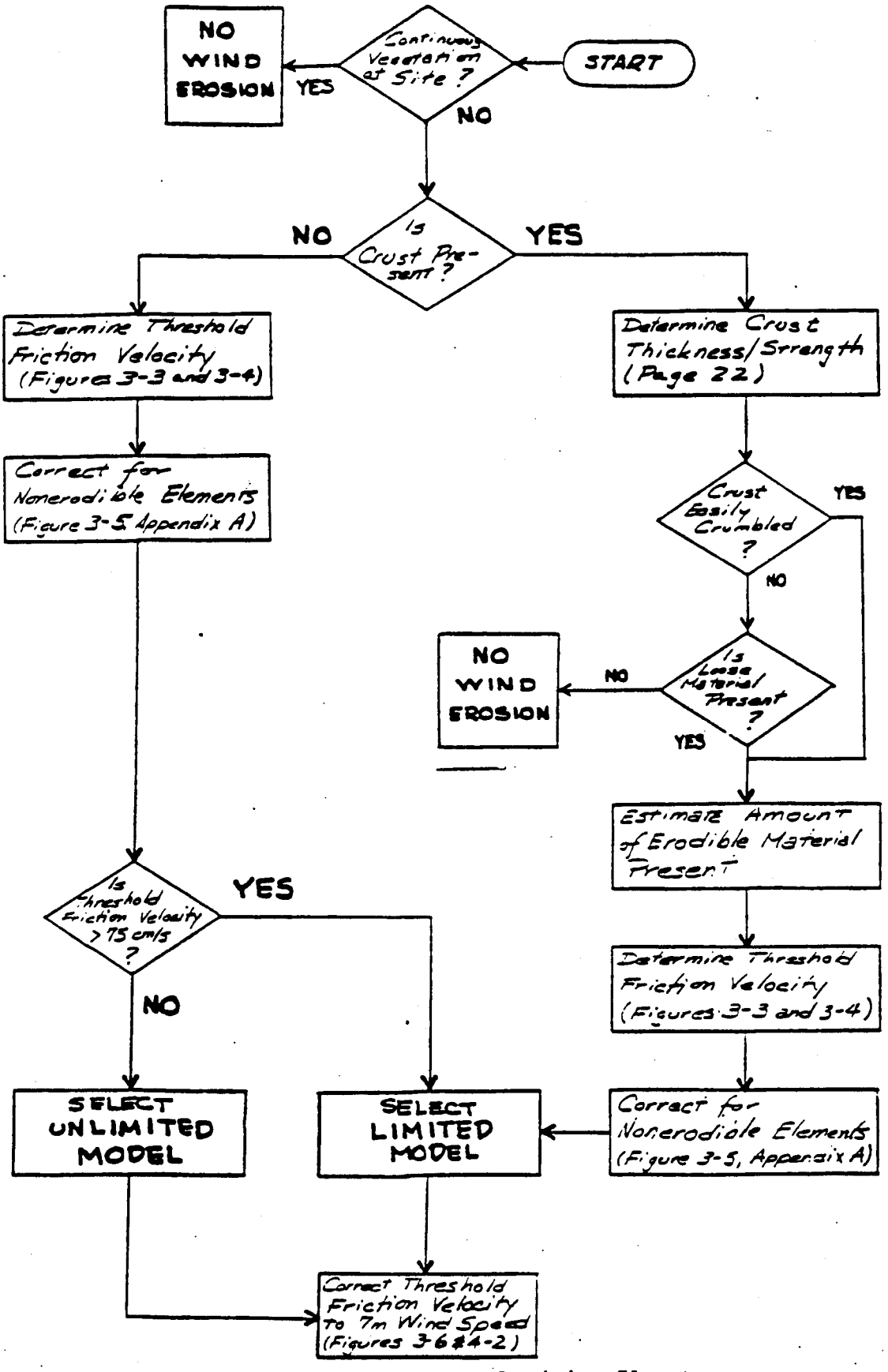


Figure 3-2. Site Survey Decision Flowchart

The second step in the estimation of emissions from an abandoned waste dump or spill site is the determination of the potential for entrainment of contaminated soil by wind or by mechanical disturbance. This determination will be based on a visual site inspection coupled with optional hand sieving of surface material.

3.2 CHARACTERIZATION OF WIND EROSION POTENTIAL

With regard to estimating particulate emissions from wind erosion of contaminated surface material, site inspection can be used to determine the potential for continuous wind erosion. The two basic requirements for wind erosion are that the surface be dry and exposed to the wind. For example, if the contaminated site lies in a swampy area or is covered by unbroken grass, the potential for wind erosion is virtually nil. The same would be true if a substance spilled or otherwise applied to the surface solidifies and acts as impervious binder. If, on the other hand, the vegetative cover is not continuous over the contaminated surface, then the plants are considered to be nonerodible elements which absorb a fraction of the wind stress that otherwise acts to suspend the intervening contaminated soil.

For estimating emissions from wind erosion, either of two emission factor equations are recommended (Section 4) depending on the erodibility of the surface material. Based on the site survey, the contaminated surface must be placed in one of two erodibility classes described below. The division between these classes is best defined in terms of the threshold wind speed for the onset of wind erosion.

Nonhomogeneous surfaces impregnated with nonerodible elements (stones, clumps of vegetation, etc.) are characterized by the finite availability ("limited reservoir") of erodible material. Such surfaces have high threshold wind speeds for wind erosion, and particulate emission rates tend to decay rapidly during an erosion event. On the other hand, bare surfaces of finely divided material such as sandy agricultural soil are characterized by an "unlimited reservoir" of erodible particles. Such surfaces have low threshold wind speeds for wind erosion, and particulate emission rates are relatively time independent at a given wind speed.

For surface areas not covered by continuous vegetation the classification of surface material as either having a "limited reservoir" or an "unlimited reservoir" of erodible surface particles is determined by estimating the threshold friction velocity. Based on the authors' analysis of wind erosion research, the dividing line for the two erodibility classes is a threshold friction velocity of about 75 cm/sec. This somewhat arbitrary division is based on the observation that highly erodible surfaces, usually corresponding to sandy surface soils that are fairly deep, have threshold friction velocities below 75 cm/sec. Surfaces with friction velocities larger than 75 cm/sec tend to be composed of aggregates too large to be eroded mixed in with a small amount of erodible material or of crusts that are resistent to erosion (Gillette et al., 1982).

The cutoff friction velocity of 75 cm/sec corresponds to an ambient wind speed of about 10 m/sec (22 mph), measured at a height of about 7 m.

In turn, a specific value of threshold friction velocity for the erodible surface is needed for either wind erosion emission factor equation (model).

Crusted surfaces are regarded as having a "limited reservoir" of erodible particles. Crust thickness and strength should be examined during the site inspection, by testing with a pocket knife. If the crust is more than 0.6 cm thick and not easily crumbled between the fingers (modulus of rupture > 1 bar), then the soil may be considered nonerodible. If the crust thickness is less than 0.6 cm or is easily crumbled, then the surface should be treated as having a limited reservoir of erodible particles. If a crust is found beneath a loose deposit, the amount of this loose deposit, which constitutes the limited erosion reservoir, should be carefully estimated.

For uncrusted surfaces, the threshold friction velocity is best estimated from the dry aggregate structure of the soil. A simple hand sieving test of surface soil is highly desirable to determine the mode of the surface aggregate size distribution by inspection of relative sieve catch amounts, following the procedure specified in Figure 3-3. The threshold friction velocity for erosion can be determined from the mode of the aggregate size distribution, following a relationship derived by Gillette (1980) as shown in Figure 3-4.

A more approximate basis for determining threshold friction velocity would be based on hand sieving with just one sieve, but otherwise follows the procedure specified in Figure 3-3. Based on the relationship developed by Bisal and Ferguson (1970), if more than 60% of the soil passes a 1-mm sieve, the "unlimited reservoir" model will apply; if not, the "limited reservoir" model will apply. This relationship has been verified by Gillette (1980) on desert soils.

If the soil contains nonerodible elements which are too large to include in the sieving (i.e., greater than about 1 cm in diameter), the effect of these elements must be taken into account by increasing the threshold friction velocity. Marshall (1971) has employed wind tunnel studies to quantify the increase in the threshold velocity for differing kinds of nonerodible elements. His results are depicted in terms of a graph of the rate of corrected to uncorrected friction velocity versus L_c (Figure 3-5), where L_c is the ratio of the silhouette area of the roughness elements to the total area of the bare loose soil. The silhouette area of a nonerodible element is the projected frontal area normal to the wind direction.

A value for L_c is obtained by marking off a 1 m x 1 m surface area and determining the fraction of area, as viewed from directly overhead, that is occupied by non-erodible elements. Then the overhead area should be corrected to the equivalent frontal area; for example, if a spherical nonerodible element is half imbedded in the surface, the frontal area is one-half of the overhead area. Although it is difficult to estimate L_c for values below 0.05, the correction to friction velocity becomes less sensitive to the estimated value of L_c.

FIELD PROCEDURE FOR DETERMINATION OF THRESHOLD FRICTION VELOCITY*

1. Prepare a nest of sieves with the following openings: 4 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm. Place a collector pan below the bottom sieve (0.25 mm opening).

2. Collect a sample representing the surface layer of loose particles (approximately 1 cm in depth for an uncrusted surface), removing any rocks larger than about 1 cm in average physical diameter. The area to be sampled should not be less than 30 cm x 30 cm.

3. Pour the sample into the top sieve (4 mm opening), and place a lid on the top.

4. Rotate the covered sieve/pan unit by hand using broad sweeping arm motions in the horizontal plane. Complete 20 rotations at a speed just necessary to achieve some relative horizontal motion between the sieve and the particles.

5. Inspect the relative quantities of catch within each sieve and determine where the mode in the aggregate size distribution lies, i.e., between the opening size of the sieve with the largest catch and the opening size of the next largest sieve.

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* Adapted from a laboratory procedure published by W. S. Chepil (1952).

Figure 3-3.

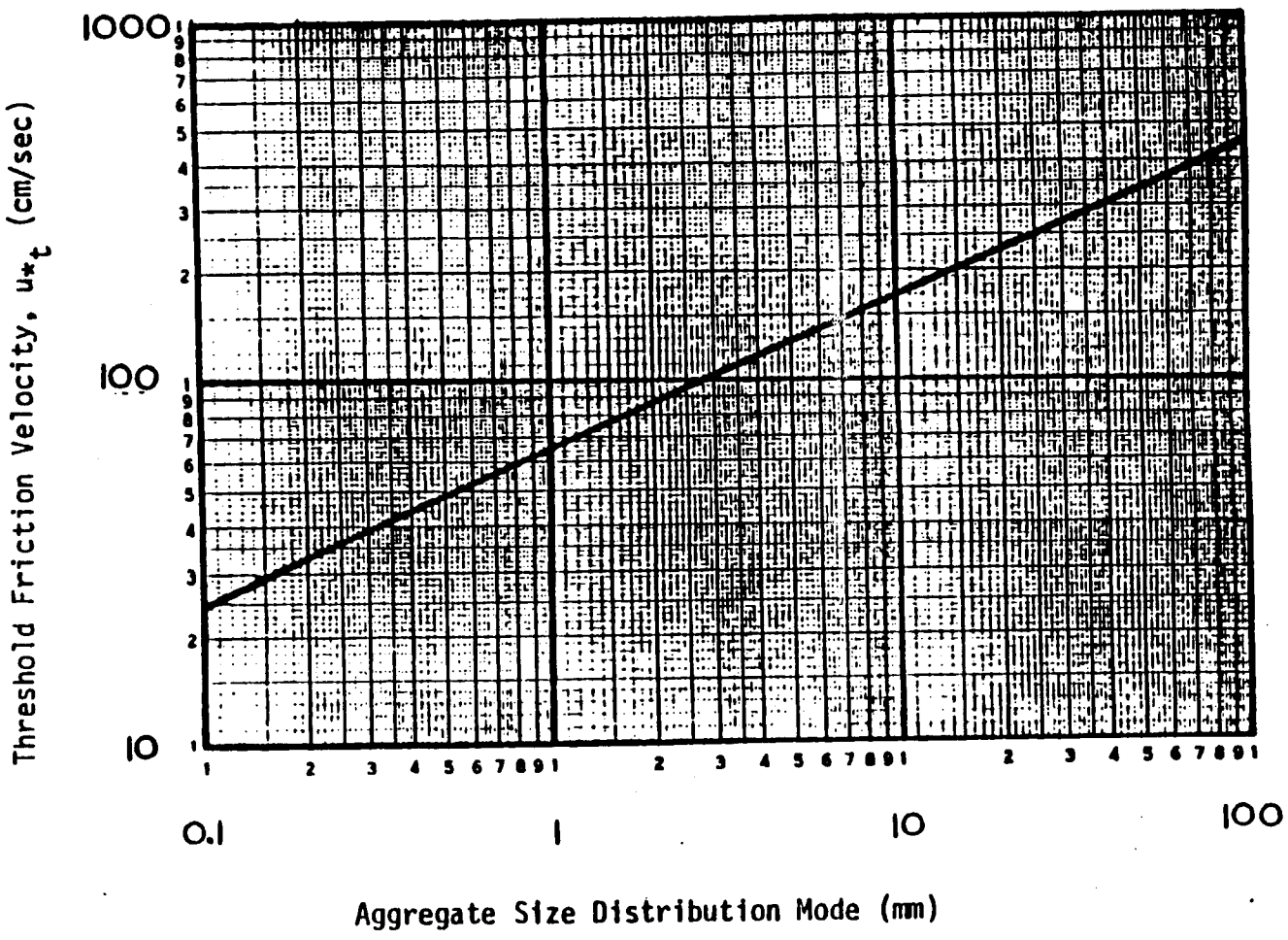

Figure 3-4. Relationship of Threshold Friction Velocity to Size Distribution Mode

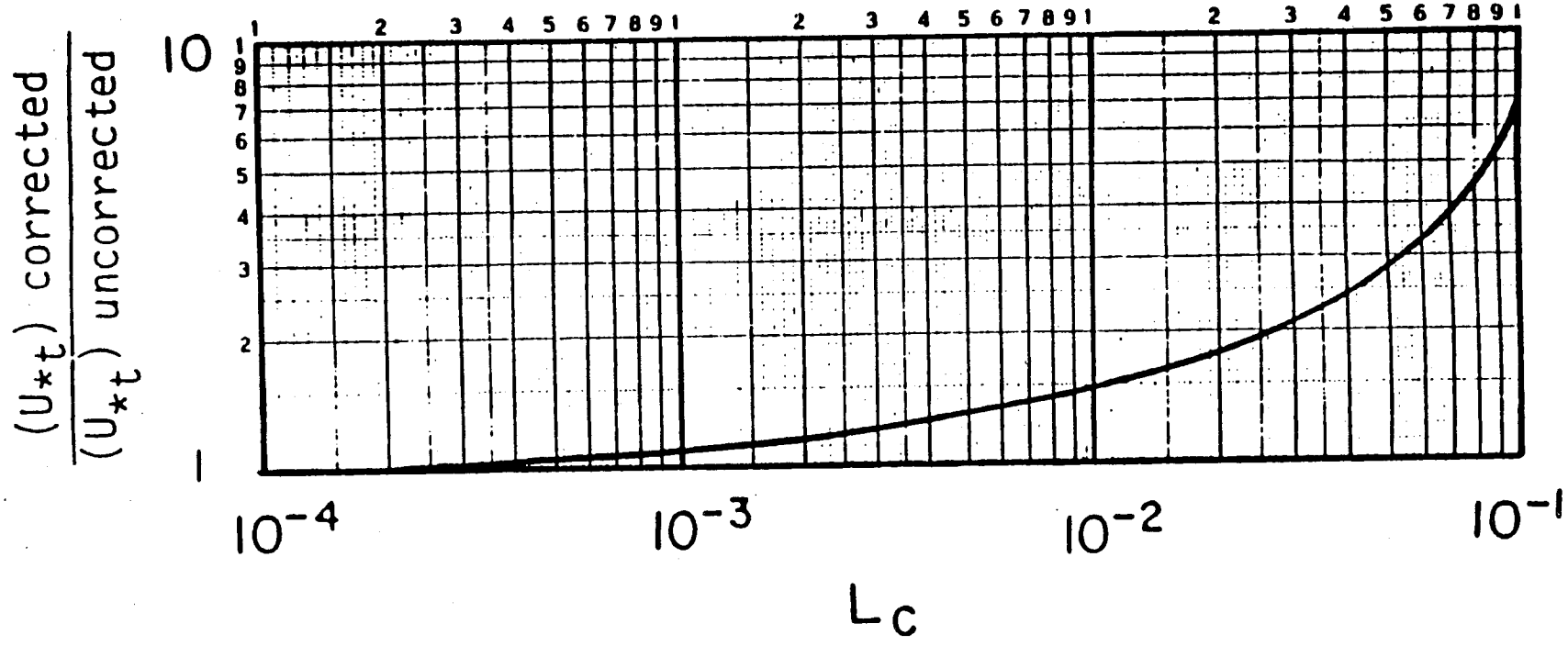

Figure 3-5. Increase in Threshold Friction Velocity with L_c

The difficulty in estimating L_c also increases for small non-erodible elements. However, because small non-erodible elements are more likely to be evenly distributed over the surface, it is usually acceptable to examine a smaller surface area, e.g., 30 cm x 30 cm. The photographs of various non-erodible element distributions presented in Appendix A can be used as an aid in estimating L_c for surfaces with small non-erodible elements. These photographs illustrate the physical appearance corresponding to various values of L_c.

The least acceptable technique for classifying the erodibility of the surface material is by visual surface examination and matching with the photographs given in Appendix A. Once again, loose sandy soils fall into the high erodibility ("unlimited reservoir"). These soils do not promote crust formation, and show only a brief effect of moisture addition by rainfall. On the other hand, compacted soils with a tendency for crust formation fall into the low ("limited reservoir") erodibility group. Clay content in soil, which tends to promote crust formation, is evident from crack formation upon drying.

The roughness height, z_o, which is related to the size and spacing of surface roughness elements, is needed to convert the friction velocity to the equivalent wind speed at the typical weather station sensor height of 7 m above the surface. Figure 3-6 depicts the roughness height scale for various conditions of ground cover (Cowherd and Guenther, 1976). The conversion to the 7 m value is discussed in Section 4 (Figure 4-2).

In addition to these surface properties, it is also important that the field personnel note the location and orientation of significant topographic features that are likely to influence the dispersion of contaminated material from the site. Significant topographic features will include not only the terrain of the surrounding area but also the large-scale roughness elements such as trees and buildings that might enhance or obstruct the wind flow for the site in question. A consideration of these features is important in the proper interpretation of the modeling results presented in Section 4.2. In order to ensure the best possible characterization of the local-scale wind flow, it is recommended that the response team contact both the nearest National Weather Service office and an American Meteorological Society (AMS) Certified Consulting Meteorologist[1].

3.3 CHARACTERIZATION OF MECHANICAL RESUSPENSION BY VEHICLE TRAFFIC

The most typical type of intensive mechanical disturbance occurs with vehicle travel over the contaminated surface material. The occurrence of traffic over the site can be determined by inspection of the site for existence of roads. Other less common forms of mechanical disturbance are associated with any operation which moves or turns over surface material (i.e., scraping, grading, tilling, etc.). All of these operations not only release suspended particulate matter into the air, but greatly increase the potential for subsequent wind erosion by destroying protective surface crusts and removing vegetative cover. Because these types of disturbance are rare, the following discussion is limited to vehicle traffic as the typically significant mechanical resuspension process.

[1] A list of Certified Consulting Meteorologists is available from the American Meteorological Society, 45 Beacon Street, Boston, Massachusetts 02108. Telephone: (617) 227-2425

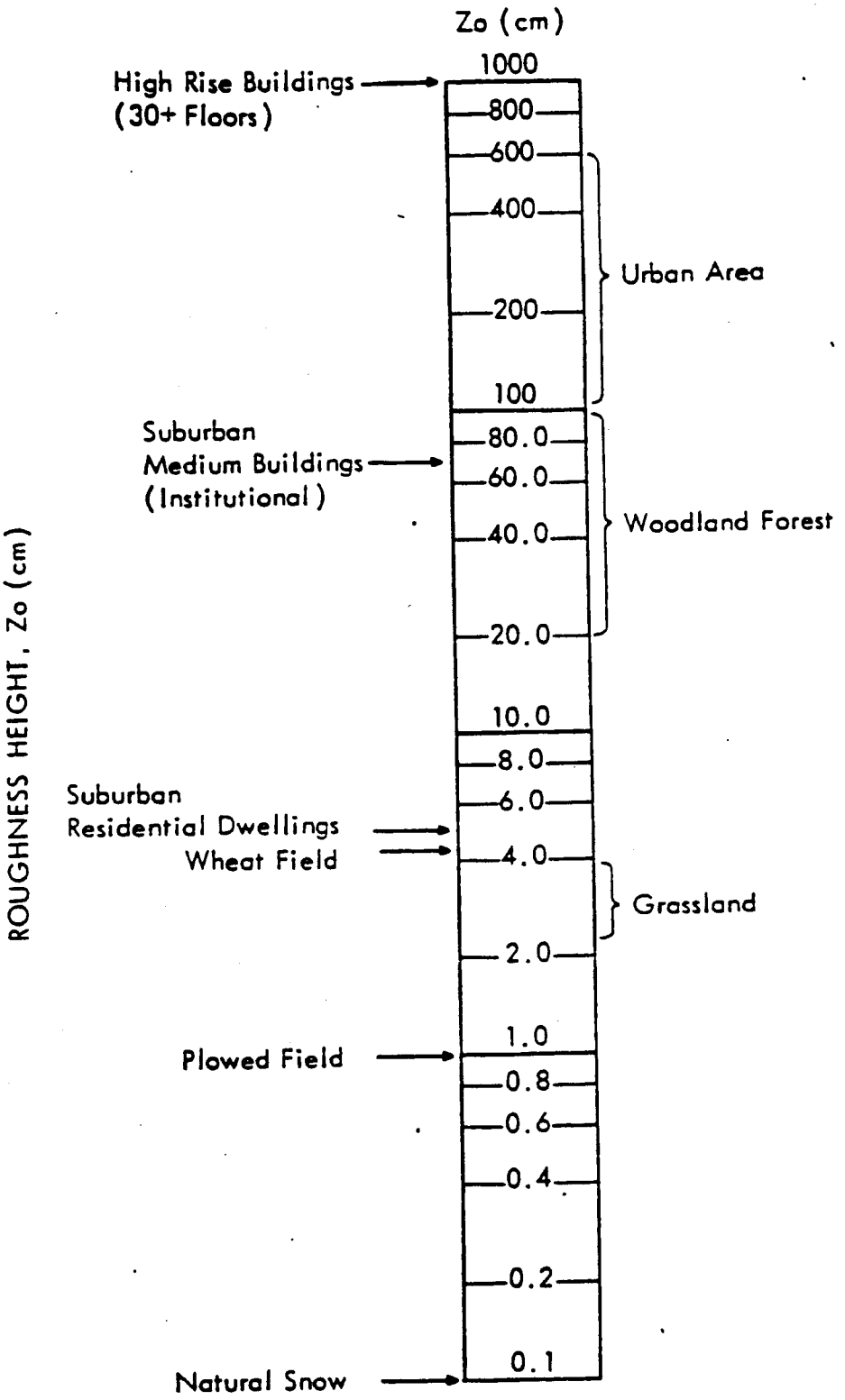

Figure 3-6. Roughness Heights for Various Surfaces (Cowherd and Guenther, 1976)

The emission factor equation for vehicle travel on unpaved surfaces, as presented in Section 4, requires estimates of site-specific traffic and surface parameters. Average vehicle speed and number of wheels can be estimated from direct observation of traffic, site inspection of road condition, and interviews with people living or working near the site. Vehicle weight can be estimated from vehicle type and number of wheels, using a chart presented in Section 4. Default values for road surface silt content are also provided.

SECTION 4

CALCULATIONS AND GATHERING OF RESULTS

The assessment procedure developed in this manual follows a source-oriented approach. It requires the user first to estimate particulate emission rates for the contamination site, and then to link these estimates to the results of a general Gaussian dispersion algorithm in order to estimate ambient concentrations of contaminant in the form of respirable particulate matter. The following sections describe the emission factor models used to estimate contaminant emissions generated by wind erosion and mechanical entrainment, and the procedure for "translating" these results into ambient concentrations and associated exposures.

4.1 CALCULATION OF AVERAGE/WORST-CASE EMISSION RATES

This section describes the emission factor models used to estimate particulate emissions generated by mechanical entrainment and by wind erosion of contaminated surface material. Also this section describes the sources of data and the procedures used to estimate the parameters required for input to the emission models.

In the case of wind erosion emissions, there are no "ready-made" models fully capable of meeting the requirements of rapid assessment. As such, the information presented in Sections 4.1.1 and 4.1.2 provides best estimates for wind generated emissions, based on current knowledge of the suspension of surface material by wind action.

4.1.1 Wind Erosion from Surfaces with Limited Erosion Potential

For estimating respirable particulate emissions from surfaces characterized by a "limited reservoir" of erodible material, a predictive emission factor equation developed by Cowherd (1983) from field measurements using a portable wind tunnel at surface mines is recommended. In relating the annual average rate of respirable particulate emissions to surface and climatic factors, the equation takes the following form:

$$E_{10} = 0.83 \frac{f\ P(u^{+})\ (1-V)}{(PE/50)^2} \qquad (4\text{-}1)$$

where: E_{10} = PM_{10} emission factor, i.e., annual average PM_{10} emission rate per unit area of contaminated surface (mg/m^2-hr)

f = frequency of disturbance per month

u^+ = observed (or probable) fastest mile of wind for the period between disturbances (m/s)

$P(u^+)$ = erosion potential, i.e., quantity of erodible particles present on the surface prior to the onset of wind erosion (g/m^2)

V = fraction of contaminated surface area covered by continuous vegetative cover (equals 0 for bare soil)

PE = Thornthwaite's Precipitation Evaporation Index used as a measure of average soil moisture content

Although Equation 4-1 is based primarily on field tests of nonsoil surfaces (e.g., coal with a top size of 3 cm and a silt content exceeding 4%), subsoil and other crustal materials showed similar behavior. The erosion potential (in g/m^2) depends on the fastest mile (in m/s) as follows:

$$P(u^+) = 6.7\,(u^+ - u_t), \quad u^+ \geq u_t \qquad (4\text{-}2)$$
$$0 \quad , \quad u^+ < u_t$$

where u_t is the erosion threshold wind speed (in m/s), measured at a typical weather station sensor height of 7 m.

The threshold friction velocity determined from the site survey is converted to the equivalent wind speed at a height of 7 m using Figure 4-1. This figure assumes a logarithmic velocity profile near the earth's surface:

$$\frac{u(z)}{u_*} = \frac{1}{0.4} \ln (z/zo) \qquad (4\text{-}3)$$

where:
u = wind speed at height z (m/s)
z = height above surface (cm)
u_* = friction velocity (m/sec)
z_o = roughness height (cm)

Mean annual fastest mile (u^+) values are presented in Table 4-1. The value for the weather station closest to the surface contamination site should be used.

Emissions generated by wind erosion of "limited reservoir" surfaces are also dependent on the frequency of disturbance (f) of the erodible surface, because each time that a surface is disturbed, its erosion potential is restored. A disturbance is defined as an action which results in the

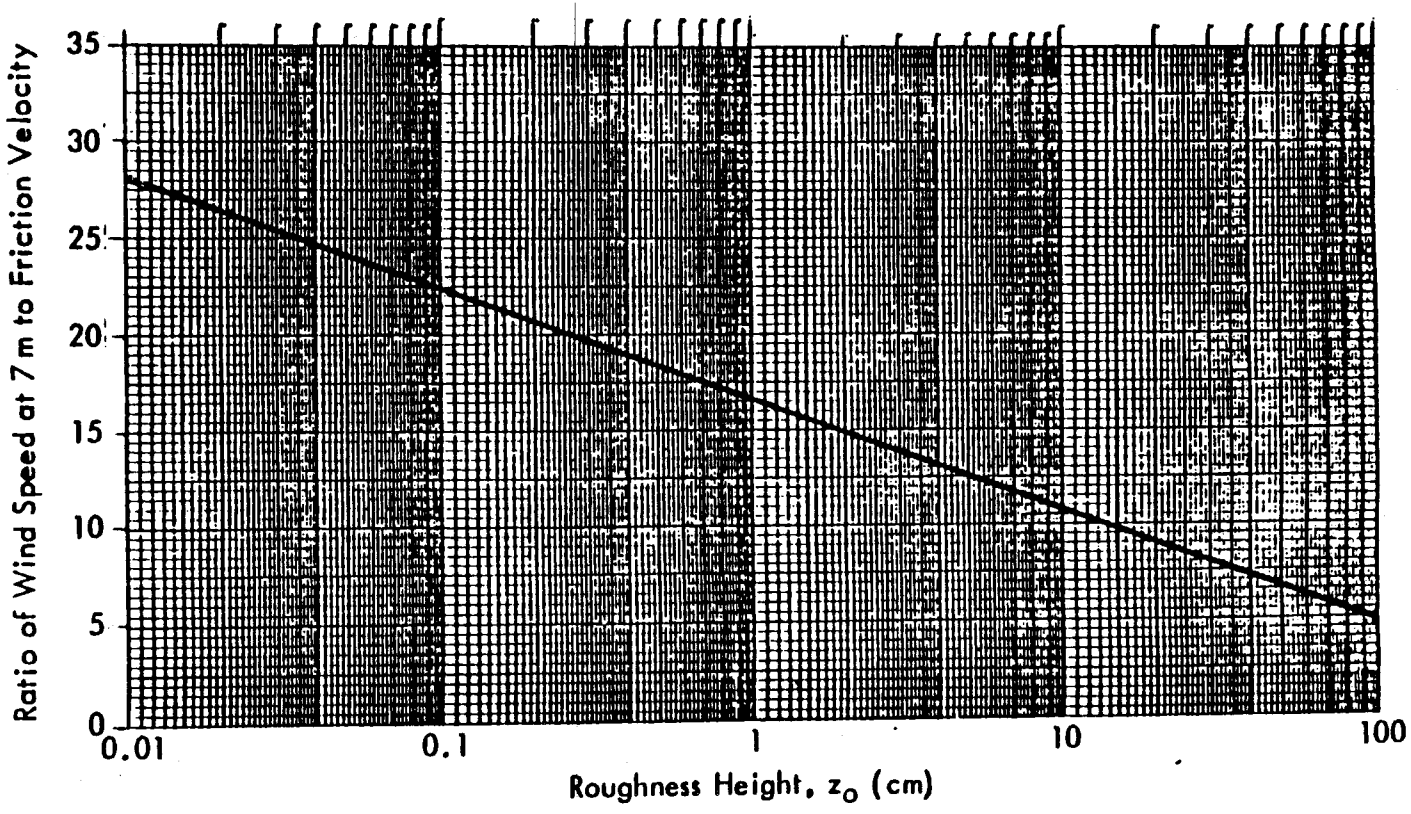

Figure 4-1. Ratio of wind speed at 7 m to friction velocity as a function of roughness height.

TABLE 4-1. FASTEST MILE[a] $[u^+]$ AND MEAN WIND SPEED[b] $[u]$ FOR SELECTED UNITED STATES STATIONS

Station	State	$[u^+]$ (m/s)	$[u]$ (m/s)	Station	State	$[u^+]$ (m/s)	$[u]$ (m/s)
Birmingham	AL	20.8	3.3	Detroit	MI	21.8	4.6
Montgomery	AL	20.2	3.0	Grand Rapids	MI	21.6	4.5
Tucson	AZ	23.0	3.7	Lansing	MI	23.7	4.6
Yuma	AZ	21.8	3.5	Sault St. Marie	MI	21.6	4.3
Fort Smith	AR	20.8	3.4	Duluth	MN	22.8	5.1
Little Rock	AR	20.9	3.6	Minneapolis	MN	22.0	4.7
Fresno	CA	15.4	2.8	Jackson	MS	20.5	3.4
Red Bluff	CA	23.3	3.9	Columbia	MO	22.4	4.4
Sacramento	CA	20.6	3.7	Kansas City	MO	22.6	4.6
San Diego	CA	15.4	3.0	St. Louis	MO	21.2	4.2
Denver	CO	22.0	4.1	Springfield	MO	22.4	5.0
Grand Junction	CO	23.6	3.6	Billings	MT	26.6	5.1
Pueblo	CO	28.1	3.9	Great Falls	MT	26.4	5.9
Hartford	CT	20.2	4.0	Havre	MT	25.9	4.5
Washington	DC	21.6	3.4	Helena	MT	24.7	3.5
Jacksonville	FL	21.7	3.8	Missoula	MT	21.6	2.7
Tampa	FL	22.2	3.9	North Platte	NE	27.7	4.6
Atlanta	GA	21.2	4.1	Omaha	NE	24.6	4.8
Macon	GA	20.1	3.5	Valentine	NE	27.1	4.8
Savannah	GA	21.3	3.6	Ely	NV	23.5	4.7
Boise	ID	21.4	4.0	Las Vegas	NV	24.4	4.0
Pocatello	ID	23.8	4.6	Reno	NV	25.2	2.9
Chicago	IL	21.0	4.6	Winnemucca	NV	22.4	3.5
Moline	IL	24.5	4.4	Concord	NH	19.2	3.0
Peoria	IL	23.2	4.6	Albuquerque	NM	25.6	4.0
Springfield	IL	24.2	5.1	Roswell	NM	26.0	4.1
Evansville	IN	20.9	3.7	Albany	NY	21.4	4.0
Fort Wayne	IN	23.7	4.6	Binghampton	NY	22.0	4.6
Indianapolis	IN	24.8	4.3	Buffalo	NY	24.1	5.5
Burlington	IA	25.0	4.6	New York	NY	22.5	5.5
Des Moines	IA	25.8	5.0	Rochester	NY	23.9	4.3
Sioux City	IA	25.9	4.9	Syracuse	NY	22.5	4.4
Concordia	KS	25.7	5.4	Cape Hatteros	NC	25.9	5.1
Dodge City	KS	27.1	6.3	Charlotte	NC	20.0	3.4
Topeka	KS	24.4	4.6	Greensboro	NC	18.9	3.4
Wichita	KS	26.0	5.6	Wilmington	NC	22.3	4.0
Louisville	KY	22.0	3.8	Bismarck	ND	26.1	4.7
Shreveport	LA	19.9	3.9	Fargo	ND	26.6	5.7
Portland	ME	21.7	3.9	Cleveland	OH	23.6	4.8
Baltimore	MD	25.0	4.2	Columbus	OH	22.1	3.9
Boston	MA	25.2	5.6	Dayton	OH	24.0	4.6

TABLE 4-1 (concluded)

Station	State	$[u^+]$ (m/s)	[u] (m/s)	Station	State	$[u^+]$ (m/s)	[u] (m/s)
Toledo	OH	22.7	4.2	Dallas	TX	21.9	4.9
Oklahoma City	OK	24.1	5.7	El Paso	TX	24.8	4.2
Tulsa	OK	21.4	4.7	Port Arthur	TX	23.7	4.5
Portland	OR	23.5	3.5	San Antonio	TX	21.0	4.2
Harrisburg	PA	20.4	3.4	Salt Lake City	UT	22.6	3.9
Philadelphia	PA	22.1	4.3	Burlington	VT	20.4	3.9
Pittsburgh	PA	21.6	4.2	Lynchburg	VA	18.3	3.5
Scranton	PA	19.9	3.8	Norfolk	VA	21.3	4.7
Huron	SD	27.4	5.3	Richmond	VA	18.9	3.4
Rapid City	SD	27.3	5.0	Quillayute	WA	16.3	3.0
Chattanooga	TN	21.4	2.8	Seattle	WA	18.7	4.1
Knoxville	TN	21.8	3.3	Spokane	WA	21.4	3.9
Memphis	TN	20.3	4.1	Green Bay	WI	25.3	4.6
Nashville	TN	20.9	3.6	Madison	WI	24.9	4.4
Abilene	TX	24.4	5.4	Milwaukee	WI	24.0	5.3
Amarillo	TX	27.3	6.1	Cheyenne	WY	27.0	5.9
Austin	TX	20.2	4.2	Lander	WY	27.4	3.1
Brownsville	TX	19.5	5.3	Sheridan	WY	27.5	3.6
Corpus Christi	TX	24.4	5.4	Elkins	WV	22.8	2.8

[a] Data taken from Extreme Wind Speeds at 129 Stations in the Contiguous United States. Simiu, E., Filliben, J. J., and M. J. Changery. NBS Building Science Series 118. U.S. Department of Commerce, National Bureau of Standards, 1979.

[b] Data taken from Local Climatological Data - Annual Summaries for 1977. U.S. Department of Commerce, National Oceanic and Atmospheric Administration/Environmental Data Service/National Climatic Data Center.

exposure of fresh surface material. This would occur whenever aggregate material is either added to or removed from the old surface. A disturbance of an exposed area may also result from the turning of surface material to a depth exceeding the size of the largest pieces of material present.

Although vehicular traffic alters the surface by pulverizing surface material, several vehicle passes may be required to restore the full erosion potential, except for surfaces that crust before substantial wind erosion occurs. In that case, breaking of the crust over the area of the tire/surface contact once again exposes the erodible material beneath.

Thornthwaites' P-E (PE) Index is a useful indicator of average surface soil moisture conditions. In the present context, the P-E Index is applied as a correction parameter for wind generated emissions in the limited reservoir case. Figure 4-2 provides a basis for selecting an appropriate P-E value.

The worst-case emission rate is calculated by assuming that a disturbance occurs just prior to the annual fastest mile event, both within the 24-h period of interest. For this calculation, use Equation (4-1) with $f = 30\ mo^{-1}$.

4.1.2 Wind Erosion from Surfaces with Unlimited Erosion Potential

For estimating respirable particulate emissions from wind erosion of surfaces with an "unlimited reservoir" of erodible particles, a predictive emission factor equation developed from Gillette's (1981) field measurements of highly erodible soils is recommended. In relating the annual average rate of respirable particulate emissions (per unit area) to field and climatic factors, the equation takes the following form:

$$E_{10} = 0.036\ (1-V)\ \left(\frac{[u]}{u_t}\right)^3 F(x) \qquad (4\text{-}4)$$

where: E_{10} = PM_{10} emission factor, i.e., annual average PM_{10} emission rate per unit area of contaminated surface (g/m^2-hr)

V = fraction of contaminated surface vegetative cover (equals 0 for bare soil)

$[u]$ = mean annual wind speed (m/s), taken from Table 4-1

$x = 0.886\ u_t/[u]$ = dimensionless ratio

$F(x)$ = function plotted in Figure 4-3

u_t = threshold value of wind speed at 7 m (m/s)

This follows from the empirical relationship that the vertical flux of particles smaller than 10 μm diameter is proportional to the cube of wind speed. Because highly erodible soils do not readily retain moisture, no moisture-related parameter is included in the equation.

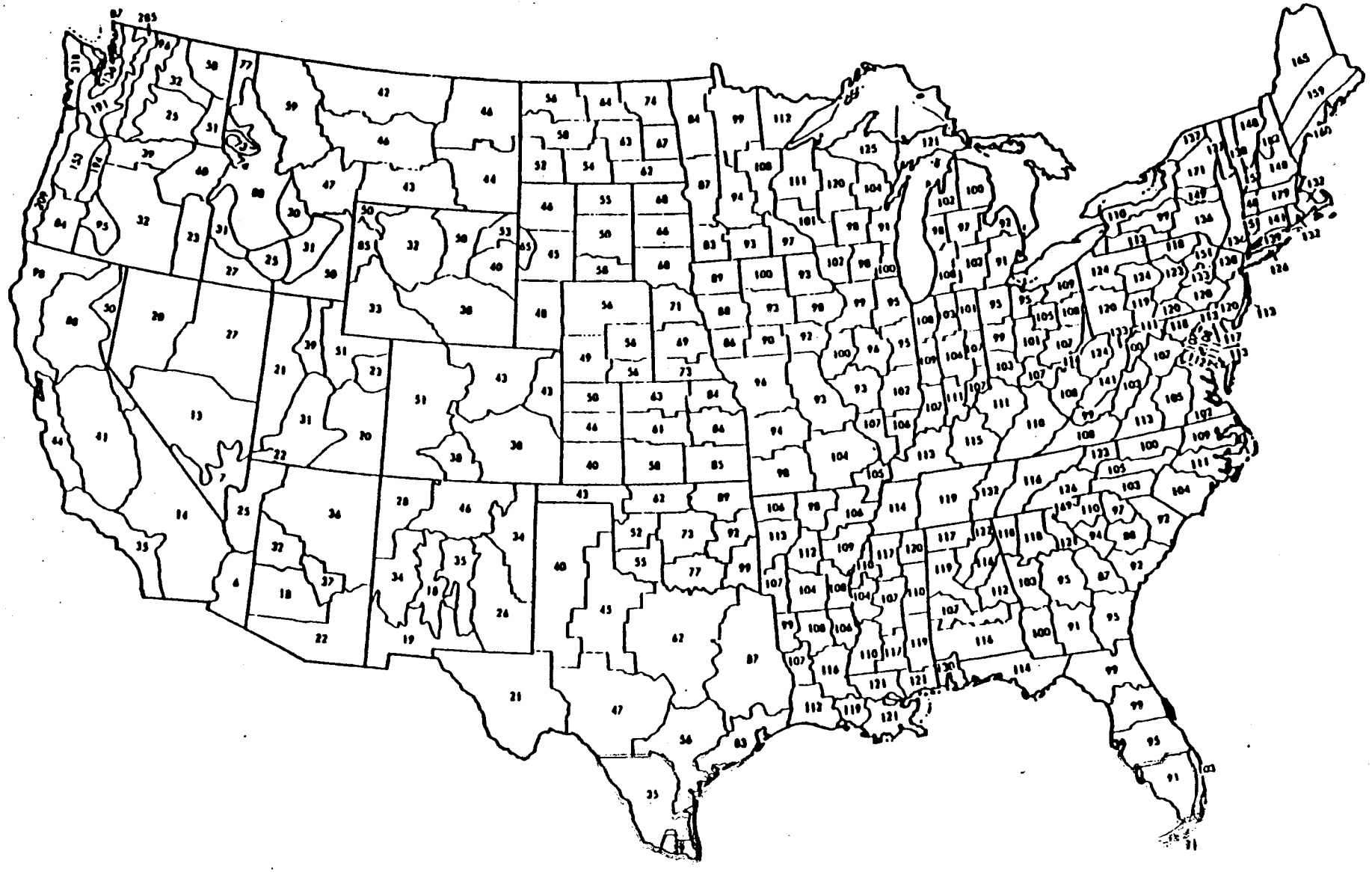

Figure 4-2. Map of P-E Index for State Climatic Divisions

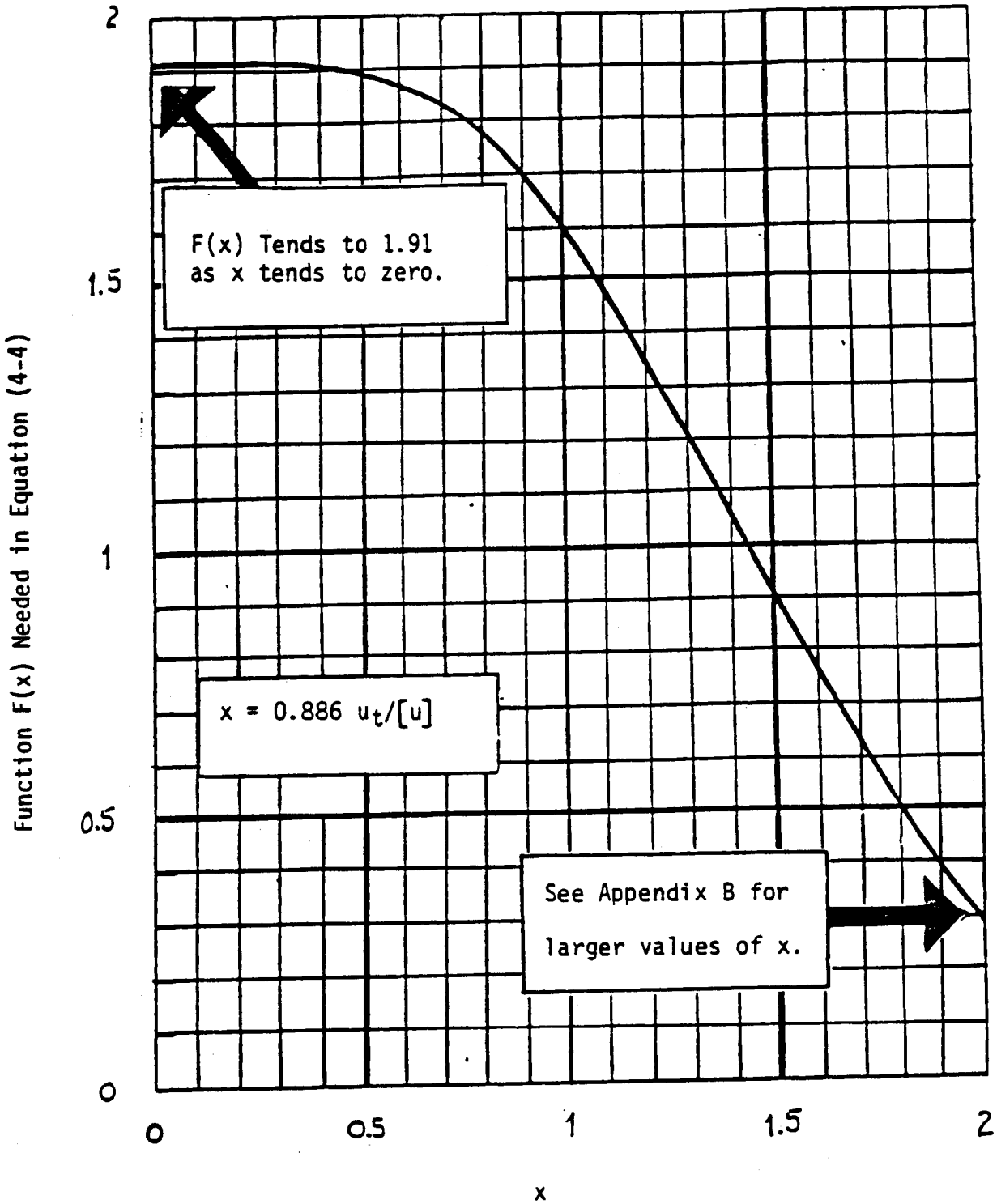

Figure 4-3. Graph of Function F(X) Needed to Estimate Unlimited Erosion

In this assessment process, the mean annual wind speed ([u]) for the weather station nearest the site (Table 4-1) should be used. The threshold wind speed at 7 m (u_t) is found by converting the threshold friction velocity (determined from the site survey) using Figure 4-2. Equation 4-3 is based upon an expected value using an estimated annual wind speed probability distribution as the weighting function. The function F(x) is proportional to this expected value. Details of the integration are presented in Appendix B.

The worst-case emission factor is calculated using a simplified form of Equation (4-3):

$$E_{10} = 0.036\ (1-V)\ [u_{6\text{-}hr}]^3 \qquad (4\text{-}5)$$

where: $[u_{6\text{-}hr}]$ = expected maximum 6-hr mean wind speed during the year. From a physical viewpoint, it is apparent that the maximum 6-hr mean wind speed must be somewhat lower than the corresponding annual fastest mile.

In order to roughly account for the influence of increasing averaging time, the following expression should be applied to the $[u^+]$ values in Table 4-1:

$$[u_{6\text{-}hr}] = [u^+] - 2\ \text{m/s} \qquad (4\text{-}6)$$

This relationship has been proposed by the World Meteorological Organization (1961) for correction of 1-min to corresponding 1-hr extremes.

4.1.3 Vehicle Traffic

For estimation of PM_{10} emissions from vehicle traffic over unpaved surfaces, the following equation should be used:

$$E_{10} = 0.85 \left(\frac{s}{10}\right) \left(\frac{S}{24}\right)^{0.8} \left(\frac{W}{7}\right)^{0.3} \left(\frac{w}{6}\right)^{1.2} \left(\frac{365-p}{365}\right) \qquad (4\text{-}7)$$

where: E_{10} = PM_{10} emission factor, i.e., the quantity of PM_{10} emissions from an unpaved road per vehicle-kilometer of travel (kg/VKT)

s = silt content of road surface material (%)

S = mean vehicle speed (km/hr)

W = mean vehicle weight (Mg)

w = mean number of wheels

p = number of days with at least 0.254 mm (0.01 in.) of precipitation per year

Default values for the various parameters in the equation are given in Table 4-2. These should only be applied when site-specific information from local sources is unavailable.

TABLE 4-2. DEFAULT VALUES FOR INDEPENDENT VARIABLES OF EQUATION 4-6[a]

Site	s(%)		S(km/hr)		W(Mg)	w
Rural/Residential	15	(5-68)	48	(40-64)	2	4
Industrial	8	(2-29)	24	(8-32)	3	4
					15	6
					26	10

[a] Numbers in parentheses are ranges of measured values.

Values for p (wet days per year) are obtained from Figure 4-4 or from a local source. Worst-case 24-hr emissions would occur on a dry day (p = 0) with the highest volume of traffic expressed as vehicle-kilometers traveled. If the vehicle mix varies, periods with a greater portion of larger vehicles produce greater emissions.

4.1.4 Determination of Emission Rates

Contaminant emission rates (R_{10}) are determined from the above emission factors (E_{10}) using Equation 2-1:

$$R_{10} = \alpha \; E_{10} \; A \qquad (2\text{-}1)$$

where R_{10} = emission rate of contaminant as PM_{10}

α = mass fraction of contaminant in PM_{10} emissions

A = source extent (for a specified averaging time in the case of mechanical resuspension)

For wind erosion, the source extent is simply the contaminated area. For example, if an area of 2,000 m^2 is contaminated, the annual emission factor is 0.17 mg/m^2-hr and α = 16 ppm, the annual contaminant emission rate is:

$$R_{10} = (16 \cdot 10^{-6})\ (0.17\ mg/m^2\text{-}hr)\ (2{,}000\ m^2) = 5.4\ \mu g/hr \qquad (4\text{-}9)$$

In the case of mechanical resuspension in the form of travel on unpaved surfaces, the source extent is found as the product of the contaminated travel length times the daily traffic count. Note that the daily traffic count for a worst-case would be greater than that for annual conditions. An example is provided in Section 5.2.

MEAN NUMBER OF DAYS WITH 0.01 INCH OR MORE OF PRECIPITATION, ANNUAL

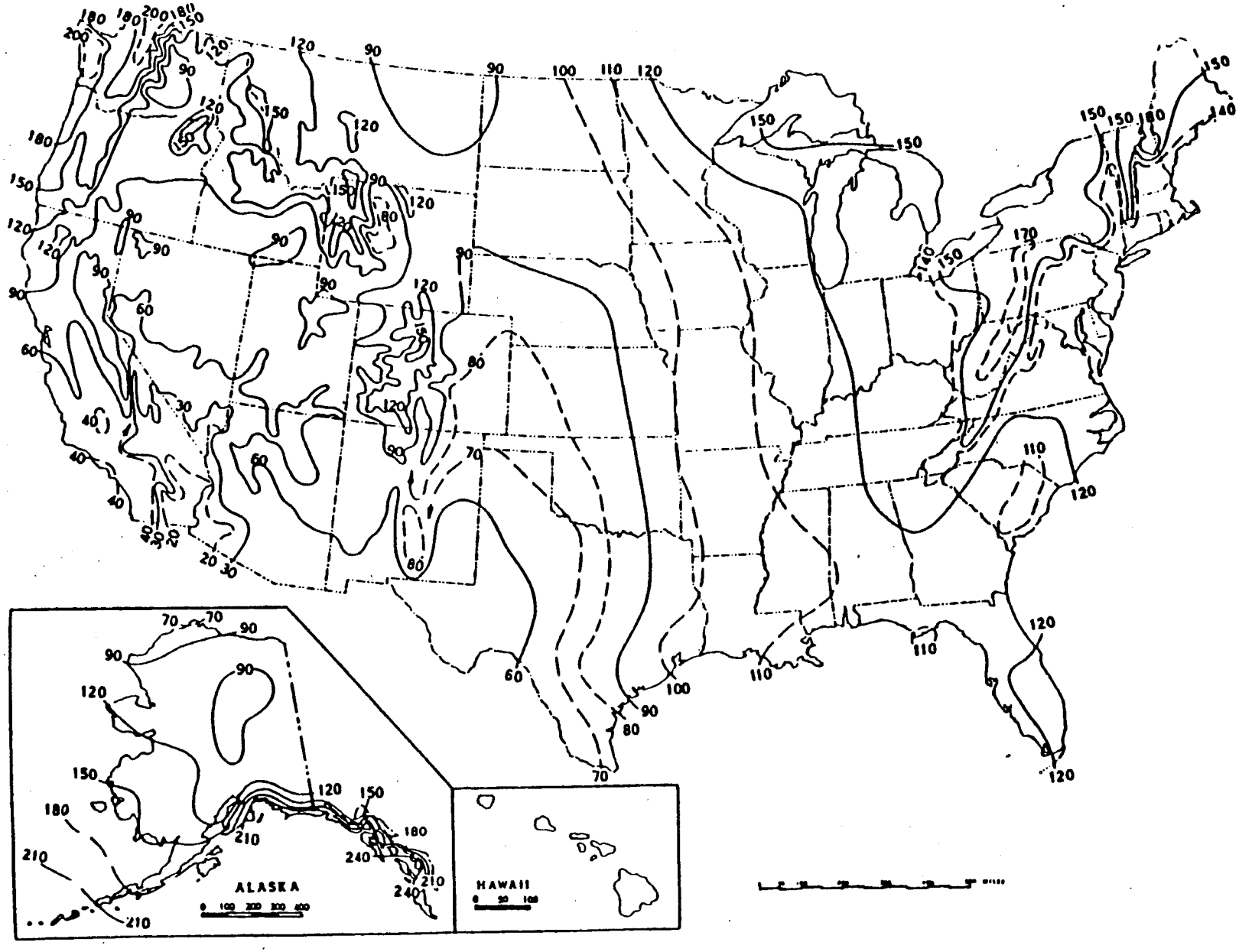

Figure 4-4. Map of Precipitation Frequency

Once the contaminant emission rates associated with wind and traffic entrainment have been calculated, the next step is to estimate the duration of exposure to the airborne contaminant. This is done by comparing the annual average contaminant mass emission rate to the total mass of contaminant available for entrainment. In the case of a deep horizon of surface contamination, long-term wind erosion will be limited to the depth of surface material that is unprotected by large non-erodible elements; on the other hand mechanical entrainment by vehicle traffic can wear the surface indefinitely.

As a first approximation of the duration of exposure, the total initial mass of contaminant in the form of PM_{10} particles on the surface should be divided by the initial value of the annual average contaminant emission rate (R_{10}). If the resulting value exceeds 70 years (the time basis for lifetime exposure assessment), no correction for decay in emission rate is required. Otherwise, the annual average contaminant emission rate must be adjusted downward, to account for the significant depletion in the contaminant mass. This situation would be expected, for example, in the case of a spill of a powder which neither penetrates nor adheres to the soil.

If the duration of exposure obtained above does not exceed 70 years, it is recommended that the expected decay in emission be derived from first order kinetics, based on the principle that the contaminant emission rate at any point in time is proportional to the amount of contaminant remaining in the exposed surface material. The decay constant is given by:

$$k = R_{10}/M_{10} \qquad (4\text{-}10)$$

where k = decay constant (1/time)

R_{10} = initial value of combined annual average emission rate (mass/time)

M_{10} = initial mass of the contaminant in the form of PM_{10} particles on the surface (mass)

Based on this model, the times required to entrain 90% or more of the initial mass of contaminant, and the average emission rates during these time periods are as follows:

Fraction of initial mass remaining	Time required	Ratio of average to initial emission rate
10%	2.3/k	0.39
1%	4.6/k	0.21
0.1%	6.9/k	0.14

It is recommended that exposure assessment be carried out to the point in time at which 10% of the initial contaminant mass remains. Thus, the calculated initial annual average emission rate should be multiplied by 0.39.