AGENCY FOR INTERNATIONAL DEVELOPMENT
WASHINGTON, D. C. 20523

BIBLIOGRAPHIC INPUT SHEET

FOR AID USE ONLY

1. SUBJECT CLASSIFICATION

A. PRIMARY: Science and Technology

B. SECONDARY: Environment

2. TITLE AND SUBTITLE

Air Quality Management, Reading References, Volume 3 of 5

3. AUTHOR(S)

McJunkin, F. E.

4. DOCUMENT DATE	5. NUMBER OF PAGES	6. ARC NUMBER
1976	215 p.	ARC

7. REFERENCE ORGANIZATION NAME AND ADDRESS

International Programs, Department of Environmental Sciences and Engineering, School of Public Health, University of North Carolina, Chapel Hill, North Carolina 27514

8. SUPPLEMENTARY NOTES *(Sponsoring Organization, Publishers, Availability)*

Prepared for international seminar on the environment conducted at the University of North Carolina. A limited number of sets are available for libraries of international organizations.

9. ABSTRACT

This volume of four papers dealing with air quality management is the third of five volumes assembled for use by participants in the IPEAID seminar conducted at the University of North Carolina in March-April, 1975. Volume 1 is entitled Environmental Planning; Volume 2, Water Quality Management--Solid Wastes; Volume 4, Industrial Pollution; Volume 5, Resources and the Environment. The authors and papers in this third volume::

Kornreich, Lawrence D. Air pollution and its control.
Peterson, James T. Diffusion Processes at large and small scales.
Reist, Parker C. Control of gaseous emissions by combustion.
Turner, D. Bruce. Workbook of atmospheric dispersion estimates.

10. CONTROL NUMBER

PN-AAB-938

11. PRICE OF DOCUMENT

12. DESCRIPTORS

13. PROJECT NUMBER

14. CONTRACT NUMBER

AID/ta-C-1127 GTS

15. TYPE OF DOCUMENT

AID 590-1 (4-74)

ipeaid

international program in the environmental aspects of industrial development

department of environmental sciences and engineering

school of public health • university of north carolina

PN-AAB-738

READING REFERENCES

AIR QUALITY MANAGEMENT

VOLUME 3 OF 5

Assembled By

F. Eugene McJunkin

International Program in Environmental

Aspects of Industrial Development

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U.S.A.

1975 - 1976

INTERNATIONAL ENVIRONMENTAL PROGRAMS AT THE UNIVERSITY OF NORTH CAROLINA

The Department of Environmental Sciences and Engineering at the University of North Carolina has a long standing interest and involvement in international activities and programs concerned with environmental quality and, in particular, with the environmental problems of developing countries. Departmental activities have included special educational programs, on campus and abroad, long and short term; technical assistance; research and development; information transfer, including publications; and consulting and service activities by faculty and staff. These programs have included the International Program in Sanitary Engineering Design, the AID Engineers' Environmental Program, the International Program in Environmental Aspects of Industrial Development, the publication series Water Supply and Sanitation in Developing Countries, technical assistance to several overseas universities, and numerous technical studies.

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AIR POLLUTION AND ITS CONTROL

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May, 1975

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AIR POLLUTION AND ITS CONTROL

1. Introduction

1.1 Purpose

The following material is an introduction to the study of air pollution and its control. It is a survey of the many topics that are included in such a broad area of study and is meant to provide the participant in the IPEAID course with a foundation of basic information, and to point the way to sources of more specific and more detailed information. This presentation is oriented towards people with industrial technical backgrounds who will be concerned with environmental decision making in the future.

1.2 Areas Covered

The topics discussed in the syllabus include the nature, sources, and transport of air pollution; the effects of air pollution on humans, plants, and the physical environment; air pollution standards; the nature of process emissions from selected industries; measurement and monitoring needs in air pollution control; control technology for industrial emissions; siting of industrial facilities; consideration of land use planning and energy; and the impact of the manufactured product on the environment.

The material that is presented is by no means inclusive. In many cases, considerable detail has been avoided to preserve the readability of the syllabus and to be consistent with the purpose of this course. More detailed discussion is provided for

topics that have direct bearing on industrial processing. References that can be used to obtain additional information are included in the last section of the syllabus.

2. Nature of Air Pollution

The Atmosphere

The earth's atmosphere is composed of several layers, including the ionosphere, the warm layer, the stratosphere and the troposphere The ionosphere, which begins at about 40 miles above the surface of the earth, is itself composed of several layers, and is characterize among other things, by its ability to reflect low-frequency radio waves. The warm layer is found from about 25 to 40 miles above the earth's surface. The temperature in this layer is reasonably stable and is higher than the temperature that prevails near the earth surface. The stratosphere is located from approximately 7 to 25 miles above the earth. In this layer, the ozone content reaches its peak and the temperature is relatively stable. The layer closest to the surface of the earth extends upwards for an average of 7 miles and is called the troposphere. The air in this layer is subject to considerable movement which results in what we call weather. Within the troposphere the temperature generally decreases with height, or "lapses." This rate of decline, or lapse rate, is about 10°C per kilometer (4°C per mile).

Nearly 3/4ths of the mass of the atmosphere, and almost all of the moisture and the solid particulate matter is contained in the troposphere. Over 99.9% of the volume of dry atmosphere is made up of four gases:

Nitrogen	78.1%
Oxygen	20.9%
Argon	0.9%
Carbon Dioxide	0.03%

In addition, the remaining rare gases and numerous trace gases, such as nitrous oxide, nitrogen dioxide, nitric oxide, carbon monoxide, ammonia, and sulfur dioxide, can also be found. In addition to the gases, solid particles also present. These include condensation nuclei - submicron particles that serve as nuclei for the condensation of water and other vapors - sea salt from the evaporation of the ocean's spray, and solid particles introduced into the atmosphere by industrial processes related to man's activity and by the wind. The amount of moisture in the atmosphere will vary widely depending upon location and season. The average concentration range is 1 to 2%.

The concentration of any trace component in the atmosphere will vary for each locality in which the concentration is being measured. This is because the sources of these components are localized. For example ammonia is introduced into the atmosphere largely from the decay of organic material. The concentration of ammonia in the atmosphere will be higher near marshes and other areas where decay processes occur.

Not only are there sources for the particles and gases found in the atmosphere, but there are also processes and places in which these materials are destroyed and removed from the atmosphere, called "sinks". The existence of sources and sinks means that the trace components will have varying lifetimes in the atmosphere that may range from several seconds to several years. The major sinks are the ocean (for many gases including CO_2 and ammonia), the earth's surface (for ozone and particulate matter), the biosphere, and the upper atmosphere. It is important to remember that the atmosphere is a dynamic system, one that is constantly undergoing change.

2.2 Air Pollution

The gases, vapors and particles that are introduced by natural and man-associated (anthropogenic) sources are removed from the atmosphere by the processes of dispersion, diffusion, reaction, absorption and adsorption. When the rate of introduction of unwanted materials into the atmosphere exceeds the rate at which they are dispersed, diffused, reacted with, absorbed or adsorbed, these gaseous and particulate materials will accumulate. At certain concentration levels, some of the particles and gases introduced into the atmosphere affect man and his environment because of their toxicity, their ability to damage, or their ability to create discomfort. Air pollution may be defined as the (local) accumulation of unwanted, undesirable, or toxic materials in the atmosphere to the point that they can cause insult to the environment, ranging from psychological irritation to death.

Although numerous gases and particulates could be considered pollutants, the U. S. has focused on a small group which are considered important because of two factors: a) amounts emitted by sources, and b) potential environmental impact. The principal pollutants include carbon monoxide, ozone (oxidant), nitrogen dioxide, nitric oxide, sulfur dioxide, inorganic sulfates, suspended particulate matter, and hydrocarbons. The term particulate matter includes solid materials, such as dust and flyash, and liquids in the form of fine mists, for example sulfuric acid mist.

The earliest air pollution was a visual insult—the clouding of the air in cities by smoke. There are references in the literature to the displeasure caused by air pollution in the 11th century.

In the 12th century, King Edward II of England is supposed to have beheaded the operator of a coal fired furnace whose smoke was allowed to drift across the grounds of the castle. The term smog, meaning a combination of smoke and fog, was applied to the visible pollution associated with the severe (acute) episodes recorded in London, England; the Mevese Valley in Belgium; Donora, Pennsylvania; and other locations. The killer fog in London in 1952 was responsible for some 4,000 excess deaths; a Thanksgiving weekend episode in New York City in 1966 was responsible for some 200 excess deaths.

In recent years, there has been increasing concern for the damage potential of the pollutants that cannot be seen. Combinations of gases and particulate matter, or gases alone, can cause significant damage to man and his environment. There has also been an increased awareness of the potential dangers from exposures to low-levels of pollutants over long periods of time. These have led to the establishment of air quality standards and control strategies to meet them.

3. Pollutants and Their Sources

Although natural events such as forest fires and volcanic activity introduce tremendous quantities of pollutants into the atmosphere, this discussion will be limited to a consideration of gases and particulate matter produced by man's activities.

3.1 Units of Concentration

Typically the concentrations of air pollutants have been reported in units of parts per million (ppm), or parts per billion (ppb). This is a ratio of the volume of a given gas to a unit volume of the atmosphere. Recently there has been a shift towards using a mass per volume unit in the metric system - milligrams (mg) or micrograms per cubic meter ($\mu g/m^3$). The reasons for this probably include: the current trend to use metric units; ppm cannot be used for particulates, requiring separate units for gases and solids; and ppm does not reflect the fact the mass of the gases in the atmosphere decreases with height. In this summary, both units will be noted.

3.2 Particulate Matter

Particulate matter refers to discrete particles of solids or liquids emitted into or formed in the atmosphere. Particulates may result from the physical treatment of solids or liquids, the combustion of fuels, and natural processes. Examples of particulates include fly ash; fugitive dust from mining, crushing or grinding operations; mists produced by liquid scrubbers or cooling towers; wind driven soil; and volcanic ash. The U. S. Environmental Protection Agency estimated that in 1971, 27 million tons of particulates were emitted. Approximately 1/2 of this resulted from industrial processes and nearly 1/4 from fuel combustion by stationary sources.

Particles smaller than 1 micron (μ) are generally formed by condensation processes in the atmosphere. Crushing and grinding of solids can produce particles as small as about 2μ. Incomplete combustion and the unburnable portion (ash) of the fuel are two other sources of small particles. Particles larger than 10μ typically are produced by mechanical processes such as grinding, and wind erosion. Generally, particles larger than 10μ have high settling velocities and do not stay in the atmosphere very long. The average mass concentration of suspended particles (smaller than 10μ) ranges from 10 to 60 μ/m^3 in nonurban areas, and from 60 to 200 $\mu g/m^3$ in urban areas. In heavily polluted areas these concentrations may be even higher.

3.3 Sulfur Oxides

The predominating form of oxidized sulfur in the atmosphere is sulfur dioxide (SO_2). Oxidized sulfur will be present in particulates in the form of sulfuric acid and sulfate. Sulfur dioxide primarily occurs from the combustion of fossil fuels, refining of petroleum, the smelting of sulfur-containing ores, and the manufacture of sulfuric acid. It is estimated by EPA that 32.6 million tons of SO_2 was emitted in 1971. A little more than 80% of this was produce by fuel combustion in stationary sources.

Estimated ground level concentrations for SO_2 in nonurban areas are from 0.5 to 5 $\mu g/m^3$ (0.2 to 1.9 ppb). In any particular area, the ground level concentration will depend upon the amount and type of fuel burned, and meteorological factors. Typically in larger cities, concentration of 75 $\mu g/m^3$ (0.3 ppm) are not uncommon.

3.4 Nitrogen Oxides

The term "nitrogen oxides" (NO_x) includes two gases: nitric oxide (NO) and nitrogen dioxide (NO_2). On a global bases the major source for these oxides, primarily emitted as NO, is bacterial action. In the United States and in other industrial countries, NO_x emissions are produced by fuel combustion. Some NO_2 can be emitted from specializ industrial processes such as the manufacturing and use of nitric acid, welding, and electroplating. However these make up a small portion of the total emissions. EPA estimates that 22 million tons of NO_x were emitted in 1971. Approximately 50% of this was from transportatio sources (internal combustion engines), and 49% was from fuel combustion in stationary sources. Miscellaneous sources accounted for a very small fraction of the total emissions because the principal mechanism of formation of NO_x is the reaction of the nitrogen and oxygen at temperatures typically found in combustion processes.

Concentrations in urban areas are usually from 10 to 100 times those concentrations founded in rural areas. The average background concentrations in the U. S. are 8 $\mu g/m^3$ (4.3 ppb) for NO_2 and 2 $\mu g/m^3$ (1.6 ppb) for NO Nitrogen oxides are considered important pollutants because they damage the environment and they start the formation of photochemical smog.

3.5 Carbon Oxides

Both carbon monoxide (CO) and carbon dioxide (CO_2) are important atmospheric components because of their significance to vegetative and photosynthetic processes. Carbon dioxide has been the subject of much study because of its ability to absorb long-wavelength radiation that otherwise would be lost to the outer atmosphere, producing what is called the "greenhouse effect." Catastrophic damage could occur if

the temperature of the earth would rise or fall significantly. Study of the factors causing temperature and climatic changes is continuing. However, no generally acceptable conclusions have been reached.

Carbon monoxide is a widely distributed air pollutant. Total emissions of carbon monoxide exceed those of all other pollutants combined. EPA estimated that in 1971, over 100 million tons of CO were emitted. Approximately 78% came from transportation sources, resulting from the imcomplete combustion of fuel. Some small amounts of CO can be produced by biological processes, but compared to that produced by man's activity it is almost negligible. Background concentrations of CO in relatively unpolluted areas may range from .03 to 1.2 mg/m^3 (.03 to 1 ppm). In polluted areas, concentrations may be a hundred times greater than in nonpolluted areas. As examples, maximum 8-hour CO concentrations in Los Angeles, California ranging from 12 to 46 mg/m^3 (10 to 40 ppm) have been measured; concentrations in excess of 100 mg/m^3 (87 ppm) have been measured in underground garages and tunnels.

Carbon dioxide is emitted in the largest quantities of any gas—some 13 billion tons globally in 1971. However CO_2 is not generally considered a pollutant because of its involvement with biological processes and because of the enormous interchange of the gas between the atmosphere and the oceans—it comprises 0.3% of the atmosphere.

3.6 Ozone and Photochemical oxidants

Up to this point the pollutants that have been discussed have been "primary pollutants", that is, they exist in the atmosphere as a result of being emitted. There is another class of pollutants called

"secondary pollutants." These are formed in the atmosphere by the chemical reaction of primary pollutants. Chief amount of this group are ozone and photochemical oxidant, which are formed by the action of sunlight on NO_2, and subsequent reactions with hydrocarbons. The reactions in this process for forming ozone are:

$$NO_2 + \text{sunlight} \rightarrow NO + O$$

$$O + O_2 + M \rightarrow O_3 + M$$

The oxygen atom formed from the photodissociation combines with atmospheric molecular oxygen to form ozone. However, the presence of reactive hydrocarbons in the atmosphere allows formation of considerable ozone to occur through subsequent reactions. Furthermore, in addition to ozone, other oxidative compounds are formed such as PAN (peroxyacetyl nitrate) organic peroxides and hydroperoxides, and others. These compounds as a group are referred to as photochemical oxidant.

In addition to the ozone formed by the photochemical reactions, ozone is brought to the surface of the earth from the ozone layer by the mixing associated with major weather systems. Maximum ozone levels of from 20 to 100μg/m^3(10 to 50 ppb) have been recorded in nonurban areas, however most measurements were between 20 to 60μg/m^3(10 to 30 ppb). This natural background is primarily the result of atmospheric mixing, although a small amount is formed by natural electrical discharges. The concentration of ozone and photochemical oxidant vary widely from area to area, depending on the ratio of NO_2 to NO in the air and the amounts of reactive hydrocarbons emitted into the atmosphere, as well as local meteorology and topography, ambient temperature and the amount of sunlight that is received on a given day. In a few urban areas, peak concentrations of 17mg/m^3 (0.85 ppm) have been recorded, while

maximum hourly-averages of 5.9 to 12mg/m^3 (0.3 to 0.6 ppm) are typical.

Hydrocarbons

The largest source of methane in the atmosphere is the natural decomposition of vegetation. Background concentrations of 0.7 to 1mg/m^3 (1.1 to 1.5 ppm) have been recorded. In more inhabited areas, methane levels are often much higher—values of 4mg/m^3 (6.1 ppm) have been observed. Volatile terpenes are another group of hydrocarbons that are produced by vegetation, specifically pine trees. The amount emitted into the atmosphere is considerable. In fact the blue haze associated with the Appalachian Mountain Region of the U.S. is a natural photochemical aerosol resulting from photochemical reactions involving these terpenes.

Methane does not participate in the reactions that generate photochemical smog. Thus non-methane hydrocarbons are considered more important pollutants. The primary sources of non-methane hydrocarbons are incomplete combustion of fuels, industrial emissions, storage and transfer of liquid fuels such as gasoline, and the use of hydrocarbons as solvents. It is estimated that in 1971 a total of 26.6 million tons of non-methane hydrocarbons were released to the atmosphere. Of this amount, 55% was emitted from mobile sources and slightly more than 20% from industrial processes. Concentrations of non-methane hydrocarbons in polluted areas have been measured in the range of 1.3mg/m^3 (2 ppm) as methane.

3.8 Miscellaneous Gases

In addition to the gases and particulates discussed, other compounds may make significant contributions in the total air pollution picture. In any locality, emissions or accidental releases of ammonia, hydrogen

sulfide, and other gases and odors may have a tremendous impact. Hydrogen sulfide is formed from industrial processes, such as the manufacture of kraft paper. Although it is a toxic gas, concentrations in the atmosphere rarely approach dangerous levels. Its sickening odor and its ability to darken certain paints make it an undesirable component of ambient air. Ammonia is largely produced by natural decay, and frequently is found in particulate matter as ammonium salts. Odorants associated with various processes such as fermentation, coffee roasting, and animal rendering are generally emitted in low concentrations but are frequently annoying in the locale in which they are emitted. They are probably more psychologically damaging than physically damaging.

4. Transport of Pollutants

As indicated in previous chapters, the atmosphere is not a static system. It is a dynamic system in which pollutants are continuously discharged or formed and also continuously removed or destroyed. The mechanisms by which solid and gaseous pollutants are dispersed in, and removed from the air include diffusion, settling, chemical reaction, rain-out and wash-out. The movement of the atmosphere has a significant influence on these mechanisms.

4.1 Air Pollution Meteorology

In the troposphere, the layer of the atmosphere next to the earth's surface, the temperature of the air generally decreases with height above the earth's surface. The rate of this temperature-decrease with height is called the lapse rate. If a parcel, or small volume, of dry air moves upward, it will expand as the atmospheric pressure decreases. If no heat is added or removed, the temperature will fall at a rate called the dry adiabatic lapse rate. The amount of temperature decrease of the dry adiabatic lapse rate is approximately 10°C per kilometer of elevation. The <u>actual</u> decrease in the temperature of the troposphere with height at any point in time is called the environmental lapse rate. The rate may be less than, equal to, or greater than the dry adiabatic lapse rate. Depending upon which condition exists, the troposphere will be called unstable, neutral or stable. These terms describe the stability of the atmosphere, or its tendency to move in a vertical direction. The transport of pollutants in the atmosphere is dramatically affected by the stability.

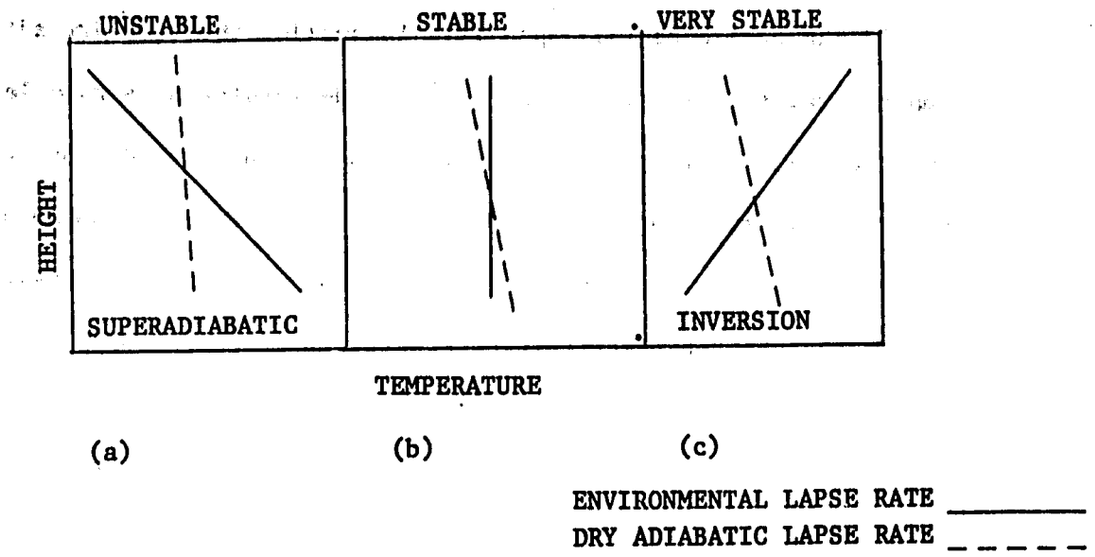

Figure 4-1. Stability of the air determined by the environmental lapse rate.

Figure 4-1 illustrates the variation of the stability of the atmosphere with changing environmental lapse rates. In figure 4-1a the superadiabatic or unstable situation is graphically represented. Under unstable conditions, the environmental lapse rate is greater than the dry adiabatic lapse rate, that is, there is a decrease of temperature with height greater than 10°C per kilometer. Recall that as a parcel of air rises, it cools at the adiabatic lapse rate. Under superadiabatic conditions, the temperature of the parcel will be warmer than the surrounding air, which will be at a temperature indicated by the environmental lapse rate. Because this parcel is warmer, and more buoyant than the surrounding air, it will rise even

faster. Thus vertical movement in the atmosphere will be accelerated. This is referred to as an unstable condition.

If the environmental lapse rate is smaller than the dry adiabatic lapse rate, that is, the temperature is decreasing at a rate less than 10°C per kilometer, as shown in Figure 4-1b stable conditions will prevail. In this case, a rising parcel of air will be cooler and more dense than its surroundings. Because it will tend to fall vertical, motion will be depressed. This is referred to as a stable atmosphere.

If the environmental lapse rate is the same as the adiabatic lapse rate, then a rising parcel will neither be accelerated nor depressed. This condition is called neutral.

If the temperature increases with height, as shown in Figure 4-1c then the environmental lapse rate would be negative describing a condition is called an inversion. An inversion is an example of extreme atmospheric stability. Vertical motion in the atmosphere may be severely reduced or even halted.

Both unstable conditions, when vertical motion is accelerated, and very stable conditions, when vertical motion is depressed, have considerable effect on the movement of pollutants in the troposphere. This is most easily seen in the behavior of smoke plumes from stationary source stacks. In general there are five major types of plume behavior: looping, coning, fanning, lofting and fumigation. These are shown schematically in Figure 4-2.

Looping occurs during superadiabatic or unstable conditions. The visible plume will appear to loop because of the increased vertical mixing. Gases and particulate matter are diffused rapidly. Occasionally, air parcels will be pushed to the ground near the base of the stack.

Looping usually occurs when skies are cloudless because strong solar heating of the ground is necessary to obtain a large superadiabatic

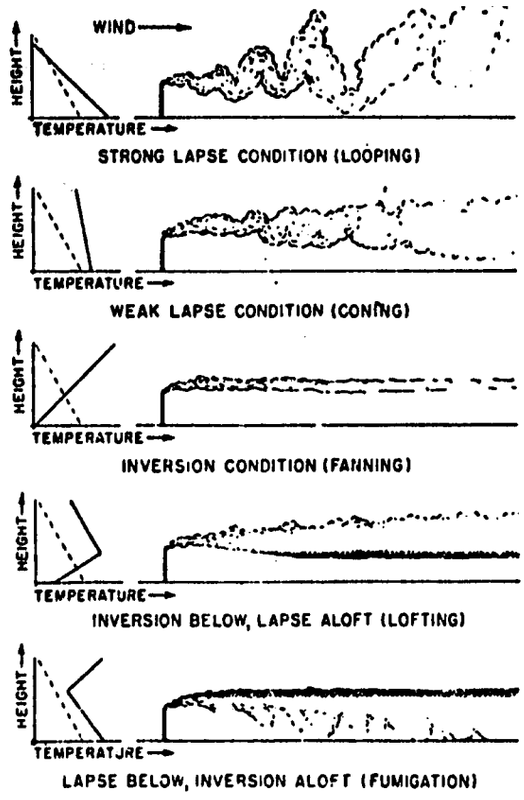

Figure 4-2. Schematic representation of stack plume behavior under various conditions of vertical stability.

looping rate.

Coning occurs during the weakly stable situation that occurs when the environmental lapse rate is less than, but near the dry adiabatic lapse rate. Under these conditions vertical motion is damped slightly, and so the plume cones, or fans, out in all directions. Coning typically occurs under cloudy skies with a brisk wind.

Fanning occurs during temperature inversions. The plume fans out from the stack almost in thin sheets because vertical motion is

severely damped. Under such conditions, it is not unusual for the plume to travel for distances of many miles with very little dispersion. Most fanning occurs during the night time when ground-level inversions usually occur.

Lofting occurs when the plume is released at the top of an inversion, typically occuring late in the day. Here vertical motion is possible only above the inversion and so the upper edge of the plume spreads out far more than the lower edge.

Fumigation results from the emission of pollutants within an inversion layer. The gases and particles accumulate in the inversion, as in the description of a fanning plume. When solar heating breaks the inversion, the air will become completely mixed and the pollutants will be brought to the ground level. This typically will occur early in the morning as the inversion slowly breaks.

From the standpoint of atmospheric transport, there is a maximum opportunity for diffusion of the plume to occur under looping conditions. Nonetheless, because of the rapid motion of the plume, high concentrations of pollutants can be brought to the surface within relatively short distances of the stack. Under coning conditions little diffusion occurs. The pollutants eventually reach the surface, but at considerable distances from the stack.

Similarly, under fanning conditions, very little diffusion can occur. The pollutants can be carried for great distances without reaching the surface. The problems begin when the inversion begins to break and the accumulated pollutants then touch down during fumigation. If the inversion has persisted for several days, when it does break, very high concentrations of pollutants may be brought to the surface.

Under lofting conditions, diffusion possibilities are excellent because vertical motion above the inversion is not limited. Further the pollutants cannot reach the surface because of the inversion below the plume.

5. Effects of Air Pollution

Air pollution affects various sectors of the environment. Plants and other vegetation are susceptible to damage which can destroy them, or in the case of agricultural crops, reduce and impair the quality of their yield. The physical environment can be affected by erosion, and chemical weathering, or dirtied by soot or other particulate deposits. Animals and humans can be made sick or possible even killed by air pollution.

The total damage to the environment done by air pollution is difficult to assess. Direct effects, for example, the medical costs of treating pollution-caused illnesses, the market value of a crop that is destroyed, or the cost of cleaning more frequently, are often easy to quantify. Indirect effects, such as the unpleasantness of odors, risks to human health and welfare or the visual effect of vegetation damage, are often very difficult to quantify.

Another cost of air pollution is called the avoidance cost. This is what must be spent to avoid the effects of pollution. As an example, EPA reported that coating low-voltage electrical contacts in electronic devices with gold,platinum and other precious metals to avoid the destructive effects of air pollution,cost over 20 million dollars in 1968. Another example of an avoidance cost is found in the use of clothes dryers. Of the $600 to 900 million spent on clothes dryers in 1972,how much was spent to buy increased convenience, and how much was spent to avoid hanging clean clothes in dirty air?

One estimate of the air pollution damage costs in the U. S. in 1968 is $16.2 billion. This estimate includes damage to materials, crops, and human health, and reduced property values. It does not include the cost of cleaning soiled materials, damage to animal

health, avoidance costs, and other miscellaneous costs.

5.1 Effects on Vegetation

The nature of air pollution damage to vegetation has been changing as new pollutants reach significant concentrations in air. The destruction of foilage on large scale was initially the result of sulfur dioxide emitted from smelters and power plants. With the development of new industrial processes and products, and a tremendous increase in automobile emissions, extensive injury to trees and shrubs, farm crops and ornamentals from new causes has been reported. Nitrogen oxides, ozone and other photochemical oxidants such as peroxyacetyl nitrate (PAN) damage several crops including grapes, tobacco, and spinach. Damage from these pollutants was reported all over the U.S., as well as in other countries, and was not limited to the immediate vicinity of urban areas. Fluorides have caused extensive vegetation damage in the vicinity of fertilizer plants. Not only are plants susceptible, but livestock that feed on the vegetation on which the fluorides have been deposited, can be killed by a debilitating disease call fluorosis. The estimate for air pollution damage to crops alone in 1968, is $100 million.

5.2 Effects on the Physical Environment

Many materials are affected by air pollution. Metal corrodes, fabric weakens and fades, leather weakens and becomes brittle, paint discolors, concrete in buildings, and stone discolors and erodes, glass becomes etched and paper becomes brittled. Sulfuric acid, a common contaminant of the air in areas where large amounts of sulfur dioxide are emitted, causes the deterioration of many materials. When sulfuric acid is present on the surface of the particles, considerable damage may be done to painted surfaces and other metal parts. Ozone will

cause rubber to crack; nitrogen oxides can produce considerable fading of textile and other dyes; particulates can soil buildings. Particulate air pollution decreases visibility and may also affect weather.

Recreational, aesthetic and psychological factors accompany the direct affects of air pollution on the environment. What is the psychological damage to the owner of the destruction of an ornamental shrub? What is the aesthetic damage caused by smog or haze that spoils a scenic view? What is the recreational damage to vacationers and sportsmen of the destruction of a forest area? The estimated damage to materials and property values in 1968 was estimated at $10 billion in the U. S.

Effects on Human Health

It is difficult to measure accurately in dollars the damage to human health caused by air pollution. Air pollution has been shown to aggravate existing illnesses, and to bring on death in the aged and the weak. There is strong evidence that air pollution is associated with a number of respiratory illnesses including chronic bronchitis, bronchial asthma, pulmonary edema, emphysema and lung cancer. This may be the result of the irritants that make up air pollution, such as acids and oxidants, and it may be the result of a reaction with specific chemical, such as benzo(α)pyrene, a known cancer-producing material. Because of the difficulty in accurately defining the relationship between air pollution and human sickness, it is difficult to determine what portion of the cost from lost work and health care resulting from respiratory injuries, colds, etc., are attributable to air pollution. One estimate of the damage to human health in the U. S. in 1968 is $6.1 million.

6. Air Quality Standards

Air quality standards are values that mark the limits of desired air quality. There are several kinds of standards that have been developed and applied in different situations. In this country, primarily ambient air quality standards and emission standards are used.

Ambient air quality standards were developed from the relationships between air pollution concentrations and the resulting environmental effects, called air quality criteria. Much of the data come from laboratory experimentation and so there is an added difficulty of extrapolating from short-term exposures to animals, to long-term exposures to humans, as would occur in the ambient air. Air quality goals were set from the criteria. These are the concentrations of pollutants with which we are willing to live, considering our desire to protect the health and welfare of the people and provide for technological growth. Once the goals are established, standards are set to allow for the orderly achievement of desired air quality. It follows that there must be standard methods of measurement and analysis of air pollutants to be sure that collected data are comparable.

In the United States, national emission standards were set as part of the strategy to reach the ambient air quality standards. Standards were set for both stationary and mobile sources, as a result of relating the impact of the emissions from such sources on existing air quality. At present, about 40 countries in the world have some kind of air quality standards.

7. Nature of Process Emissions

This syllabus will discuss two kinds of sources: mobile and stationary. Mobile sources include automobiles, trucks, buses, airplanes, etc. Stationary sources include fossil fuel fired power plants, cement plants, steel mills and other heavy and light manufacturing processes.

7.1 Mobile Combustion Sources

Although mobile combustion sources include all transportation vehicles, in terms of its impact on the atmospheric environment, the gasoline powered automobile is the most important. The pollutants emitted by automobiles include carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x) and particulates. Some of these alone are toxic,but it is the role they play in the photochemical reactions that produce smog that makes them particularly important.

There are three types of emissions that comes from the automobile: exhaust emissions—those that comes directly out of the tailpipe; evaporative emissions—gasoline vapors that are lost directly to the atmosphere from the storage fuel and delivery system; and crankcase emissions—those that escape the combustion chamber past the piston rings in the cylinder and into the crankcase. Figure 7-1 shows the approximate distribution of emission from an uncontrolled automobile.

The principal emissions from the exhaust include CO, unburned HC, NO_x and particulate matter. Also emitted are partial oxidation products of hydrocarbons such as aldehydes, alcohols, etc., and high molecular weight HC. The amounts of CO and unburned HC emitted will depend on the air/fuel ratio and the stoichiometric completeness of the burning of the fuel in the engine's cylinders.

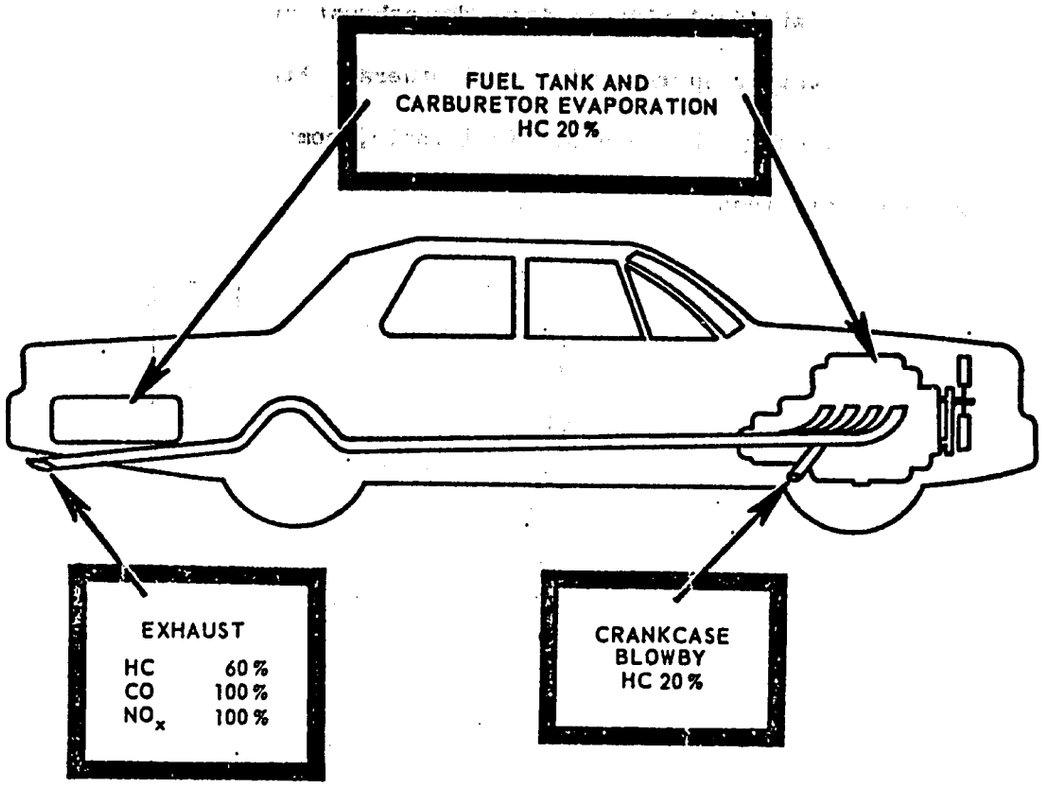

Figure 7-1. Approximate distribution of emissions by source for a vehicle not equipped with any emission control systems.

As the ratio of air to fuel increases, theoretically, combustion becomes more complete, reducing the amounts of CO and unburned fuel to essentially zero. However as the combustion becomes more complete, combustion temperature increases, increasing the formation of NO_x dramatically. To reduce the NO_x, combustion temperature must be reduced. One way this can be achieved is by reducing the air/fuel ratio, however, then the production of CO and unburned HC will be increased. In theory this is what should occur, however the previous discussion does not take into account such factors as cylinder misfiring, which discharges

the entire air/fuel mixture into the exhaust system, engine combustion characteristics, spark timing, and others. Figure 7-2 illustrates the relationships between air/fuel ratio, combustion temperature and gaseous emissions

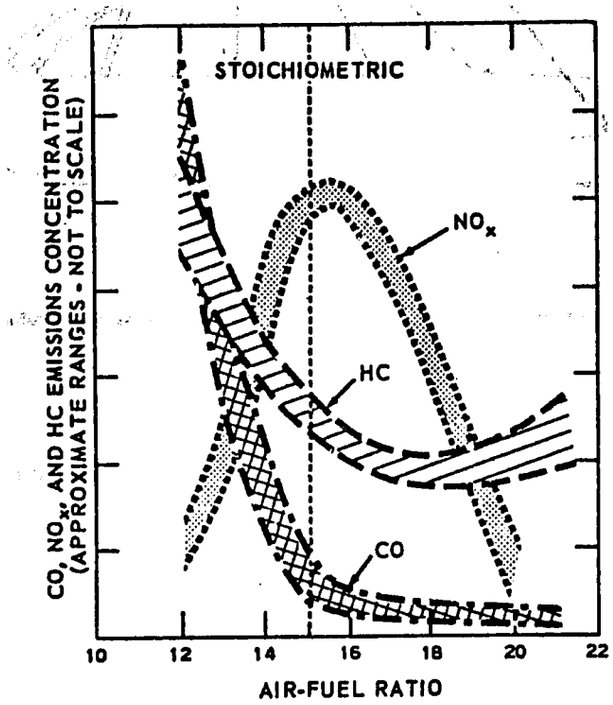

Figure 7-2. Effects of air-fuel ratio on exhaust composition.

Of the three types of emissions from the automobile, the exhaust emissions have proven to be the most difficult to control. Presently the U. S. auto makers have adopted a catalytic converter which insures complete combustion of organic material. Evaporative emissions have been drastically reduced by eliminating any vents to the atmosphere in the fuel storage and delivery system.

Crankcase blowby is the term used to describe the gases forced around the piston rings of the cylinder into the crankcase during the

compression cycle. Prior to 1963 models, these gases, mainly HC, were discharged directly into the atmosphere. Newer cars use a system of crankcase ventilation that recycles the blowby back into the air intake, preventing the emission.

A cautionary note, in considering the impact of changes in automobile design and added air pollution control packages, it is important to keep in mind that a change in a model year takes nearly 10 years, at the present rate of automobile consumption in the U. S., to become spread over the entire automobile population. Thus emission changes introduced in 1975 will not produce an immediate change in ambient air quality.

7.2 Stationary Sources

7.2.1 Fossil Fuel Fired Power Plants. The major pollutants emitted from fossil fuel fired steam generators are particulates, sulfur oxides and NO_x. More particulates are emitted from the combustion of coal than from oil or gas. The composition of the particulate matter will vary with the fuel, but it is largely carbon, silica, aluminum and iron oxide.

The uncontrolled combustion of coal generates an amount of particulates (in pounds) approximately equal to seventeen times the percentage of ash in the fuel. Thus if the ash content is 10%, the estimated particulate emissions to the atmosphere would be 170 pounds of particulates per ton of coal. Approximately 30 pounds of this is collected in the furnace. The uncontrolled emission factors for fuel oil and gas are 8 pounds per thousand gallons of oil, and 15 pounds per million cubic feet of gas. The use of fuel oil instead of coal reduces the amount of particulates by a factor of a hundred.

The amount of sulfur oxides that are emitted is directly related to to the sulfur content of the fuel. Nitrogen oxides in the emission are generated from two mechanisms: a) the fixing of nitrogen and oxygen at the temperature of combustion and, b) the oxidation of nitrogenous compounds contained in the fuel. Other pollutants emitted include CO, the amount of which will depend upon the efficiency of the fuel combustion, and trace metallic oxides, which will vary in composition depending upon the fuel and its source.

Most large central-station power plants that burn coal use a pulverized coal furnace. The advantage of such a furnace is that it provides for more complete combustion of the coal. The principal disadvantages of the furnace is that the fly ash is more difficult to collect and handle. The following table shows the typical gaseous effluents from a thousand megawatt (electrical) - MW - power station.

Table 7-1. Emissions from a thousand MWE power station in tons per year

Pollutant	Fuel Type (coal)	Oil	Gas
Carbon Monoxide	600	90	0
Carbon Dioxide	7.0×10^6	5.2×10^6	4.1×10^6
Sulfur Dioxide	102×10^3	54×10^3	12
Hydrocarbons	240	736	0
Oxides of Nitrogen	24×10^3	24×10^3	13×10^3
Particulate	6×10^3	2.3×10^3	465
Totals (Not including carbon dioxide)	1,032, 840	81,945	13,477

7.2.2 Iron and Steel Manufacturing. The principle emissions from iron and steel manufacture are particulate matter (metal oxides) and volatile hydrocarbons. These are emitted in two different stages in the production of iron and steel. Coke production, most commonly performed in by-product ovens, produces large amounts of volatile materials from the coal. The remaining processes in the production, refining and use of iron and steel primarily produce particulate matter. The size ranges of the particulates produced and their content will vary with the nature of the process. As examples, from 35 to 50% of the emissions from a blast furnace may be iron oxides and silicates; two-thirds or more of the particulate emissions from open-hearth furnaces will be iron oxide. The composition and size range will vary upon the charge to the furnace, the type of fuel used, etc.

7.2.3 Non-Ferrous Metal Industries. The smelting of zinc, copper and lead introduce large quantities of SO_2 into the atmosphere. This occurs primarily because the most important ores for these metals are the sulfides. Copper and zinc smelting introduced more SO_2 to the atmosphere than lead smelting largely because the lead ore is richer in the native metal. Refining processes for each of these metals generally produce more particulate matter than gases. The SO_2 content of the waste gas from zinc roasting and copper smelting is sufficiently high that it can be converted into usable sulfuric acid.

7.2.4 Pulp and Paper Manufacturing. The chemical production of wood pulp produces much of the emissions associated with the pulp and paper industry. Approximately 63% of the total production of pulp in the United States is generated by the kraft process.

The primary emissions from the kraft process are hydrogen sulfide, mercaptans, organic sulfides, and particulates. The principle problem with the gases is they have sickening odors. The types and quantities of sulfur compounds in the gases are dependent upon processing variables and the type of wood being pulped. Emissions occur primarily from the black liquor oxidation process, evaporation and concentration of the black liquor, the recovery furnace and the lime kiln.

Paper production may produce similar emissions although in lower concentrations than the pulping processes. Coating the paper may introduce other organic materials into the atmosphere depending upon the process involved.

7.2.5 Petroleum Refining. The principal emissions from petroleum refining are, hydrocarbons, sulfur oxides, and CO. Lesser amounts of particulates, miscellaneous gases and vapors, and odor-producing compounds are also emitted. These are generated in the various processes by which the oil is distilled, cracked and reformed for the variety of end products that refinery produces.

7.2.6 Mining and Mineral Products. Most of the pollution associated with the mining and mineral products industry results from the mechanical processing of solids. Leaks in and around the mechanical equipment cause dust to be emitted. These particulates are referred to as fugitive dust.

7.2.7 Central Station Incinerators. Generally central station incinerators are of two types: single and multiple chamber. Typically the emissions from these incinerators are mainly CO, miscellaneous organic and inorganic compounds, and particulate matter. The amount that is emitted from each type of incinerator will vary. In general

the multiple chamber incinerator produces fewer emissions because of better control over combustion. Table 7-2 presents typical emissions from single and multiple chamber incinerators.

Table 7-2. Comparisons of Emissions from Single and Multiple Chamber Incinerators

Emissions	Miltiple Chamber	Single Chamber
Particulate Matter (grains per standard cubic foot at 12% CO_2)	.11	.9
Volatile Matter (grains per standard cubic foot at 12% CO_2)	.07	.5
Total grains per standard cubic foot at 12% CO_2	.19	1.4
Total pounds per ton refuse burned	3.50	23.8
Carbon Monoxide (pounds per ton of refuse burned)	2.9	197 to 991
Ammonia (pounds per ton of refuse burned)	0.9	4
Organic Acids as Acetic Acid (pounds per ton of refuse burned)	.22	>3
Organic Aldahydes as Formaladahyde (pounds per ton of refuse burned)	.225	64
Nitrogen Oxides (pounds per ton of refuse burned)	2.5	>.1
Hydrocarbons as Hexane (pounds of tone per refuse burned)	>1	Not recorded

Chamber temperature, burning rate and the uniformity of the charge are the principle factors that determine the completeness of the burning, and in turn, the nature and amount of emissions.

7.2.8 Odor-Producing Industries. There are several industries that substantial amounts of odor-causing materials. These include rendering, coffee roasting and chemical fermentation. In most cases, leaks at various points in the processes are the primary escape route for these materials. In some cases, however, emissions from the stack produce the problem. Most odor-causing materials are nitrogen- or sulfur-containing compounds produced by the destruction of organic matter. The transportation and storage of material collected for rendering may also create odor problems. Particulates and odor-causing compounds emitted from coffee roasting are mainly organic in composition.

Measurement and Monitoring

Measurement and monitoring refer to two different techniques or determining pollutant concentrations. The term measurement describes the process of determining concentrations at a given point in time. The term monitoring describes the process of determining the variation of concentration over a period of time. Measurement and monitoring of air pollutants determines how close the air quality is to the desired air quality, whether in the general atmosphere or inside a stack.

Ambient air monitoring and measurement techniques are used to determine community air quality. In-stack, or source monitoring and measurement techniques are used to determine the amount of source emissions. Both ambient air and source sampling are a necessary part of a strategy to meet community air quality standards.

Concentrations of pollutants in stacks, or at their source, are much higher than in the ambient air. Generally, special instrumentation is required to measure concentrations of pollutants in the very small quantities that they might be found in the general atmosphere. Although acceptable measurement methods exist for most air pollutants, acceptable continuous monitoring methods have yet to be developed for several key pollutants. A typical approach to developing a monitoring method has been to mechanize the measurement method. In some cases, the West-Gaeke for example, the approach worked. In others, for example the continuous Saltzman, it did not.

Both measurement and monitoring procedures require two distinct steps: sampling and analysis. Sampling refers to the selection of the air to be sampled and its delivery to the analytical system.

Analysis refers to the techniques of measuring the concentration of the pollutant in the air sample. Sampling considerations include how representative is the portion of air sampled to the atmosphere or the stack emission; what changes in the air are introduced by the sampling mechanism; how much air should be sampled to obtain a good answer. Analytical considerations include: how fast does the analytical procedure take; how accurate is the method; how reproducible is the method.

A commonly used analytical technique is the colorimetric method. With this type of method, a colored solution is formed as a result of the reaction of the pollutant and the collecting or analyzing solution, the intensity of which is directly proportional to the concentration of the pollutant. The color intensity is measured by a spectrophotometer, which records the difference in the absorption of light of a specific wavelength by the colored solution and a non-colored or reference solution. Colorimetric techniques are convenient and reliable, and are generally usable over a range of pollutant concentrations.

Sulfur Oxides

One of the earliest techniques for measuring total sulfate was the lead peroxide candle method. This was developed in England in 1932 and was based on the reaction of SO_2 and lead peroxide. A paste of lead peroxide was applied to a cylinder of gauze acting as a carrier for the paste. The cylinders or "candles" were set out in the atmosphere in weather-proof shelters for about a month. During this time, the SO_2 reacted to form a black precipitate of lead sulfate. The candle was then stripped and the amount of lead sulfate weighed. The results were reported as milligrams of sulfate per hundred square centimeters of lead oxide per day, which is a sulfation rate. Over

some concentration ranges, sulfation rates are proportional to the SO_2 concentration of the atmosphere.

The sulfation plate method is a greatly simplified version of the lead candle. The principle of the technique is the same, however small plates are used instead of candles. Lead peroxide converts reduced sulfur gases as well as SO_2 and SO_3 to sulfate. It also fixes sulfuric acid mist. Because of its lack of specificity the method has been replaced by techniques specific for the pollutants to be measured.

Early SO_2 concentration data were obtained with a conductometric technique. A change in the conductance of water is produced by absorption of SO_2. The method corrected for carbon dioxide absorption, but other gases such as hydrogen chloride, NO_2 and ammonia, etc., that probably were present in varying amounts, could have interfered with the technique.

The development of a colorimetric procedure, the West-Gaeke method, meant that the SO_2 could be measured specifically, even in the presence of the previously named interfering gases. The West-Gaeke procedure is based on the chemical reaction that occurs between the absorbing solution and the SO_2 producing a colored solution. Typically the ambient air measurement of SO_2 is accomplished through the use of bubblers, devices that mix the sampled air and the collecting liquid together under turbulent conditions to permit the transfer of the gas to the liquid phase.

We are also concerned about concentrations of sulfuric acid in the ambient air. As yet no acceptable measurement or monitoring technique has been developed. There is a method for measuring total sulfur content that has been used. It utilizes a flame photometric technique, in which the sample is burned and the number of sulfur

atoms is measured.

Different measurement and monitoring methods are used to determine SO_2 concentrations in stacks because of the higher concentrations than are found in ambient air. The method currently in wide use, is the barium chloranilate method, another colorimetric method that is useful in the concentration range of several hundred to several thousand mg/m^3 (ppm) SO_2 found in stack gases.

Special instruments that use ultraviolet and infra-red light have been developed to monitor SO_2 in stacks. These are continuous read-out devices that show the behavior of SO_2 concentrations with time. They are reported to be reliable and to require relatively little maintenance.

8.2 Nitrogen Oxides

For measuring NO_2 in ambient air, perhaps the most widely used method has been the Saltzman technique. It is a colorimetric procedure requiring the sampling of the gas using a bubbler. By using a parallel sampling line and either scrubbing the sample free of NO_2, or oxidizing the gas stream, it is possible to use the Saltzman technique to determine the NO concentration as well. This technique was designed for short-term gas sampling, of the order of an hour; modifications have been made which permit the use of this technique of monitoring NO_2 and NO over a 24-hour period. Other chemical techniques have been developed that attempt to correct some of the inaccuracies and difficulties associated with the Saltzman technique. These are also colorimetric methods, but they use different absorbing solutions. None of these have been generally accepted.

In an attempt to get the continuous monitoring data that is needed for air quality management, an instrumental technique utilizing the principal of chemiluminesence has been developed. The chemical reaction

of NO with ozone produces a small amount of light. The amount of light produced is directly proportional to the concentration of the reacting gases. This phenomenon, called chemiluminescence, provides a method for accurately measuring and monitoring low concentrations of NO and NO_2. (By reducing the NO_2 in the sample to NO, the NO_2 concentration can be determined).

A static monitor, patterned after the lead candle method, was developed using nylon fibers for collection of NO_2, as an indicator of the nitric acid concentration in the atmosphere. The NO_2 was removed from the nylon and measured by one of several analytical procedures. The method has not been used widely.

For NO_2 concentrations in stacks, a colorimetric procedure called the phenoldisulfonic acid method is employed. Here the concentration is reported as total NO_x. Continuous in-stack monitors have been developed for measuring NO_2. These also employ ultraviolet absorption techniques.

3.3 Hydrocarbons

There are two techniques that are most widely used to measure and monitor hydrocarbon concentrations: gas chromatography and total hydrocarbon analysis. Use of gas chromatography makes it possible to determine whether a particular gas is present, in addition to its concentration. Although originally used as a measurement technique, recent developments have made it possible to use gas chromatography for monitoring. In the total hydrocarbon analysis, the hydrocarbons are burned and the atoms of carbons are counted. Thus hydrocarbon concentrations are reported as methane concentrations. No information about the kinds of hydrocarbons present in the sampled air is available with this technique.

It is possible through the use of an infra-red or ultraviolet absorbing instrument to determine the concentration of a specific hydrocarbon in the atmosphere, or in the stack.

8.4 Oxidant

Oxidant refers to a group of oxidizing gases in the atmosphere. These include ozone, peroxides, hydroperoxides, NO_2, and others. Oxidant concentrations have been measured and monitored using the Mast instrument, which continuously records the amount of oxidizing material present in the atmosphere by using a coulometric technique. Potassium iodide solution is brought in contact with the sampled air. The iodide is oxidized to free iodine, which is reduced to iodide at the instrument's cathode. The amount of electrons required is directly proportional to the oxidant concentration. The presence of reducing gases such as hydrogen sulfide and others will interfere, but techniques have been developed for removing these.

Ozone is the component of oxidant that has generated the most concern. It has been measured by the neutral buffered potassium iodide method. This is another bubbler-colorimetric method, generally accepted as the reference method for ozone concentration determinations Chemiluminescence also has been used to measure and monitor ozone levels. The reaction of ozone with Rhodamine B, or ethylene is most often used. Such measurements are specific for ozone, and also are reliable and allow for continuous monitoring.

8.5 Carbon Oxides

Both CO and CO_2 are very conveniently measured by infra-red spectroscopy, by measuring the difference in absorption of air containing the gases, and air free of the gases. These infra-red techniques can be applied to in-stack measurement and monitoring as

as well.

Because of the high concentration of CO_2 in the air—about 0.3%—chemical methods can be used to measure atmospheric and source concentrations of the gas. In one method, a chemical reaction occurs between the CO_2 and an absorbing solution containing a known amount of barium hydroxide. The amount of barium hydroxide consumed is proportional to the amount of CO_2 in the sample.

For chemically measuring CO_2 and CO in stack gases, the Orsat gas analyzer has been used.

8.6 Particulates

Dust fall buckets are static monitors for particulates that are easy to use. They are placed at designated locations and collected once-a-month. The collected particulates are dried and weighed. Data are reported as tons of particulates per square mile. These buckets will collect only those particulates that fall from the atmosphere and so provide information on the soiling potential of the air. This technique does not provide information about the suspended particulates, which are important from a health standpoint. To measure and monitor the suspended particulate matter, filtration techniques have been used. These include tape, and high volume (HI-Vol) samplers. The tape sampler collects the dust on a roll of filter paper. The Hi-Vol collects particulates on an 8" x 10" filter held in a frame and mounted in a characteristically shaped enclosure.

In general airborne suspended particulates range in diameter from submicron particles up to about 100μ. The paper tape sampler was developed to measure amd monitor the level of suspended particulates in the air. The tape passes a sampling port where the particulates

are collected for about 1 hour. The tape then advances so that a clean area is moved in front of the sampling port. After the sampling is completed, the tape has a series of regularly spaced spots of filtered particulates. The particulates levels in the spots are analyzed in one of two ways. Either the transmission of light through the collected particulates, or the reflectance from the surface is measured. The transmission measurement is recorded in units called COH's, meaning "coefficient of haze." The reflectance measurements are reported in units called Ruds, meaning "reflectance units of dirt shade." COH's are intended to reflect the loss in visibility, while Ruds are intended to reflect soiling.

The Hi-Vol sampler filters a large volume of air over a 24 hour period through a square filter, typically 8" x 10" in size. Other techniques involving smaller filters and in some cases, reduced sampling flow rates, have been tried. The filters are efficient enough to trap submicron particles. The technique permits the collection of enough material not only to measure the concentration of particulates, but also to analyze the pollution composition. Once the particulate matter has been collected on the filter, it is equilibrated to a standard humidity and then weighed. The amount of particulate matter is reported in $\mu g/m^3$. Portions of the filter can be cut and treated to analyze for metals or other material collected. The remainder of the filter is saved for future analyses and reference.

No single monitoring technique for particulates has been generally accepted. It is important to know how visibility and soiling, as well as human health are affected by particulates. Unfortunately, a concentration of suspended particulates in $\mu g/m^3$ cannot give all the answers, therefore a number of measurement techniques are used

to monitor the air quality.

For in-stack sampling, a very specific set of procedures must be followed to be sure that a representative sample of the air stream is obtained. Sampling must be performed iso-kinetically, meaning that the rate at which the air is drawn into the sampling line must be the same as the rate at which the air passes the sampling intake. To sample at rates lower or greater than the air flow rate would mean that certain sizes of particles would not be captured. In iso-kinetic sampling, the pressure drop across the sampler must be continuously measured along with the pressure in the stack, so that adjustments can be made to make sure that the gas flows are always matched. In addition, the plan of sampling must be carefully prepared so that the results are independent of the different air flow patterns that are found in each stack. A number of measurements are taken across the diameters of the stack and averaged. This insures that the amount of material collected will most closely approximate the amount of material that is emitted. The particulates are collected on a filter or in a thimble, and are weighed to determine the amount of material present in the stack emissions.

9. Control of Industrial Emissions

The control of industrial emissions can be accomplished using a wide variety of control equipment, often tailored specifically to the process and operating conditions of the source. There are six basic types of control equipment currently in use:

a. Mechanical collectors - generally for collecting solid particulate matter.

b. Scrubbers - for collecting particulates and gases.

c. Filters - for collecting particulate matter

d. Electrostatic precipitators - for collecting solid and liquid particulate matter.

e. Afterburners - for removing gases.

f. Adsorbers/absorbers - for collecting gases and vapors.

9.1 Mechanical Collectors

Mechanical collectors are generally used to remove solid particulate matter - dust, fly ash, fibers wood dust, etc., - in the size ranges larger than 5μ in diameter. They utilize the forces of gravity, inertial impingement and centrifugal separation to remove particulate matter from the exit air stream. Some of the mechanical collectors are used in conjunction with water sprays to remove particulates and gases. Most often they are used to recover the solid in a dry state.

9.1.1 Settling Chamber. Settling chambers rely on the gravitational force exerted on particles moving in an air stream to overcome the forces of flow when the velocity has been drastically reduced. Settling chambers are low in cost and are operated with low pressure drops. However their collection efficiencies are only about 50%-60%. Settling chambers typically are used to remove very large particles (larger than 50μ) from an air stream prior to the use of a high-efficency collector. The

The settling chamber consists simply of a large chamber in which the velocity of the air stream is markedly reduced to allow the particles to settle, as shown in Figure 9-1. For the settling chamber to be effective, the air velocity through the collector must be uniform and relatively low,—60 feet per minute (fpm) or less. Baffles and shelves may be added to the chambers in an effort to increase their efficiency. Baffles force sharp changes in direction for the air stream and so introduce some inertial impaction to the gravitational collection. Horizontal shelves make the velocity distribution more uniform and provide a surface for collecting the particles. However, the plates make the removal of the dust rather difficult. In addition to these drawbacks, settling chamber require considerable space for their installation. They are not very widely used.

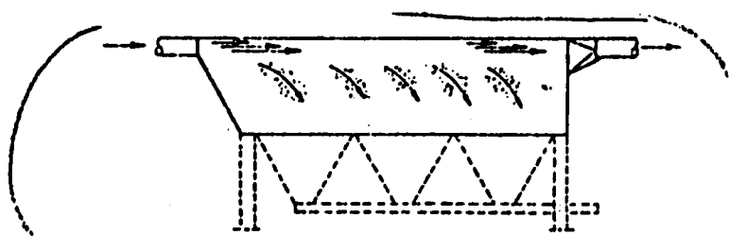

Figure 9-1. Gravity settling chamber.

9.1.2 Dry Centrifugal Collectors. Dry centrifugal collectors utilize the centrifugal force created by the design characteristics of the collector to separate the particulate matter from the carrier gas or air stream. In the conventional cyclone, a vortex is established by the tangential gas inlet. The dust particles are thrown toward the walls of the collector and are removed through a receiver at the base of the cyclone, as shown in Figure 9-2. The conventional cyclone is the most common example of the dry centrifugal collector.

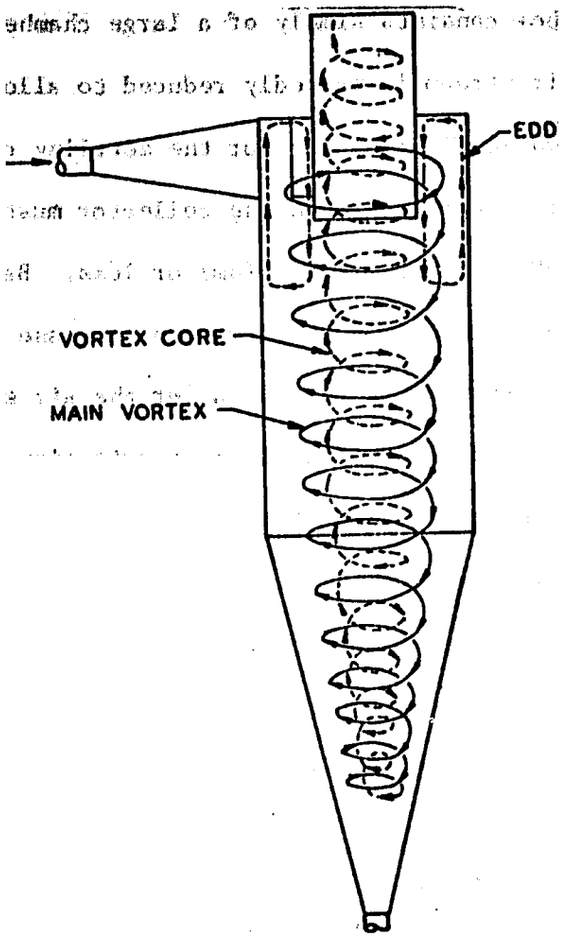

Figure 9-2. Typical cyclone

Depending upon the design characteristics of the cyclone, it can operate with relatively low or high efficiencies of collection. It has the advantages of having few moving parts, being able to handle large flow rates, and being able to operate at high temperatures. Often three efficiency ranges are applied to cyclones - low, medium and high - depending upon their weight collection efficiences. These ranges are 50%-80%, 80%-95%, and 95%-99%, respectively, and are related to the particle size - the larger the particle size the more efficient a given cyclone will be. In general, conventional cyclones are useful

for collecting particles greater than 15μ in diameter. High efficiency cyclones may be used for collecting particles above 5μ in diameter. Cyclones may be packed together in a parallel arrangement called a multi-cyclone collector to obtain the benefits of both high efficiency and high gas flow. Cyclones are typically used in feed and grain mills, cotton gins, fertilizer plants, petroleum refineries, asphalt-mixing plants, and metallurgical, chemical and plastics plants. Table 9-1 shows representative performance of cyclone collectors.

TABLE 9-1. TYPICAL PERFORMANCE OF CYCLONES

Process	Material	Air Flow (CFM)	Pressure Drop (inches of water)	Efficiency (weight percent)	Inlet Load (grains per cubic foot)
Cleaning	Talc	2,300	0.33	93.0	2.2
Drying	Sand & gravel	12,300	1.9	86.9	38.0
Grinding	Aluminum	2,400	1.2	89.0	0.7
Planing Mill	Wood	3,100	3.7	97.0	0.1

9.1.3 Impingement Collectors. Impingement collectors depend upon a series plates to produce a radical change in air stream direction causing the particles to impinge on the plates, as shown in Figure 9-3. The type of collector shown is a flat louver impingement separator in which particles impinge upon the louvers. The particles than bounce off, or are washed off, the individual louver elements into an air stream called the dust circuit, which washes the bottom surface of the collector to remove the accumulated dust. These collectors can be used in series to increase their overall collection efficiency.

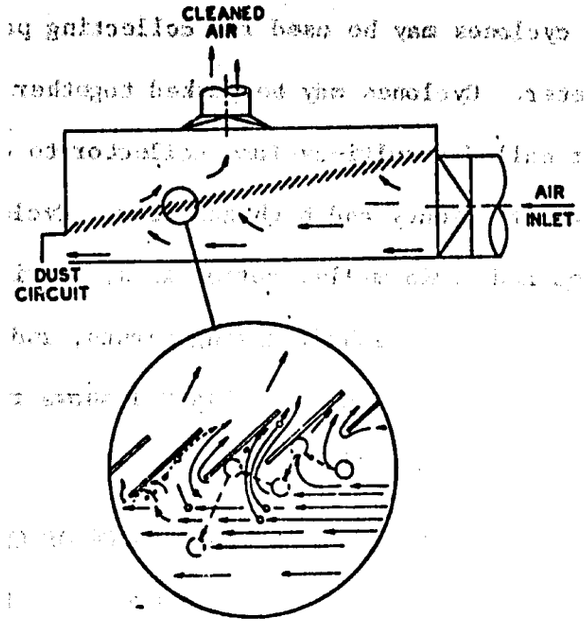

Figure 9-3. Flat louver impingement separator.

9.1.4 Dynamic Precipitator. The dynamic precipitator combines the operations of the fan and a dust collecting device in one package. The principle advantages of this unit are its compactness and the fact that the collection efficiency are relatively uniform over a limited size range. The major limitations are a tendency toward plugging, rotary imbalance resulting from the build-up of solids on the rotating impeller, and temperature limitations of the bearings and seals in the fan. The dynamic precipitator has a collection efficiency in between that of a conventional cyclone and a high efficiency cyclone.

9.1.5 Summary. Dry mechanical collectors can be used with a variety of solid particulate matter, and over a wide range of air flows, particles sizes and temperatures. The collectors are primarily used in situations where particle sizes are larger than 7.5-10μ, because

they have relatively high collection efficiencies. If the air stream contains particles of smaller size, then they must be removed by other techniques. Table 9-2 summaries the use of mechanical collection equipment.

Table 9-2. Use of Mechanical Collectors

Collector Type	Space Requirements	Volume Range CFM	Efficiency by Weight	Pressure Loss[a] in Inches H_2O	Temperature Limitations	Applications
Settling Chambers	Large	Space Available Only Limitation	Good Above 50μ	0.2 to 0.5	700-1000°F Limited only by Materials of Construction	Pre-collect for fly ash, an metal-lurgica dust.
Conventional Cyclone	Large	Normal Range up to 50,000 cfm	Approx. 50% on 20μ	1 to 3	700-1000°F Limited only by Materials of Construction	Wood-working paper, buffing fibers, etc.
High Efficiency Cyclone	Medium	Normal Range up to 12,000 cfm	Approx. 80% on 10μ	3 to 5	700-1000°F Limited only by Materials of Construction	Wood-working materia conveyi product recovery etc.
Multi-Tube Cyclones	Small	Normal Range up to 100,000 cfm	90% on 7 1/2μ	4.5	700-1000°F	Pre-collector for electro-static pre-cipitator for fly ash product recovery, etc.

Table 9-2 (cont'd). Use of Mechanical Collectors

Collector Type	Space Requirements	Volume Range CFM	Efficiency by Weight	Pressure Loss[a] in Inches H_2O	Temperature Limitations	Applications
Impingement Separator	Small	Space Available Only Limitation	90% on 10μ	1 to 5	700°F	Coarse particle collecting boiler fly ash and cement clinker coolers. Recent design used for cleaning atmospheric air to diesel engines, an gas turbine
Dynamic Precipitator	Small	17,000 cfm	80% on 15μ	No loss (True fan)	700°F	Wood-working, non-production buffing, metal-working, et

[a]Pressure drop is based on standard conditions

Wet Collectors

In simple terms, wet collectors are scrubbers that use a liquid, usually water, to remove particulate matter and gases from an air stream by contact between the particles or gas molecules with the scrubbing liquid. For the collection of particles the scrubbing liquid may perform several functions:

a. carry away the collected particles,

b. capture the particles by impingement, and

c. absorb or react with gases in the air stream.

There are many designs for scrubbers. They may be modifications of dry mechanical collectors, as is the wet cyclone, or they may be designed for a particular cleaning application. Scrubbers may be filled wih packing material (packed) to increased the surface area for contact between the scrubbing liquid and the particles or gases to be collected, or they may be unpacked. If the liquid flow is in the same direction as the air flow, the scrubber is called cocurrent; if it is opposite to the air flow, counter-current; or if it is at right angles to the air flow, cross-flow. A simplified diagram of a cross-flow and a counter-current flow packed scrubber is shown in Figure 9-4.

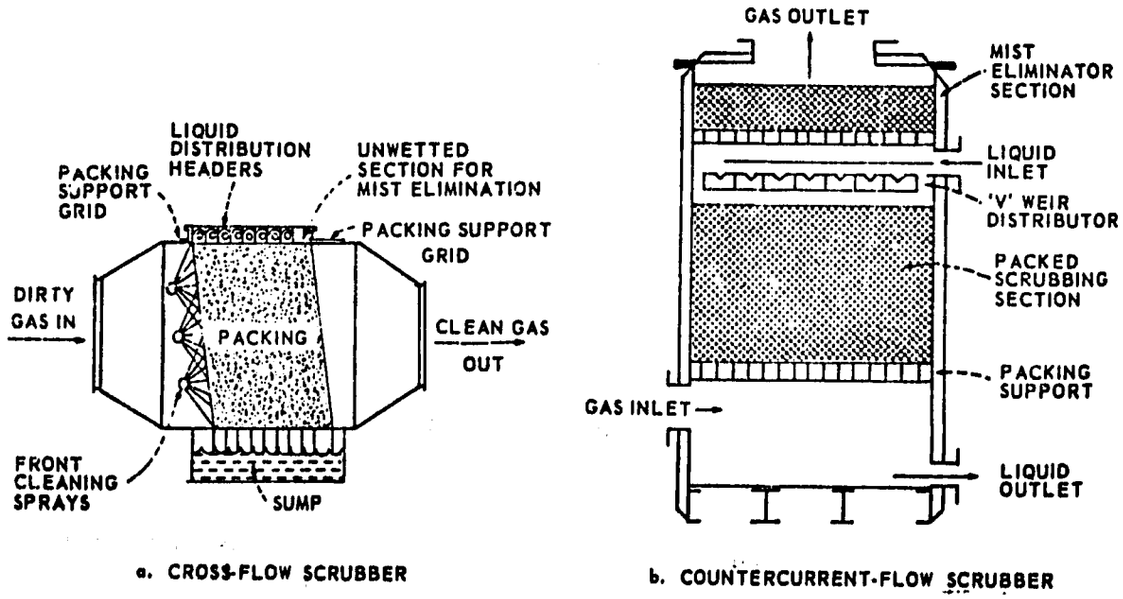

Figure 9-4. Packed-bed scrubbers

When gases need to be removed, only the counter-current scrubbers are used. The gas about to be discharged through the top of the scrubber is contacted by the cleanest liquid, and the incoming, most contaminated,

gas is contacted by the most contaiminated liquid.

The most commonly used packed scrubbers are counter-current, where the gas flow is upwards, vertically, against the gravity feed, downwards, of the absorbing liquid. One of the simpliest types of wet scrubbers is the gravity spray tower. This is an unpacked scrubber in which liquid droplets either from spray nozzles or atomizers fall

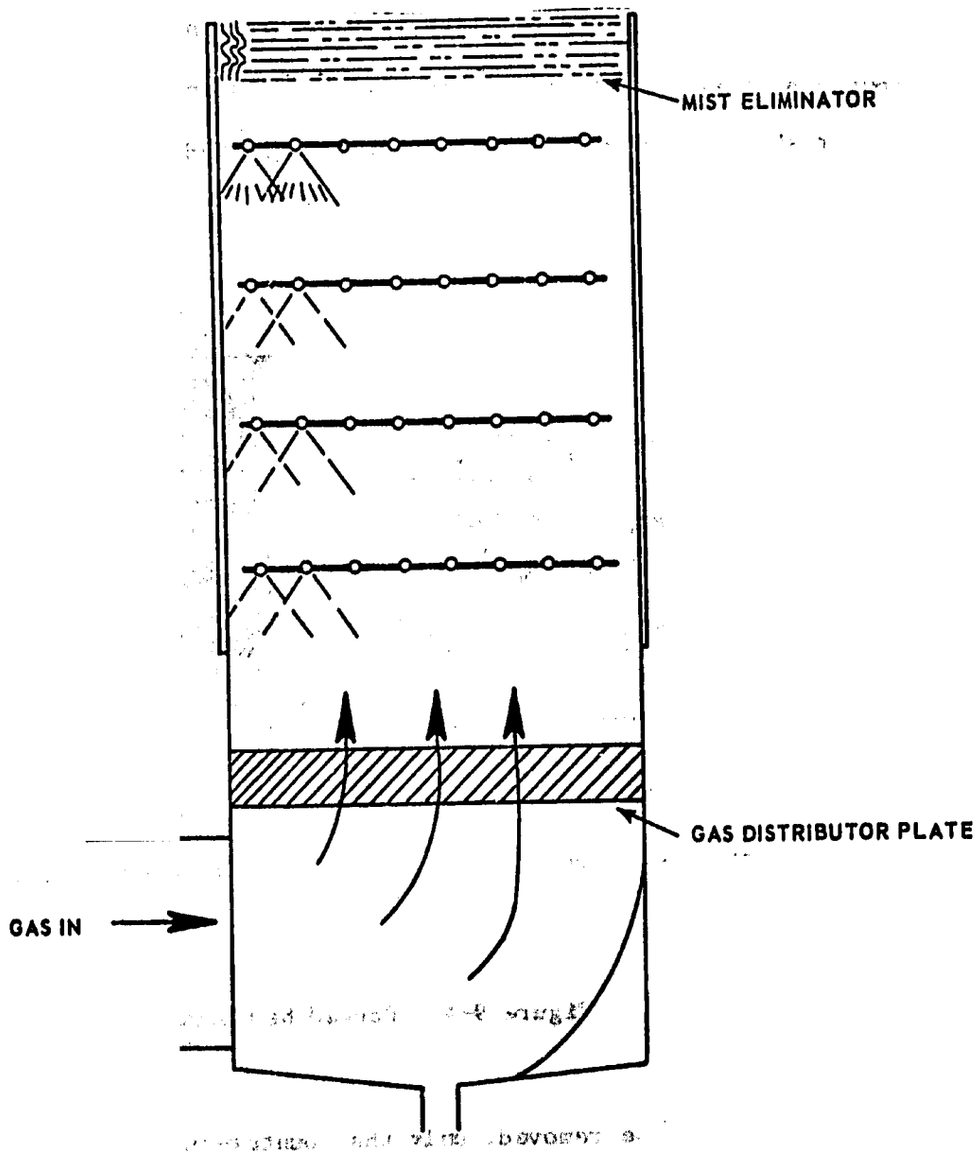

Figure 9-5. Typical layout for spray tower.

downward on a counter-current, rising air stream containing the dust particles. A mist eliminator is used at the top of the tower to prevent carry over of the droplets. A typical spray tower is shown in Figure 9-5. Irrigated cyclones may also be used to collect dust particles. In general they have higher efficiencies than their dry counterparts largely because of their abilities to reduce re-entrainment of the particles. Here the water is serving as a means of washing the collected surfaces free of collected particulate matter. One of the considerations in designing the scrubber system is the removal of the contaminant from the scrubbing liquid. It is easier to remove particulate matter from the scrubbing liquid than gaseous matter or material that is soluble in the scrubbing liquid.

Usually, higher pressure drops are required for higher efficiencies of collection. As an example, a pressure drop of 6 inches of water might provide 95% of collection of particles 5μ or larger, whereas a pressure drop of 10 to 12 inches of water might provide efficiencies of 90% or greater on particles 1-2μ in size. Much higher pressure drops would be required for efficient collection of particles less than 1μ in size. As particles become very small, diffusion and electrostatic forces are more important than inertial forces. Thus 1μ and smaller become increasingly difficult to remove by scrubbing.

9.2.1 Summary. Simple gas washers such as unpacked towers can be effective and efficient in removal of large diameter particles, particularly in the 7.5-10μ range. Packed towers improve the efficiency of collection and these can be effective down to 1 or 2μ. Use of higher energy scrubbers, such as venturi scrubbers - those that operate at high pressure drops - it is possible to obtain 90% collection efficiencies of particles in the sub-micron range.

9.3 Filtration

Filtration is one of the oldest and most reliable methods for removing dust, mist, fumes and other solid materials from gas streams. Although there are several types of filtering media used, fabric filters are in widest use. The fabric filter is capable of high collection efficiencies for particles as small as a 0.5μ and can remove substantial quantities of particles as small as 0.01μ. Fabric filters are used extensively in industrial operations because they are capable of handling high particle loads. The filters are usually made in the form of a tubular bag or envelope, that is slipped over a wide frame and hung in a container which allows a multiple number of the bags to be arranged. The dust can either be collected on the inside surface, or on the outside surface of the bag, depending upon the cleaning mechanism that will be employed. Figure 9-6 shows a simplified diagram of a dust collector called a bag house, where the dust is collected on the inside surface of the bag.

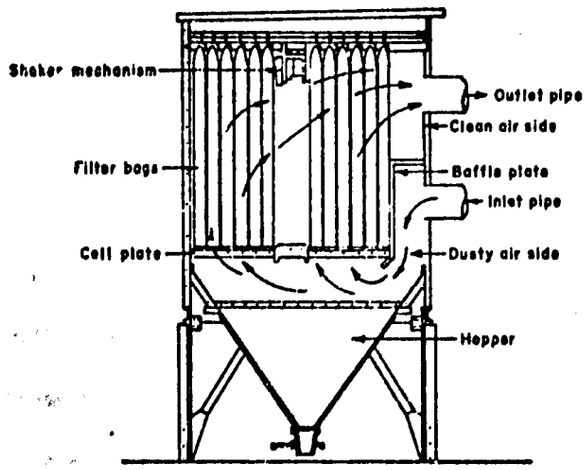

Figure 9-6. Single compartment baghouse filter. Mechanical cleaning is intermittently applied.

Figure 9-7 shows a picture of a baghouse in which the dust is collected on the outside. As many as several thousand bags may be installed in a bag house, usually compartmented to permit the cleaning of groups of bags while others remain in service. Particulate matter is removed from the air gas stream by impinging on, or adhering to, the fibers of the bag. The process is not simply fiber sieving because open spaces are sometimes a 100μor larger, yet dust particles 1μ or smaller can be captured. Other processes involved in the filtration probably include inertial impaction, diffusion or electrostatic attraction, and possibly, gravitational settling. Certainly once mats or cakes of dust accumulate on the fabric, sieving as well as one of the other mechanisms is involved. It is necessary to build up a small cake on the fabric surfaces in order to achieve maximum collection efficiency.

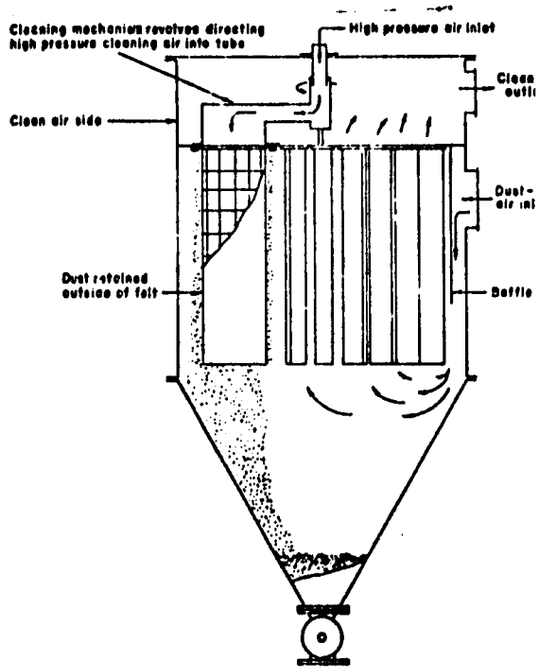

Figure 9-7. Reverse pulse filter.

Periodically the accumulated dust is removed but some small amount of the cake is always allowed to remain on the bag. Removal of the particulate matter is usually timed to occur when the particulate-generating processing is off or stopped. In most situations, the bag house is located above a hopper into which the particles or dust may fall when blown off, or shaken from the fabric. Mechanical shaking of the bags causes the dust to fall into the hopper. A reverse flow of air may also be used to help remove the cake from the filter bag. For large installations it is common to have the baghouse compartmentalized so that a section can be shut down for cleaning while other sections are operational. The removal of the accumulated dust is scheduled so that one portion of the total filter capacity is always being cleaned.

Dust removal can also be done during the filtering operation. This is generally accomplished by a reverse air flow either through a ring that traverses the length of the bag and pushes the air back through the bag; or through high pressure air jets that create a shock wave along the length of the bag to remove the cake, as shown in Figure 9-7.

Natural fibers are usable at lower temperatures, synthetics in the mid-ranges and inert materials like "Teflon", graphite, asbestos and "Nomex" nylon can be used at high temperatures. The nature of the fiber will also determine whether it is relatively resistent to attack by acids, bases, or organic solvents, or moisture. By the selection of appropriate filter media and structural materials for the baghouse, collection of particulates can be done in relatively corrosive atmospheres.

9.3.1 Summary. Some 80% of all manufacturing plants contain operations that produce dust particles of such a small size that use a highly

efficient collection device such as a baghouse is desirable. In many cases, where the material that is filtered is reclaimed, the fabric collectors are an integral component of the manufacturing process. Examples of solids that are reclaimed are metal oxides, carbon black, cement, clay and pharmaceuticals. Fabric filters can also be used to remove harmful or irritating emissions such as chemicals and abrasives. When alakaline additives are add to oil fired power plants to reduce the SO_2 concentration, baghouses are used to collect the solid product of the reaction. In general the efficiency of performance is high even for particles in the sub-micron range. The solid material can be collected either on the inside surface or the outside surface of the bag. A variety of the bag cleaning methods maybe used depending upon the requirements of a particular installation.

9.4 Electrostatic Precipitators

Electrostatic precipitation permits the high efficiency removal of particulate matter down to the sub-micron range, with high gas volumes (50,000 to 2 million cfm), over broad temperature and pressure ranges. There are three steps to the separation of the particulate matter from the gas stream:

a. the charging of the particles of suspended matter,

b. the collection of the charged particles at a ground surface,

c. the removal of the accumulated particulate matter.

There are two principal types of precipitators: high-voltage and low-voltage, also called single-stage and double-stage.

9.4.1 High-Voltage Precipitators - By far the type of electrostatic precipitator most widely used for industrial applications is the high-voltage or single-stage precipitator. Two designs are used in most single-stage precipitators: the flat-surface-type and the tube-type.

In the first design, the particles are collected on flat collecting surfaces spaced from 6 to 12 inches apart. A wire or rod discharge electrode is located centrally between the surfaces. In tube-type precipitators the grounded collecting surfaces are cylindical instead of flat and the discharged electrode is centered along the longitudinal axis of the tube. Both these kinds of precipitators are shown schematically in Figure 9-8 and 9-9. The potential difference between the discharged electrode and the collecting surfaces is high enough so that a corona discharge surrounds the electrode. Typically the electrodes are made from round wires however they can also be in the form of twisted roads, ribbons and barbed wire, as shown in Figure 9-10.

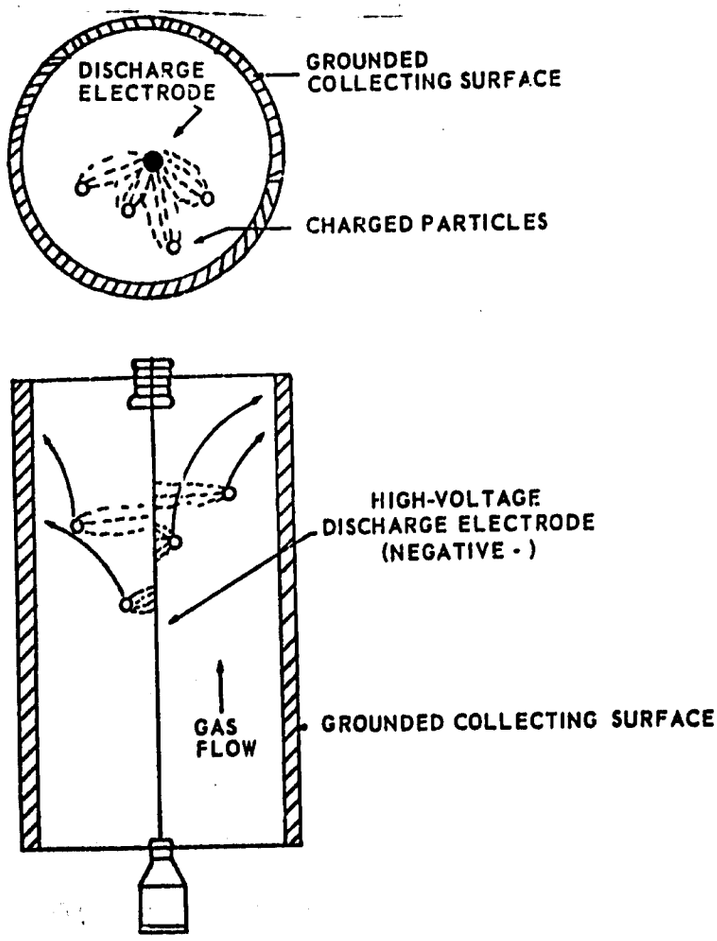

Figure 9-8. Schematic view of tubular-surface-type electrostatic precipitator.

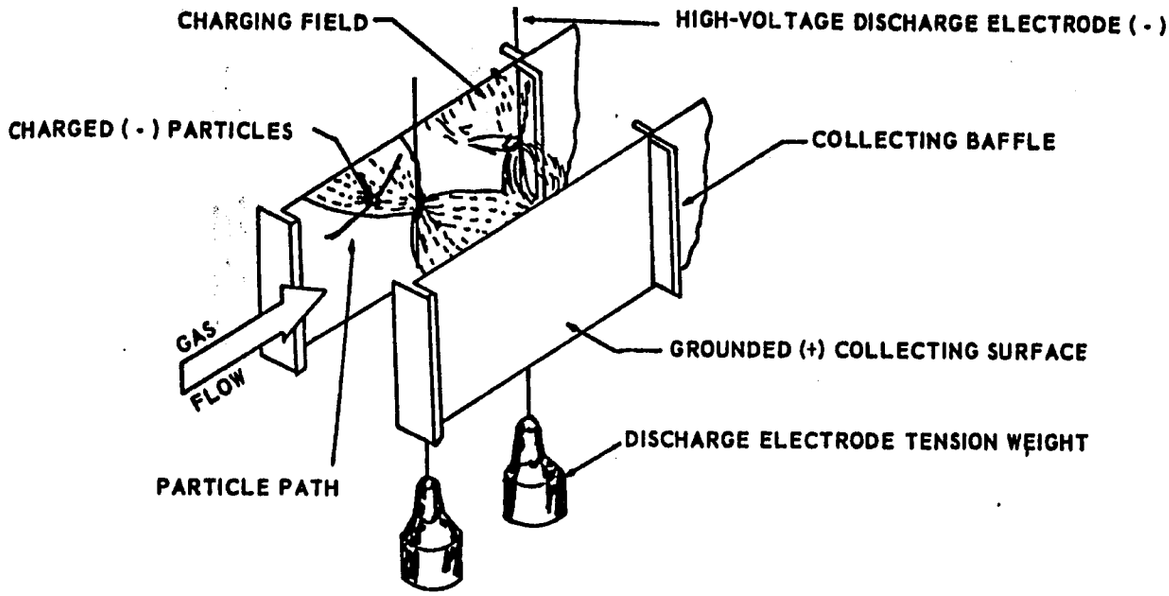

Figure 9-9. Schematic view of a flat-surface-type electrostatic precipitator.

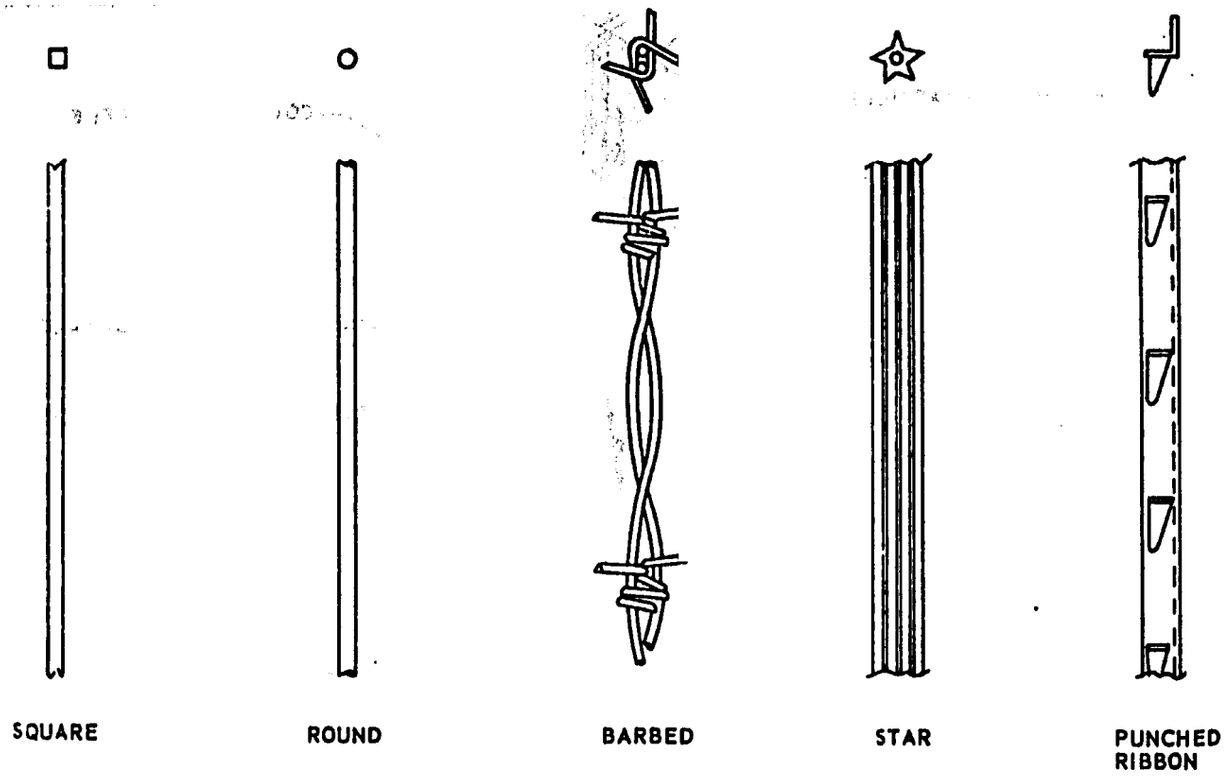

Figure 9-10. Discharge electrodes

Similarly the collecting plates, while often flat, can also have other shapes, such as expanded metal, or curtains of rods as shown in Figure 9-11. There special shapes are designed primarily to prevent re-entrainment of the dust.

Particles in the gas field passing through the corona are charged by the gas ions. The electrical field interacting with these charged particles will cause them to drift toward, and deposit on, the collecting plates or electrodes. If the particles are liquid droplets, they will collect on the electrodes and eventually drip into a sump. If the

particles are solid however, the dust layer that forms eventually builds and must be removed by rapping the electrodes, to break loose the dust. Some of the dust may be re-entrained. However because this re-entrained dust has a larger average particle size than the original particles collected, because of agglomeration, it will quickly deposit on other nearby plates. Sprays can also be used to flush material from the collecting surfaces.

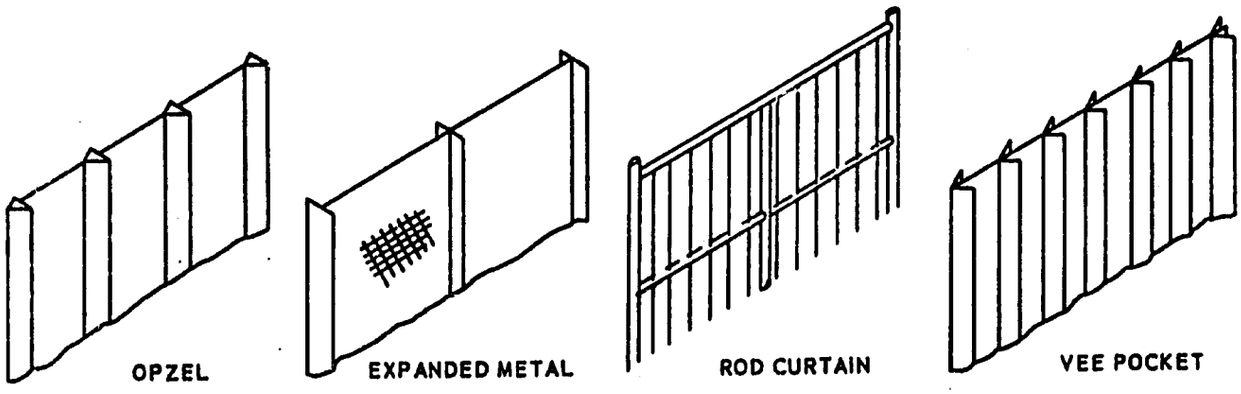

Figure 9-11. Collecting plates

Operating conditions for the precipitator are usually set for the particular solid material to be collected. Any change in the character of the emissions will change the collection performance of the precipitator. Such factors as the resistivity of the solid, flow characteristics in the precipitator, and moisture content of the air stream are important in determining the efficiency of collection. High voltage precipitators have been used to collect a wide variety of solid and liquid particles. Typically their efficiencies will be

in the range of 90-99+%. Electrostatic installations are common in fossil fuel fired power plants, steel mills, the cement plants, kraft pulp mills and sulfuric acid plants.

9.4.2 Low-Voltages Precipitators. The low-voltage, or two-stage, precipitator was originally designed as an air purifying device to be used as part of air conditioning systems. It is most effectively used in industrial applications for the collection of finely divided liquid particles as are associated with meat smoke-houses, asphalt plants, paper saturaters and pipe coating machines. Because of the need for close spacing of the plates, the use of low-voltage precipitators is generally limited almost entirely to the collection of liquid particles. Solid particles or sticky materials will accumulate and cause the plates to short. In the low-voltage precipitators, the ionizing and collection zones are separated. In the ionizing stage, fine wires, positively charged, are located 1 to 2 inches from parallel grounded tubes or rods. This creates a corona discharge through which the particles are passed. The second stage consists of parallel metal plates which are alternately charged positive and negative, or positive and ground. The latter design is shown in Figure 9-12.

The particulates are collected on the plates of the second stage. Liquid droplets will aggregate and wash off the plates into a collecting sump. Solid particles must be removed periodically by mechanical means.

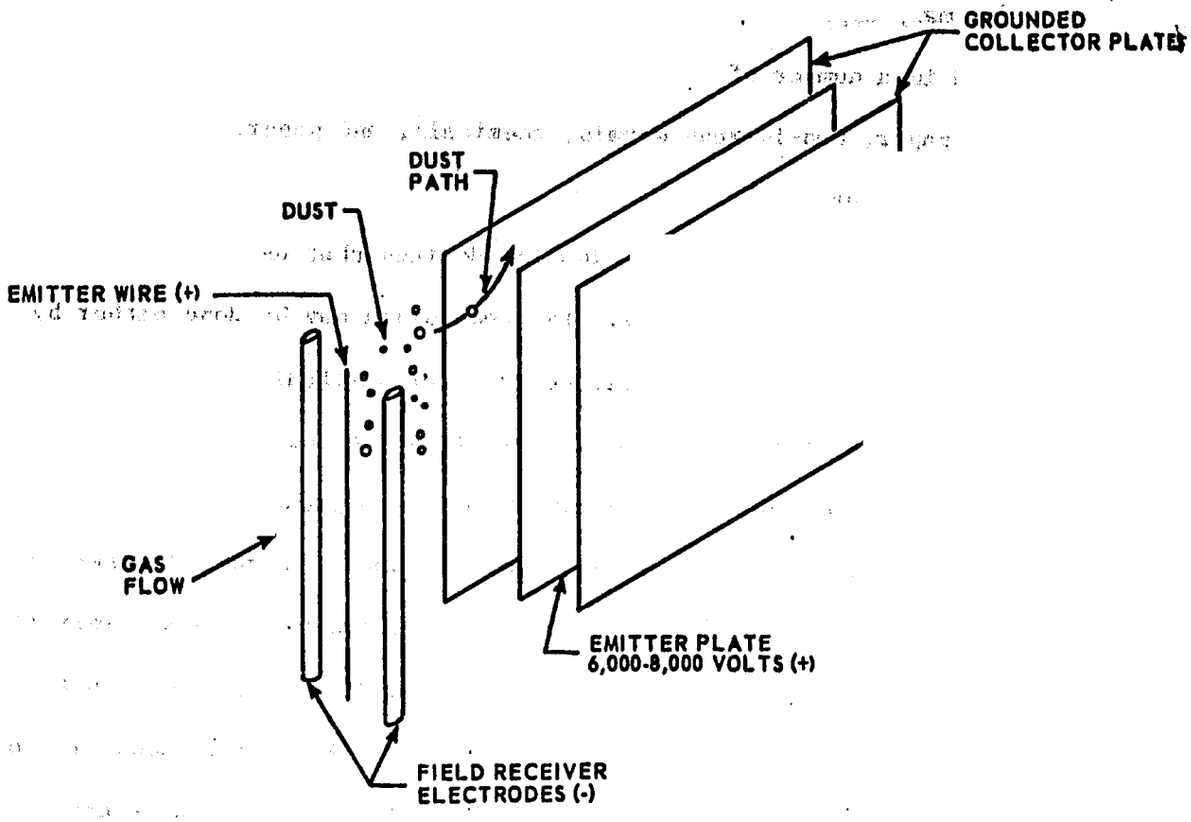

Figure 9-12. Operating principle of two-stage electrostatic precipitator.

9.4.3 Summary. Electrostatic precipitators are collection devices that can achieve high collection efficiencies, exceeding 99% in some cases, for particles of very small diameters. The design of the precipitators permits them to be used at very high gas loads and even very high temperature ranges, in some cases exceeding a 1000°F. They also operate at low pressure drops and tend to have low operating cost. Precipitators tend to be most efficient when operating conditions are constant. They cannot remove gaseous pollutants from

the air stream and have other drawbacks which make them inappropriate for many applications. Electrostatic precipitators however are widely used in a number of industries including electric power, steel, pulp and paper, non-ferrous metals, chemicals, and paper.

9.5 Afterburner

Afterburners are gas cleaning devices that use a furnace for burning gaseous pollutants. The combustion may be done either by direct flame or by catalytic means. For particulates to be removed from an air stream by this process, they must be residue-free and readily combustible. Afterburners are used primarily to dispose of fumes, vapors and odors when relatively small volumes of gases or low concentrations of particulate matter are involved. In a direct flame combustor or afterburner, the flame is in direct contact with the particle-laden gas, as is shown in Figure 9-13. In a catalytic combustion unit shown in Figure 9-14, the particles and gases are consumed at the surface of the catalyst without any direct flame, after the air stream has been preheated. In the catalytic unit, the combustion is performed at a lower temperature in the direct fired afterburner.

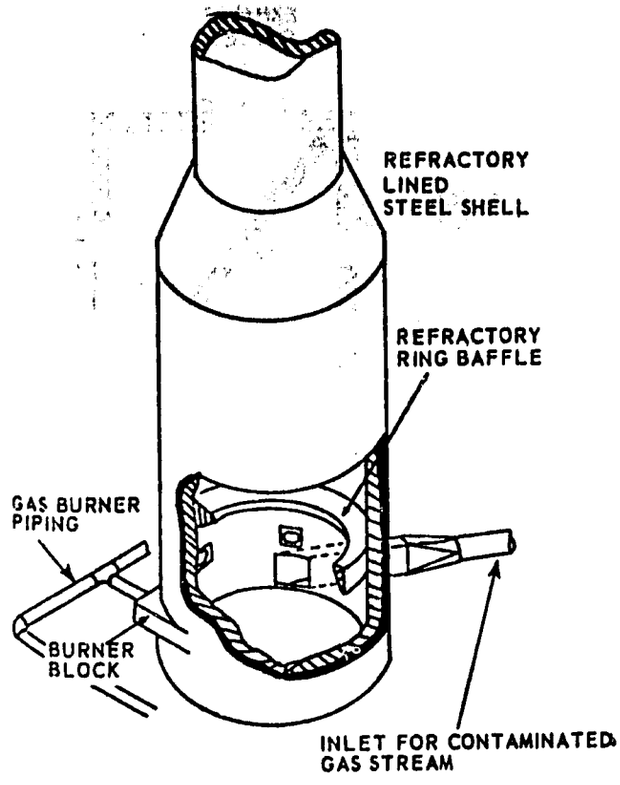

Figure 9-13. Typical direct-fired afterburner.

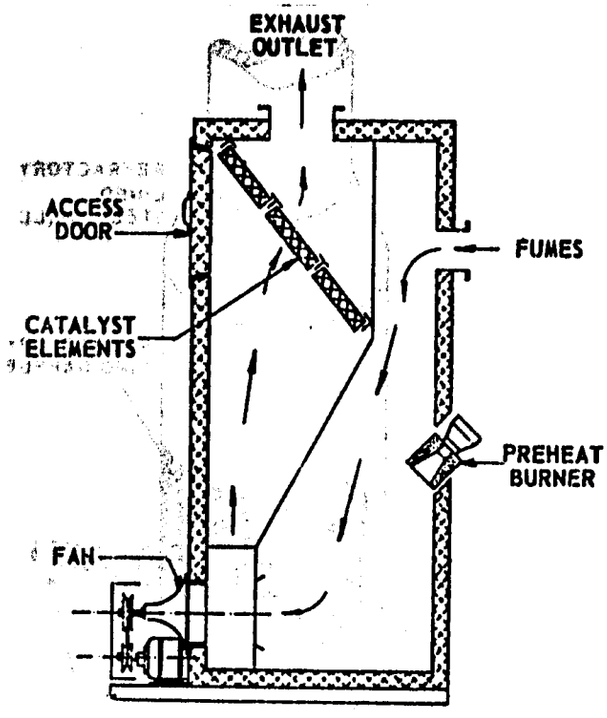

Figure 9-14. Catalytic combustion system including preheat burner and exhaust fan.

Although the catalytic afterburner requires less fuel and can operate at lower temperatures, it is sensitive to catalyst poisoning and plugging. Afterburners must be designed to allow adequate residence time to completely combust the material. Incomplete oxidation may permit the formation of other compounds that are more of a problem than the ones that are to be removed.

9.5.1 Summary. In general, incineration of gases and particulate matter is used to control odors, to reduce the opacity of plumes caused by organic aerosols, and as a means of rapidly reducing explosion hazards, for example using flares in petroleum refineries. Materials to be removed, or destroyed, must be combustible.

9.6 Removal of Gases.

For the removal of gaseous pollutants, one of the most effective means is the packed bed tower, shown in Figure 9-15. As in the packed scrubber, the flow of the gas is counter-current to the absorbing liquid. Typically, the gas flows up, and the liquid flows down. Relatively large volumes of air can be handled. Spray towers, spray chambers, and venturi scrubbers can also be used to remove gases.

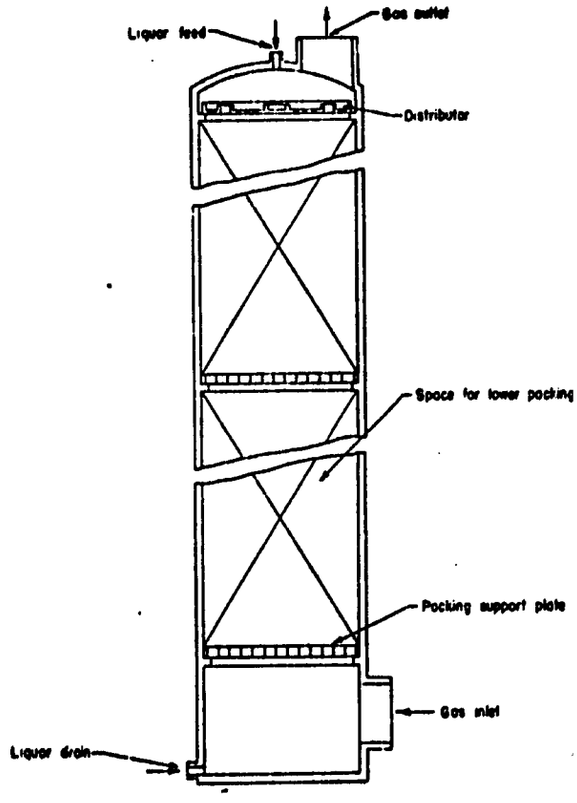

Figure 9-15. Typical packed tower.

9.6.1 Adsorption. Adsorption is another technique useful for removal of gases from an air stream. It is useful because it concentrates the pollutants, making their disposal, or recovery easier. The adsorbent may be discarded with the pollutant still attached; or

the adsorbed pollutant may be desorbed so the adsorbent may be recovered. If a chemical reaction occurs in the adsorption process the adsorbent may not be able to be recovered.

Activated carbon is a common adsorbent. Solid adsorbents are typically used in beds, either fixed or fluidized, requiring single passes or multiple passes by the air stream to get maximum recovery. Adsorption efficiencies exceeding 95% can be obtained using a well-packed bed of carbon granules. Adequate retension time in the bed is required to achieve high efficiencies. Flow rates must be limited to certain ranges to be sure that the bed is not disturbed. High humidities must be avoided because the condensed water might interfere with the adsorption process. Typical processes in which adsorbents are used are food processing, chemical processing, and in such miscellaneous applications as pulp and paper manufacturing, tanning and asphalt product manufacturing.

9.7 Dispersion

If the purpose of the control technique is to reduce the ground-level concentrations, then atmospheric dilution can be utilized - emitting gases and particulates from a tall stack. No material is removed, rather the natural dilution capacity of the atmosphere is used to disperse the pollutants sufficiently so that the concentrations at the ground are within acceptable limits. The effectiveness of the dilution by the atmosphere will depend upon local meteorological conditions, local topography, and effective stack height. Tall stacks may not be suitable for every source, but they can be used in some cases.

9.8 Summary

The selection of a control device depends upon a variety of

factors, some internal to the plant, and some external to the plant. This discussion provides some general information on the type and operation of control techniques presently being used. The following table summarizes the advantages and disadvantages of several collection techniques.

Table 9-3. Advantages and Disadvantages of Collection Techniques

Collector	Advantages	Disadvantages
Settling Chamber	Low pressure loss; simple design; low cost	Much space required; low collection efficiency; difficult to collect solid materials; limited application.
Cyclones	Simplicity of design and maintenance; little floor space required; dry continuous disposal of dust; low to moderate pressure loss; handles large, medium and small sized particles; high dust loeading; reasonably independent of temperature.	Low collection efficiency of small particles; sensitive to variable dust loading and flow rates; tends to clog.
Wet Collectors	Simultaneous gas absorption and particle removal; ability to cool and clean high-temperature, moisture-laden gases; corrosive gases and mists can be recovered and neutralized; reduced dust explosion risk; efficiency can be varied.	Corrosion and erosion problems; add cost of waste water treatment and reclamation; low efficiencies on sub-micron particles; contamination of effluent streams by liquid entrainment; freezing problems in cold weather; reduction in buoyancy and plume rise; water vapor contributes to visible plume under some conditions.

Collector	Advantages	Disadvantages
Electrostatic Precipitators	99+ percent efficiency obtainable on even sub-micron particles; particles maybe collected wet or dry; pressure drop and power requirements are small compared to other high efficiency collectors; maintenance is nominal unless corrosion or adhesive materials are handled; few moving parts; can be operated at relatively high temperatures.	Relatively high initial cost; sensitive to variable dust loadings or flow rates; resistivity changes causes some material to be economically uncollectable precaution requied to to safeguard personnel from high voltage; collection efficiencies can deteriorate gradually.
Fabric Collectors	Dry collection possible; collection of small particles possible; high efficiency possible.	Sensitivity to filtering velocity; high temperature gases must be cooled to below 500°F; affected by relative humidity; susceptibility of fiber to chemical attack.
Afterburners	High removal efficiency of sub-micron, odor-causing particles and vapors; simultaneous disposal of combustible gases and particulate matter; possible heat recovery; relatively small space requirement; simple construction; low maintenance.	High operating cost; fire hazard; can only removal combustibles; may have high initial cost if catalysts are used; catalysts may require reactivation, and are subject to poisoning.
Adsorption	High efficiencies achieveables at reasonably high flow rates; can incorporate continuous regeneration processes for the adsorbent.	May have high maintenance cost if adsorbent must be discarded; may create disposal problems of poisoned adsorbent; extra step in the removal of pollutant from adsorbent.
Dispersion	Independent of temperature; low maintenance; simple construction.	May be limited by meteorological and topographical conditions; not applicable for toxic emissions; not usable where visual emissions will be exceeded.

10. Industrial Applications of Air Pollution Control Technology

The following information was adopted from the Air Pollution Engineering Manual, Second Edition (AP-40), published by the U. S. Environmental Protection Agency. What follows are descriptions of the uses of the technology for controlling emissions presented in Chapter 9. Several industries are used to illustrate the process for selection and operation of control systems.

10.1 Woodworking Operations

Woodworking exhaust systems are almost always equipped with air pollution control devices. If they were not so equipped, the entrained sawdust would result in excessive dust loading in exit gases and could easily cause a local nuisance. Air contaminant emissions from systems such as these are functions of the particular dust encountered and the particular control device employed. The dust particles are not excessively small in most systems, and elaborate devices are not usually required.

Particles emitted by woodworking machines vary in size from less than 1μ, to chips and curls several inches long. Hammer-mill-type wood hogs emit particles running the complete size range, while sanders generate only very small dust particles. Wood waste particles from most other machines are larger in size, seldom less than 10μ, and greater in uniformity. Other factors determining particles size are the type of wood processed and the sharpness of the cutting tool. Hardwoods tend to splinter and break, yielding smaller particles than soft woods, which tend to tear and shred. A dull cutting tool increases tearing and shredding, and produces larger particles.

Generally, the configuration of waste particles is of little importance. There are, however, instances where toothpick-like splinters and curls have presented difficulties in collection and storage, and

in the emptying of storage bins.

10.1.1 Control Equipment. The simple cyclone separator is the most common device used for collecting wood dust and chips from woodworking exhaust systems. In fact, cyclones outnumber all other devices by a large margin. The main advantage of simple cyclones over most other collection devices is their simplicity of construction and ease of operation. They are relatively inexpensive, require little maintenance, and have only moderate power requirements. Properly designed cyclones have been found satisfactory for use with exhaust systems at cabinet shops, lumber yards, planing mills, model shops, and most other wood-processing plants.

The size and design of woodworking exhaust system cyclones varies with air volume and the type of wood waste being handled. Where fine sander dust predominates, cyclones should be of high-efficiency design with diameters not greater than 3 feet. Coarse sawdust, curls, and chips, such as are produced with ripsaws, moulders, and drills, can be effectively collected with low-efficiency cyclones up to 8 feet in diameter. Most woodworking exhaust systems are used to collect a mixture of wood waste that includes both fine and coarse particles. The exhaust system designer must, therefore, carefully consider the quantities of each type wood waste that will be handled. The presence of appreciable precentages of coarse particles in most systems allows the use of low- and medium-efficiency cyclones.

Baghouses are sometimes used with woodworking exhaust systems. Their use is reserved for those systems handling fine dusts, such as wood flour, or where small amounts of dust loses to the surrounding area cannot be tolerated. The efficiency of baghouses on woodworking exhaust systems is very high--99% or more. They can be used to filter

particles as small as 0.1μ in size. In some installations, lower efficiency collectors such as cyclones and impingement traps are installed upstream to remove the bulk of entrained particulates before final filtering a baghouse.

10.1.2 Disposal of Collected Wastes. Wood dust and chips collected with exhaust systems must be disposed of since they present a storage problem and a fire hazard. Very often a profit can be realized from this waste material. Wood wastes can be used productively for things such as:

- a bulking agent for plastic products such as plastic wood, masonite, and others;
- pressed woods such as firewood, fiberboard, firtex, and others;
- soil additives;
- smokehouse fuel--hardwood sawdust is burned to produce smoke for the processing of bacon, ham, pastrami, etc.;
- floor sweeping compound--with or without oil, sawdust helps hold dust particles;
- wood filler--sawdust can be mixed with water based resins and used as a wood filler;
- floor cover in butcher shops, restaurants, etc.;
- fuel for waste heat boilers--heat can be recovered to generate steam and hot water.

10.2 Open-Hearth Steelmaking

Air contaminants are emitted from an open-hearth furnace throughout the process, or heat, which lasts from 8 to 10 hours. These contaminants can be categorized as combustion contaminants and refining contaminants. Combustion contaminants result from steel scrap that contains grease, oil and other combustible material, and from the

furnace fuel.

The particulate emissions that occur in greatest quantities are the fumes, or oxides, of the various metal constituents in the steel alloy being made. The concentration of the particulates in the gas stream varies over a wide range during the heat, from 0.10 to a maximum of 2.0 grains per cubic foot (gr/scf). An average is 0.7 gr/scf, or 16 pounds per ton of material charged. The test results in Table 10-1 for the open-hearth furnace show that 64.7% of the emissions are below 5μ in size. The control device selected must, therefore, be capable of high collection efficiencies on small particles.

Another serious air pollution problem occurring with open-hearth furnace operation is that of fluoride emissions. These emissions have affected plants, which in turn, have caused chronic poisoning of animals Control of fluoride emissions presents a problem because they usually are in both the gaseous and particulate state.

TABLE 10-1. DUST AND FUME DISCHARGE FROM OPEN-HEARTH STEEL FURNACES

Furnace data	
Type of furnace	Open hearth
Size of furnace	50 ton
Process wt, lb/hr	13,300
Stack gas data	
Volume, scfm	14,150
Temperature, °F	1,270
Dust and fume data	
Type of control equipment	None
Concentration, gr/scf	1.13
Dust emissions, lb/hr	137
Particle size, wt %	
0 to 5μ	64.7
5 to 10μ	6.79
10 to 20μ	11.9
20 to 44μ	8.96
44μ	7.65
Specific gravity	5

10.2.1 Control Equipment. Open-hearth furnaces have been successfully controlled by electrostatic precipitators. On some installations, the control system has been refined by installing a waste heat boiler between furnace and control device. In this manner, heat is reclaimed from the furnace exhaust gases, and at the same time, the gases are reduced in temperature to within the design limits of the control device. In Table 10-2 are shown test results of a control system incorporating waste heat boiler and an electrostatic precipitator.

Table 10-2. DUST AND FUME EMISSIONS FROM AN OPEN-HEARTH FURNACE CONTROLLED WITH AN ELECTROSTATIC PRECIPITATOR

Furnace data:	
Type of furnace (constructed 1916)	Open hearth
Size of furnace, tons	63
Test interval	1 hr during heat working period
Fuel input	Natural gas, 21,000 cfh Fuel oil, 1.4 gpm
Waste heat boiler data:	
Gas volume, inlet, scfm	14,900
Gas temperature, inlet, °F	1,330
Gas temperature, outlet, °F	460
Water in waste gas, %	12.4
Steam production (average), lb/hr	8,400
Precipitation data:	
Gas volume, scfm	14,900
Dust and fume concentration (dry volume)	
Inlet, gr/scf	0.355
Outlet, gr/scf	0.004
Inlet, lb/hr	39.6
Outlet, lb/hr	0.406
Collection efficiency, %	98.98

10.3 Sulfuric Acid Manufacturing (Contact Process)

The only significant source of emissions from a contact sulfuric acid plant is the tail-gas discharge from the sulfur trioxide (SO_3) absorber. While these tail gases consist primarily of nitrogen, oxygen, and some carbon dioxide, they also contain small concentrations of SO_2 and smaller amounts of SO_3 and sulfuric acid mist. Table 10-3 shows the SO_2 and SO_3 discharged from two wet-gas sulfuric plant absorbers.

TABLE 10-3. SULFUR TRIOXIDE AND SULFUR DIOXIDE EMISSIONS FROM TWO ABSORBERS IN CONTACT SULFURIC ACID PLANTS

	Outlet of absorber No. 1	Outlet of absorber No. 2
Gas flow rate, scfm	9,600	7,200
Sulfur trioxide, gr/scf	0.033	0.39
% by vol as SO_2	0.002	
lb/hr	2.73	2.4
Sulfur dioxide, gr/scf	2.63	2.45
% by vol	0.22	
lb/hr	216	151.2

A well-designed contact process sulfuric acid plant operates at 90 to 95 percent conversion of the sulfur feed into product (sulfuric acid.) Thus a 250-ton-per-day plant can discharge 1.25 to 2.5 tons of SO_2 and SO_3 per day. When present in sufficient concentration, SO_2 is irritating to throat and nasal passes and injurious to vegetation.

Tail gases that contain SO_3, because of incomplete absorption in the absorber stack, hydrate and form a finely divided mist upon contact with atmospheric moisture. Generally, the process temperature of gas going to the absorber should be on the lower side of the temperature range 150° to 230°C.

The optimum acid concentration in the absorbing tower is 98.5%. This concentration has the lowest SO_3 vapor pressure. The partial pressure of SO_3 increases if the absorbing acid is too strong, and SO_3 will be emitted with the tail gases. If a concentration of absorbing acid less than 98.5% is used, the beta phase of SO_3, which is less easily absorbed, is produced. A mist may also form when the process gases are cooled before final absorption.

Water-based mists can form as a result of the presence of water vapor in the process gases fed to the converter. This condition is often caused by poor performance of the drying tower. Efficent performance should result in a moisture loading of 5 milligrams or less per cubic foot. In sulfur-burning plants, mists may be formed from water resulting from the combustion of hydrocarbon impurities in the sulfur.

The SO_3 mist presents the most difficult of the emissions to control because it generally has the smallest particle size. The particle size of these acid mists ranges from sub-micron to 10μ and larger. Acid mist composed of particles of less than 10μ in size is visible in the absorber tail gases if present in amounts greater than 1 milligram of sulfuric acid per cubic foot of gas. As the particle size decreases, the plume becomes more dense because of the greater light-scattering effect of the smaller particles. Maximum light scattering occurs when the particle size approximates the wave length of light. Thus, the predominant factor in the visibility of an acid plant's plume is particle size of the acid mists rather than the weight of mist discharged. Acid particles larger than 10μ are probably present as a result of mechanical entrainment. These larger particles

deposit readily on duct and stack walls and contribute little to the opacity of the plume.

As stated previously, even with a well designed conventional contact sulfuric acid unit, the tail gas emitted to the atmosphere contains considerable SO_2; concentrations can be as high as 5200 mg/m^3 (2000 ppm). In recent years, the intensified emphasis on air quality standards has dictated that emissions of sulfur compounds from sulfuric acid plants be greatly reduced. This can be accomplished by two methods, both utilizing basic technology that has been known for some years. One method involves "double, or total, absorption." In this process SO_2 is converted to SO_3 in a three-pass catalytic converter, and the SO_3 is abosrbed in an absorption tower. The gases from this tower, still containing unreacted SO_2, are then recycled to another single-pass catalytic converter, and then to a final absorber.

The other method consists of a tail-gas unit added to the end of a conventional acid plant. One such unit absorbs the SO_2 in the tail gas in an aqueous ammonium sulfite-bisulfite solution. The absorbing liquid is then treated in such a way that the SO_2 is stripped and then returned to the sulfuric acid plant. Other similar processes exist.

By such applications, the SO_2 concentration in tail-gas emissions can be reduced to less than 1500 mg/m^3 (500 ppm), and total plant efficiency for sulfur recovery can be increased to greater than 99 percent.

10.3.1 Control Equipment for Sulfuric Dioxide Removal. Water scrubbing of the tail gases from the SO_3 absorber can remove 50 to 75 percent of the SO_2 content. Scrubbing towers using 3-inch or larger stacked rings or redwood slats are often employed. On start-ups, when SO_2 concentrations are large, soda ash solution is usually used in place

of water. Water scrubbing is feasible where disposal of the acidic waste water does not present a problem.

Tail gases may be scrubbed with soda ash solution to produce marketable sodium bisulfite. A cyclic process using sodium sulfite-bisulfite has also been reported. Steam regeneration costs in the cyclic process are, however, relatively high, and the capacity of the scrubbing solution is limited by the low solubility of sodium bisulfite. The dilute scrubber solution has, moreover, little economic value.

The most widely known process for removal of SO_2 from a gas stream is scrubbing with ammonia solution. Single- and two-stage absorber systems respectively reportedly reduce SO_2 concentrations in tail gases to 0.08% and 0.03%. Two-stage systems are designed to handle SO_2 gas concentrations as high as 0.9%. High SO_2 concentrations resulting from acid plant start-ups and upsets could be handled adequately by a system such as this.

10.3.2 Control Equipment for Acid Mist Removal. Tube-type electrostatic precipitators are widely used for removal of sulfuric acid mist from the cold SO_2 gas stream of wet-purification systems. Tube-type precipitators have also been used for treating tail gases from SO_3 absorber towers. More recently, however, two-stage, plate-type precipitators have been used successfully. One such unit, lead-lined throughout to prevent corrosion, is designed to handle approximately 20,000 cfm tail-gas from a 300-ton-per-day contact sulfuric acid plant. This wet-gas plant processes hydrogen sulfide, sulfur, and spent alkylation acid. Dry gas containing SO_2, CO_2, oxygen, nitrogen, and 5 to 10 mg of acid mist per cubic foot of air enters two inlet ducts to the precipitator. The gas flows upward through distribution tiles to the humidifying

section. This section contains 5 feet of 3-inch single-spiral tile irrigated by 800 gpm weak sulfuric acid. The conditioned gas then flows to the ionizing section which consists of about 75 grounded curtain electrodes and 100 electrode wire extensions.

Ionized gas then flows to the precipitator section where charged acid particles migrate to the collector plate electrodes. There are twelve 14' x 14' lead plates and 375 electrode wires. The negative wire voltage is 75,000 volts. Acid migrating to the plates flows down through the precipitator and is collected in the humidifying section flows to a 5-foot-diameter, lead-lined stack that discharges to the atmosphere 150 feet above grade.

The high-voltage electrode wires are suspended vertically by three sets of insulators. Horizontal motion is eliminated by four diagonally placed insulators, which are isolated from the gas stream by oil seals. All structural material in contact with the acid mist is lead clad. Electrical wires are stainless steel cores with lead cladding. Voltage is supplied from a generator with a maximum capacity of 30 kilovolt-amperes. A battery of silicon rectifiers supplies 75,000 volts of direct current to the electrode wires.

Table 10-4 shows the SO_3 and SO_2 emissions from the previously described two-stage electrical precipitator. The acid mist collection efficiency was only 93 percent. A mechanical rectifier was, however, supplying only 36,000 volts to the precipitator during this test. During normal operation, silicon rectifiers supply 75,000 volts to the electrode wires.

Table 10-4. SULFUR TRIOXIDE AND SULFUR DIOXIDE EMISSIONS FROM A TWO STAGE ELECTRICAL PRECIPITATOR SERVING A CONTACT SULFURIC ACID PLANT

	Inlet of precipitator	Outlet of precipitator
Gas flow rate, scfm	13,400	13,100
Gas temperature, °F	160	80
Average gas velocity, ft/sec	36.5	20.6
Collection efficiency, [a]%		93
Moisture in gas, %	0.8	4.1
CO_2, % (stack conditions)	5.9	6
O_2, % (stack conditions)	9.6	8.4
CO, % (stack conditions)	0	0
N_2, % (stack conditions)	83.4	81.2
Sulfur trioxide,		
gr/scf	0.062	0.0048
lb/hr	7.1	0.54
% by volume	0.0042	0.00032
Sulfur dioxide,		
gr/scf	4.1	4.1
lb/hr	470	460
% by volume	0.345	0.345

[a]A mechanical rectifier was supplying only 36,000 volts to the precipitator. During normal operation, silicon rectifiers supply 75,000 volts to the electrode wires. This should increase the acid mist collection efficiency appreciably.

Packed-bed separators employ sand, coke, or glass or metal fibers to intercept acid mist particles. The packing also causes the particles to coalesce because of high turbulence in the small spaces between packing

Moderate-sized particles of mist have been effectively removed in a 12-inch-deep bed of 1-inch Berl saddles with gas velocities of approximately 10 ft/sec.

Glass fiber filters have not been very effectively in mist removal because of a tendency on the part of the fiber to sag and mat. Nevertheless, experimental reports on acid mist removal by silicone-treated glass wool are encouraging. A special fine glass wool with a fiber diameter between 5 and 30μ was used. The coarser fibers allowed adequate penetration of the bed by the mist particles to ensure a reasonable long life and provided sufficient support for the finer fibers in their trapping of the small acid mist particles.

The glass wool was treated by compressing it into a filter 2 inches thick to a density of 10 pounds per cubic foot. It was then placed in a sheet metal container and heated at 500°C for 1 hour. By this treatment, the stresses in the compressed fibers were relieved, and the fiber mass could be removed from the mold without losing shape or compression. The fibers were then treated with a solution of methyl chlorosilane.

The threshold SO_3 concentration for mist visibility after scrubbing has been found experimentally to be about 3.6×10^{-4} gr/scf. The discharge gases from the silicone-treated filter had an SO_3 concentration of 1.8 to 2.5×10^{-4} gr/scf and no appreciable acid mist plume. A faint plume became perceptible at approximately weekly intervals but was eliminated by flushing the filter bed with water. The average tail-gas filtering rate for the treated filter was 15.6 cfm per square foot of filtering area for a pressure drop of 9.5-10 inches of water. The effective life of the silicone fiber is estimated to be at least 5,000 hours. The use of untreated glass wool fiber proved unsatisfactory

in reducing the opacity of the acid mist plume.

Table 10-5 shows the SO_2 and acid mist emissions from the outlet of a typical silicone-treated, glass fiber mist eliminator. This control unit processes absorber discharge gas from a contact sulfuric plant. The acid mist collection efficiency for the fiber glass mist eliminator was 98.9 percent.

TABLE 10-5. EMISSIONS OF SULFUR DIOXIDE AND ACID MIST FROM THE OUTLET OF A SILICONE-TREATED, GLASS FIBER MIST ELIMINATOR SERVING A CONTACT SULFURIC ACID PLANT

	Mist eliminator inlet	Mist eliminator outlet	
	Acid mist	Acid mist	Sulfur dioxide
Concentration, gr/scf	0.30	0.035	1.50
Concentration, ppm	200	25	1,300
Weight, lb/hr	45	0.5	160
Collection efficiency, %		98.9	
Gas flow rate, scfm		14,000	
Avg gas velocity, ft/sec		19	
Gas temperature, °F		160	

Wire mesh mist eliminators are usually constructed in two stages. The lower stage of wire mesh may have a bulk density of about 14 pounds per cubic foot, while the upper stage is less dense. The two stages are separated by several feet in a vertical duct. The high-density lower stage acts as a coalescer. The re-entrained coalesced particles are removed in the upper stage. Typical gas velocities for these units range from 11 to 18 ft/sec. The kinetic energy of the mist particle is apparently too low to promote coalescence at velocities less than 11 ft/sec, and re-entrainment becomes a problem

at velocities greater than 18 ft/sec. The tail-gas pressure drop through a wire mesh mist installation is approximately 3 inches of water.

10.4 Coffee Roasting

Dust, chaff, coffee bean oils (as mists), smoke, and odors are the principal air contaminants emitted from coffee processing. In addition, combustion contaminants are discharged if chaff is incinerated. Dust is exhausted from several points in the process, while smoke and odors are confined to the roaster, chaff incinerator, and, in some cases, to the cooler.

Coffee chaff is the main source of particulates, but green beans, as received, also contain appreciable quantities of sand miscellaneous dirt. The major portion of this dirt is removed by air washing in the green coffee-cleaning system. Some chaff (about 1 percent of the green weight) is released from the bean on roasting and is removed with roaster exhaust gases. A small amount of chaff carries through to the cooler and stoner. After the roasting, coffee chaff is light and flaky, with particles sizes usually exceeding 100μ. As shown in Table 10-6, particulate emissions from coffee processing are well below the limits permitted by typical dust and fume prohibitions.

TABLE 10-6. ANALYSIS OF COFFEE ROASTER EXHAUST GASES

	Contaminant concentration		
	Continuous roaster		Batch roaster
	Roaster	Cooler	
Particulate matter, gr/scf	0.189	0.006	0.160
Aldehydes (as formaldehyde), ppm	139	--	42
Organic acids (as acetic acid), ppm	223	--	175
Oxides of nitrogen (as NO_2), ppm	26.8	--	21.4

Coffee roaster odors are attributed to alcohols, aldehydes, organic acids, and nitrogen and sulfur compounds, which are all probably breakdown products of sugars and oils. Roasted coffee odors are considered pleasant by may people. Nevertheless, continual exposure to uncontrolled roaster exhaust gases usually elicits widespread complaints from adjacent residents. The pleasant aroma apparently develops into an annoyance upon continued exposure.

Visible bluish-white smoke emissions from coffee roasters are caused by distilled oils and organic breakdown products. The moisture content of green coffee is only 6 to 14 percent, and thus there is not sufficient water vapor in the 400° to 500°F exhaust gases to form a visible steam plume. From uncontrolled, continuous roasters, the opacity of exhaust gases exceeds 40% almost continuously. From batch roasters, exhaust opacities normally exceed 40% only during the last 10 to 15 minutes of a 20-minute roast. Smoke opacity appears to be a function of the oil content, the more oily coffee producing the heavier smoke. The water quenching of batch-roasted coffee causes visible steam emissions that seldom persist longer than 30 seconds per batch.

10.4.1 Control Equipment. Air contaminants from coffee-processing plants have been successfully controlled with afterburners, cyclone separators, and combinations of the two. Incineration is necessary only with roaster exhaust gases. There is little smoke. In other coffee plants exist gas streams where only dust collectors are required to comply with air pollution control regulations.

Separate afterburners are preferable to the combination heater-incinerator that may be used on the batch roaster. When the afterburner serves as the roaster's heat source, its maximum operating temperature

is limited to about 1,000°F. A temperature of 1,200°F or greater is necessary to provide good particulate incineration and odor removal. A roaster-afterburner should always be preceded by an efficient cyclone separator in which most of the particulates are removed. A residence time of 0.3 second is sufficient to incinerate most vapors and small-diameter particles at 1,200°F. However, higher temperatures and longer residence times are required to burn large-diameter, solid particles.

Properly designed centrifugal separators are required on essentially all process airstreams up to and including the stoner and chaff collection system. Typically, cyclones are required at the roaster, cooler, stoner, chaff storage bin, and chaff incinerator. In addition, the scalper is a centrifugal classifier venting process air. Some plants also vent the green coffee dump tank and several conveyors and elevators to centrifugal dust collectors.

11. Location of Industrial Facilities

In the past, land for industrial facilities was selected primarily for its physical characteristics, for example: would the soil support the building, adequate drainage; and access to water, transportation and utilities. Less attention was given to meteorological or topographical features or the overall land use plan for the area. Land was zoned for industrial use in areas where there was little desire to have residential or commercial development. It was often felt that industrial communities should be separated from the residential communities.

Several factors have caused a shift from this simplified approach to plant siting. In the U. S., there has been a significant movement in population from rural communities toward urban communities, increasing the need to develop all available land. Industrial areas that were once separated from residential areas are now surrounded by them as a result of the growth in urban population.

There has been a greater recognition of the influence of the meteorological and topographical features on the impact of any air pollution associated with a particular industrial process. Location of major industrial facilities in mountain or river valleys, along sea coasts and in areas where there are frequent temperature inversions, has a greater impact on the local atmosphere than would be true if the facility was located elsewhere. Air pollution knows only natural boundaries and patterns established by physical features such as mountains and valleys, and peculiarities of air flow caused by local heating conditions or other factors. As a result of atmospheric dispersion, what is generated in one place will be carried to another

place, perhaps at a considerable distance. To minimize the impact of pollutant emissions it is important to be aware of wind conditions and topographical features in the selection of a particular plant site in order to take advantage of the local turbulence and diffusion conditions.

12. Impact of Industrial Products

It is important that the anticipated impact of a product on the air environment be investigated as thoroughly as practicable. Some of the products and by-products of industrial processes may have, or do have, a significant effect on the atmosphere or on man directly. Examples of these include exhaust emissions from high-altitude aircraft, fluoro-chloromethanes used as propellants for aerosol spray cans, and noise from transportation, construction or manufacturing. The exhaust emissions and propellants are believed to have a destructive effect on the ozone layer, which will create problems resulting from increased ultraviolet radiation reaching the earth's surface. Noise was not discussed in this syllabus but it is a problem that has been attracting considerable attention because of the physiological and psychological stress produced in man.

13. References for Additional Information

Air Conservation, American Association for the Advancement of Sciences, Washington, D. C., 1965.

Air Pollution, Volumes I, II, III, Second Edition, Edited by Arthur C. Stern, Academic Press, New York, N. Y., 1968.

Air Pollution Manual, Parts I and II, American Industrial Hygiene Association, Detroit, Mich., 1968.

Gaseous Fuels; Coal and Coke; Atmospheric Analysis, Part 26, American Society for Testing and Materials Standards, Philadelphia, Pa., 1974.

Meteorology and Atomic Energy, U. S. Atomic Energy Commission, 1968.

The Economics of Air Pollution, Edited by Harold Wolozin, Norton & Company, New York, N. Y., 1966.

Publications of the U. S. Environmental Protection Agency, Research Triangle Park, N. C., including:

Air Pollution Engineering Manual, Second Edition, AP-40, 1973;

Control Techniques for Particulate Air Pollutants, AP-51, 1969;

Control Techniques for Sulfur Oxide Pollutants, AP-52, 1969;

Control Techniques for Carbon Monoxide Emissions from Stationary Sources, AP-65, 1970;

Control Techniques for Carbon Monoxide, Nitrogen Oxide and Hydrocarbon Emissions from Mobile Sources, AP-66, 1970;

Control Techniques for Nitrogen Oxide Emissions from Stationary Sources, AP-67, 1970;

Control Techniques for Hydrocarbon and Organic Solvent Emissions from Stationary Sources, AP-68, 1970;

Control Techniques for Beryllium Air Pollutants, AP-116, 1973;

Control Techniques for Asbestos Air Pollutants, AP-117, 1973;

Control Techniques for Mercury Emissions from Extraction and Chlor-Alkali Plants, AP-118, 1973;

Air Pollution Aspects of Emission Sources Series - A Bibliography with Abstracts (1971):

AP-92 "Municipal Incineration"
AP-93 "Nitric Acid Manufacturing"

AP-94 "Sulfuric Acid Manufacturing"
AP-95 "Cement Manufacturing"
AP-96 "Electric Power Production"

Compilation of Air Pollutant Emission Factors, Second Edition, AP-42, 1973;

A Mathematical Model for Relating Air Quality Measurements to Air Quality Standards, AP-89, 1971.

Publications of the Committee on the Challenges of Modern Society, NATO, Brussels, Belgium (also available from U. S. EPA, Research Triangle Park, N. C.), including:

Control Techniques for Sulfur Oxide Air Pollutants, N.12.

Control Techniques for Particulate Air Pollutants, N.13.

Control Techniques for Hydrocarbons and Organic Solvent Emissions from Stationary Sources, N.19.

Control Techniques for Nitrogen Oxide Emissions from Stationary Sources, N.20.

The following Journals are good sources of current developments:

Journal of the Air Pollution Control Association

Environmental Science and Technology

Journal of the American Industrial Hygiene Association

Atmospheric Environment

Staub

'cological Systems Approaches to Aerobiology
I. Identification of Component Elements and Their Functional Relationships

Proceedings of Workshop/Conference I

Kansas State University, Manhattan, Kansas
6-8 January 1972

W. S. BENNINGHOFF
and
R. L. EDMONDS
Editors

INTERNATIONAL BIOLOGICAL PROGRAM
United States National Committee
Aerobiology Program

US/IBP Aerobiology Program Handbook Number 2
The University of Michigan
Ann Arbor, Michigan
1972

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DIFFUSION PROCESSES AT LARGE AND SMALL SCALES

James T. Peterson

I have been asked to speak about "Diffusion Processes at Large and Small Scales." Diffusion is a rather restrictive term; a better word in the aerobiology context is dispersion. Dispersion includes both transport (bulk movement) and diffusion processes. Diffusion, as defined in the Glossary of Meteorology, Huschke (1959), is "the exchange of fluid particles between regions in space, in the apparent random motions of a scale too small to be treated by the equations of motion." The term diffusion is usually associated with molecular (or very small scale) processes. In the free atmosphere, however, (turbulent) diffusion occurs on a much larger scale whereby conservative properties of the atmosphere are mixed by eddies in a turbulent flow. Finally, turbulence, or the actual motion of the air which leads to turbulent diffusion, is defined as "a state of fluid flow in which the instantaneous velocities exhibit irregular and apparently random fluctuations so that in practice only statistical properties can be recognized and subjected to analysis."

The random nature of turbulence renders it difficult, perhaps impossible, to define instantaneous wind velocities on any time scale. However, on time scales of 15 minutes, more or less, one can define statistical properties of the wind velocities. For example, when predicting the dispersion of smoke from a stack one can describe the mean position, standard deviation, and other statistical properties of the plume, rather than the instantaneous position of the plume.

Dispersion can then be considered to be composed of the mean flow plus perturbations on that flow. Both the mean flow and the perturbations show large variations on different space scales, i.e., as you move up the scale of motion from the small scale to the global scale what may have been the mean flow at one scale becomes the perturbation on the next larger scale. Thus, it is important to define the scale of flow under consideration.

The Nature of Turbulence

What do these random perturbations look like? If one examines a graph of wind speed (or direction) as a function of time, he will often see a continuous, very "wiggly" trace. These random fluctuations represent the dispersive capacity of the atmosphere. Theoretical and experimental investiations have shown that turbulent dispersion primarily depends on:

1. Lapse rate (vertical temperature distribution)
2. Surface roughness
3. Vertical wind shear

1. Lapse rate

The critical lapse rate (change in temperature with height) for

atmospheric turbulence is the dry adiabatic lapse rate. If no heat is added to or subtracted from a parcel of air displaced upwards, the parcel will cool at the rate of 10° C per kilometer. This is the dry adiabatic lapse rate. If the decrease of temperature with increasing height of the ambient atmosphere exceeds 10° C per kilometer the atmosphere is said to be unstable and vertical mixing or turbulence occurs very readily. If the ambient lapse rate equals 10° C per kilometer then the stability of the atmosphere is neutral, and if a parcel of air is displaced vertically its motion will not be retarded. If the temperature decrease is less than 10° C per kilometer (which is usually the case) the atmosphere is stable and turbulent mixing is retarded. Under inversion conditions, when temperature actually increases with height, turbulence, or dispersion of particles, is at a minimum.

The lower levels of the atmosphere typically undergo wide variations in temperature on a daily basis. During the afternoon when surface temperatures are maximum, there tends to be a large amount of vertical mixing. The reverse is true during nighttime when cooling of the ground, and a surface based inversion is usually the rule, especially outside of urban areas. A simple way to make a rough estimate of the stability of the lower atmosphere is to observe the shape of smoke plumes. Their form is indicative of the amount of atmospheric turbulence.

2. Surface roughness

The roughness of the earth's surface causes a frictional drag on the wind flow over it and the reduction in wind flow directly depends on the degree of roughness. For example, over a smooth sea surface there is little drag, but over a large city with buildings extending up hundreds of feet the effect of the rough surface extends through several thousand feet of the atmosphere. A rough rule of thumb is that surface friction affects wind speed through the lowest 1000 meters of the atmosphere. Increasing roughness of the surface tends not only to decrease wind speed near the surface but to decrease it through a greater thickness of the atmosphere. In addition to retarding the wind, greater roughness generally causes more turbulence and mixing within the atmosphere.

3. Vertical wind shear

Vertical wind shear (in either speed or direction, or both) aids dispersion by increasing turbulence and by deforming a cloud of material that has some vertical extent. As mentioned above, surface roughness acts to retard wind speed in the lowest layers and thereby creates vertical shear. During daytime when there is significant vertical mixing, the effect of friction (and thus wind shear) is distributed through a large layer of the atmosphere. Conversely, at night the stable atmosphere restricts mixing and the frictional effect is limited to a small layer where there will likely be a rapid increase of wind speed with height. Thus, during nighttime there is often a sort of competition between temperature stability, on the one hand, to retard turbulence and wind shear, on the other hand to enhance it. The specific situation determines which factor is most important.

Transport Phenomena

I originally stated that dispersion can be considered to include both bulk transport and turbulent diffusion. Transport phenomena occur on all scales of atmospheric motion. On a small scale, for example, there are many perturbations imposed on the mean flow. One of these is wind flow around buildings (see Figure 5.17, Slade, 1968). Here there is often a separation of the flow leeward of the building (called the cavity) from the free stream flow, with a return flow near the ground behind the building. Thus smoke from a short stack on top of a building may not get into the free stream to be gradually dispersed down wind, but may be brought to the ground immediately leeward of the building with resulant very high pollutant concentrations. There is little exchange between the free stream and the cavity, as the boundary tends to be quite effective.

Another example is the wind flow in the street "canyons" of large cities. The direction of the wind near the street may be quite different from that above. There may also be a marked variation in pollutant concentration from one side of the street to the other, such as in the case of CO which largely comes from auto exhaust.

On a larger scale, perturbations from the mean flow include mountain and valley winds. Winds in these valleys tend to be oriented parallel to the valley walls regardless of the direction of the flow aloft. Upper level winds oriented across-valley do not simply go into the valleys and swoop out the other side. Other examples on this scale include wind flow around thunderstorms, land and sea breezes, and air funneled through mountain passes. Sea breezes are an especially important aspect of the Los Angeles pollution problem. Pollutants emitted there during the day are blown inland, but may return at night if the overall regional flow is light. The same air can flow back and forth over the area, thus allowing the build-up of pollutant concentrations.

On a very large or global scale the typical wind flow at say 6,096 to 12,192 meters is smooth and tends toward simple meandering types of patterns. Wave lengths are on the order of the size of continents, and the wind speed may exceed 161 to 241 kilometers per hour. Wind flow at these upper levels has been studied through the GHOST (Global Horizontal Sounding Technique) balloon program. These super pressure balloons, which are designed to go up to a certain level and stay there, are periodically released in the Southern Hemisphere. One balloon at the 200 mb level (12,192 meters) was traced around the World for 102 days while it made about 10 circumnavigations (see Figure 1). They usually come down when supercooled water drops form ice on the balloon and add to its weight. The path of this balloon was mostly confined between 30 and 60° S.

One interesting fact about the average lifetime of these balloons is that it is similar to that of small particles, in spite of the very large difference in size between them. For example, at 100 mb (16,764 meters) about 1 to 1 1/2 months, and at 500 mb (5,486 meters) about 7-10 days.

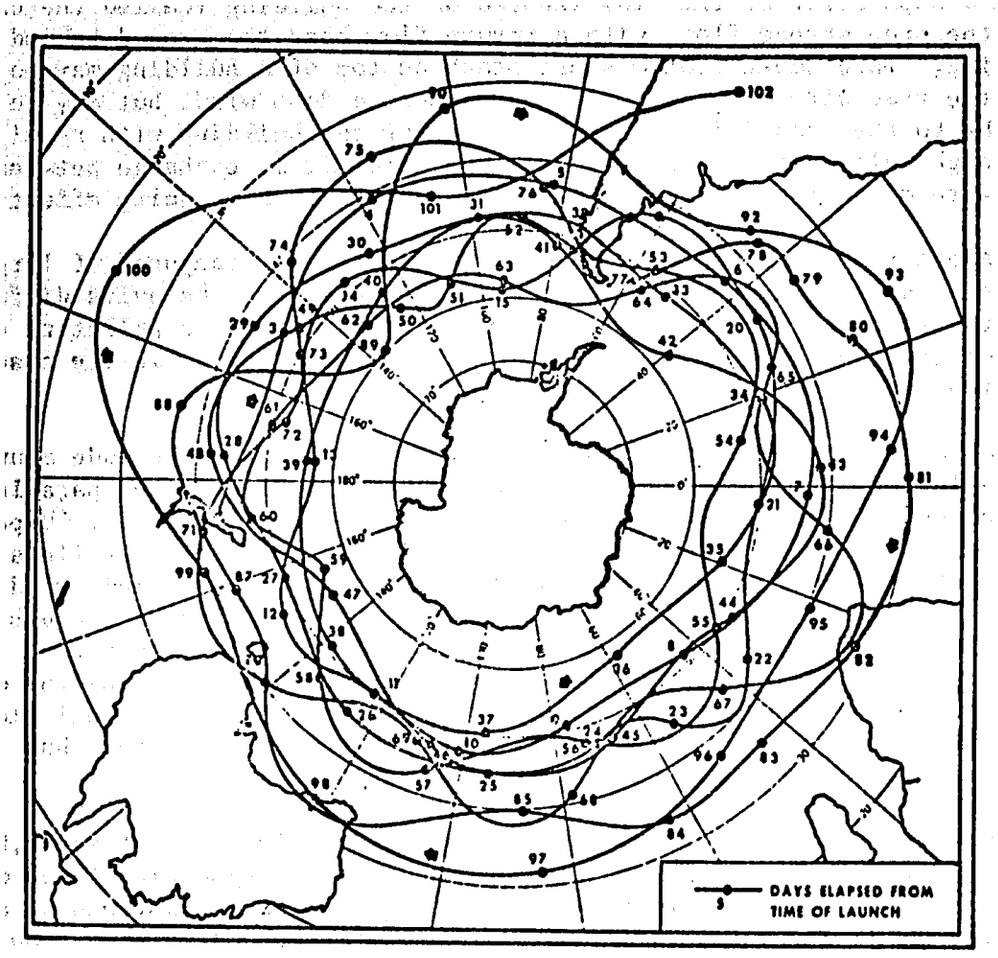

Figure 1. Complete Flight Trajectory for Balloon No. 79R, launched from Christchurch, New Zealand. Flight level 200 mb (after Lally and Lichfield, 1969)

In conclusion I would emphasize a recent example of a scheme to predict the dispersion of a cloud of material. This material might be some pollutant, pollen, insects, etc. Pasquill (1971, see his Figure 9) describes the computer prediction of air trajectories out to 18 hours in the future at 700 and 900 mb. The resulting patterns show the three dimensional deformation of the original cloud as it is transported downwind.

Questions

Thompson: Does the nature of the clouds in the area of the balloon experiments affect the lifetime of the balloons?

Peterson: Yes, to some extent. Cirrus clouds composed of ice crystals cause relatively little problem. However, clouds consisting of supercooled water drops can cause severe problems if they impinge and freeze on the balloon.

Burleigh: What is the probability of any particulate matter reaching the ground after it gets up to high altitudes.

Peterson: At high altitudes the best information on the lifetime of particles has come from the tracing of radioactive debris. Once particles reach the stratosphere their lifetime may be 1 or 2 years. Some coagulation occurs along with gravitational settling which adds up to gradual removal.

Raynor: I have some comments about your cavity flow diagram. Wind speed and direction vary a great deal in some instances and as a result a good deal of influx may occur into the cavity because the flow is not always perpendicular to the face of the building. This was also noted in some experiments with dispersion of material in hilly terrain. High concentrations occurred on the lee side of the hills of material released on the upwind site. I have done some experimentation on the removal of pollen by hedgerows and found that concentrations in the cavity behind the hedge were higher than those elsewhere. The hedge was thick and most of the air flowed up and over the hedge rather than through with the result that a good cavity was formed. Thus, you have to be careful about generalizations about cavities.

Peterson: I agree. The diagram referred to a cube with airflow perpendicular to one face.

Literature Cited

Huschke, R. E. 1959. Glossary of meteorology. Amer. Meteorol. Soc., Boston. 638 pp.

Lally, V. E. and E. W. Lichfield. 1969. Summary of status and plans for the GHOST balloon project. Bull. Amer. Meteorol. Soc. 50:867-874.

Pasquill, F. 1971. Atmospheric dispersion of pollution. Quart. J. Roy. Meteorol. Soc. 97:369-395.

Slade, D. H. (ed.) 1968. Meteorology and atomic energy. U. S. Atomic Energy Commission, Division of Technical Information, No. TID 24190. 445 pp.

Control of Gaseous Emissions by Combustion

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Prepared for the International Program in Environmental Aspects of Industrial Development, University of North Carolina, Chapel Hill, North Carolina, 1975

CONTROL OF GASEOUS EMISSIONS BY COMBUSTION

I. Introduction

A. Combustion Refers to Rapid Oxidation Processes
   1. Used to Control Odorous Emissions
      a. e.g., Kraft Pulping Operations
      b. Coffee Roasting
      c. Rendering Cookers
   2. Control of Organic Vapors
      a. Petroleum Processing
      b. Solvent operations
      c. Varnish cookers
      d. Paint baking ovens

B. Oxidation of Emissions Should Be Complete
   1. $HC \xrightarrow{O_2} H_2O + CO_2$
   2. Incomplete oxidation may exacerbate problems
      High MW Aldehydes ⟶ Low MW, more volatile and irritating Aldehydes
      Butanol ⟶ butyraldehyde + butyric acid, both highly odorous.
   3. Complete Combustion Requires Adquate Temperature
      Time
      Turbulance
      Oxygen

C. Combustion Useful to Control Combustible Aerosols, Gas and Vapors
   1. Visible emissions can be reduced or eliminated (Coffee Roasting)
   2. [C] of gases, vapors and particulate matter can be reduced
   3. Odors and nuisance problems can be reduced or eliminated.
      (Rendering Plants, Kraft Pulping (mercoptans & organic sulfides)

A reduction in explosion hazards (Refineries, chemical plants)

D. By-Product Recovery Not Possible W/ Control by Combustion
   1. Heat recovery for pre-heat of effluent gas possible
   2. Heat may be recovered for space htg., steam production etc.

E. Exhaust Gas Pre-Treatment Necessary Where Combustion Products More Offensive Than Before Combustion
   1. Organic solvents containing halogens or sulfur ($S + H_2O$ ⟶ Corrosion)
   2. Removal of Catalyst Poisons (metal fumes)
   3. Removal of non-combustible, inorganic particulate matter
   4. Removal of materials leaving combustion residue

F. Methods of Combustion Include
   1. Direct-flame (Coffee Roasting, Rubber Coring, Varnish Kettles, Enamel Baking Ovens)
   2. Catalytic (Metal Coating Ovens, foundry core ovens, fabric coating ovens)
   3. Flares
   4. Combustion in Boilers

II. Basic Combustion Theory

A. Definitions:

1. Combustion is a chemical reaction of a fuel with an oxidant involving the disappearance of the original reactants and the production of heat and oxides.
2. Complete Combustion: Combination of combustible elements & compounds of a fuel w/ all the O_2 they can utilize.

B. Complete Combustion Requisites

1. Adequate oxygen necessary

These reactions involve a complex series of chain reactions in which various radicals and aldehydes are intermediate products. Thus, danger of incomplete combustion

a. $CH_4 + O_2 \longrightarrow C + 2H_2O + Q$ Inadequate O_2, soot produced
b. $CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O + Q$ Adequate O_2, complete comb. no smoke

c. Equation b indicates a stoichiometric (theoretical) quantity of O_2.
   1. More than theoretical air, called excess air, usually added to assure sufficient O_2.
   2. Excess air req'd. due to inadequate mixing and contact between O_2 and fuel molecules.
   3. Hold excess air to minimum to limit supplementary fuel requirements in air pollution control equipment.

2. Temperature
   a. Every combustible substance has a minimum ignition T in the presence of O_2.
   b. For combustible mixtures, a sufficient T must be achieved to burn all combustibles.
   c. Combustion reaction rate increases with T (exponentially).
3. Time
   a. Relationship of combustion time to residence time at combustion conditions is important.
   b. Complete combustion requires $t_{residence} > t_{combustion}$
   c. $t_{residence} = f$ (aerodynamic factors [chamber size])
   d. $t_{reaction} = f$ (aerodynamic factors, T)
   e. Satisfying condition b most economically requires consideration of equipment size vs. operating T (i.e., capital construction cost, heat losses vs. fuel savings)
4. Turbulence
   a. Intimate mixing of fuel & O_2 required for complete combustion, elimination of separation zone formation.
   b. Depends on combustion chamber geometry, flow velocity thru chamber, burner injection arrangement.
5. Failure to consider above factors may result in incomplete combustion, formation of offensive products.
6. At times, complete combustion may not be acceptable since deleterious effects on combustion equipment may result; pre-treatment or an alternative control device may be required.

C. Self-Sustained Combustion

(Range of limits increases w/ temp., P increases)

1. Self-sustained combustion possible when
   a. Lower explosive limit $<$ fume energy concentration $(BTU/A^3) < 1$
      Explosive limit [Limits = f (T, P, vessel geometry, direction flame propagation)]

b. Temperature ≥ Auto-ignition temp. (lowest T @ which a substance will ignite and sustain combustion.)

c. Explosive limits may be expressed in terms of component concentrations. For mixtures use fume energy concentration since it is independent of specific combustibles present and = 52 BTU/ft^3 @ LEL at ambient temp.

d. Auto-ignition T = f (type of combustibles in mixture, O_2 content, fume energy concentration, flow-thru rate, etc.)

2. When fume energy concentration not between explosive limits, self-sustained combustion not possible (i.e., the available net heat of combustion possessed by mixture does not provide sufficient energy to propagate oxidation process).

3. When F.E.C. > LEL explosion and fire hazards exist
   a. Most industrial waste gas streams kept < 25% LEL. for safety (13 BTU/SA^3 @ Ambient T)
   b. Supplementary energy required to oxidize combustibles.
      1. Provide by supplying and burning a second source of fuel (natural gas, oil) in a burner (maintain ignition source)
      2. This technique brings a portion of the effluent into the combustible range, providing a temperature increase to T ignition of the remainder of the effluent
      3. Heat from burning fuel provides portion of total heat required to complete oxidation.
      4. A F.E.C. of 160 BTU/ft^3 (A stoichiometric mixture) is desirable for a flame w/ good combustion characteristics.
      5. Flame characteristics
         a. When air and fuel premixed prior to ignition, a short, intense, blue flame results (greatest fuel economy)
         b. Air in separate port (no air-gas premixing) results in large, highly radiant, yellow flame which provides large amt. of turbulence.

D. Combustion Terminology
   1. Heat of Combustion
   2. Gross Heating Value
   3. Net Heating Value
   4. Latent Heat
   5. Sensible Heat
   6. Available Heat
   7. Heat Content
   8. Specific Volume
   9. Enthalpy
   10. Specific Heat

E-G See page 4(a)

III. Methods of Combustion

A. Direct-Fired Afterburners
   1. Referred to as direct-flame incineration, furnace combustion.
   2. Proper design and operation may result in 95-98% efficiencies.
   3. Method adaptable where:
      a. A reliable supply of waste gas available for effluent pre-hea burner fuel.

b. Process exhaust temp. close to autogenous ignition T.
c. Availability of low cost fuel (purchased)
d. Gas stream volume and content not widely variable
e. Non-combustible inorganics and particulate matter preclude catalytic combustion.

4. Advantages of Direct-Flame Incineration
   a. High removal efficiency of sub-micron, odor-causing particulates.
   b. Simultaneous disposal of gaseous and particulate matter
   c. Compatibility w/ existing combustion equipment.
   d. Small space requirements
   e. Simple construction
   f. Low maintenance costs
   g. Low capital cost
5. Disadvantages
   a. Excessive weight of equipment
   b. Possible fire hazard
   c. High operational costs for fuel, instrumentation
6. Definition: Direct flame incineration is a method of heating waste Gases to the autogenous ignition temp. and maintaining this T in the presence of O_2 to cause oxidation reaction to occur in an enclosed chamber

Principle components of system
a. Combustion chamber
b. Gas burner
c. Gas burner controls
d. Temperature indicator

8. Operating principles
   a. Contaminated gases mixed w/ burner flames and combustion gases in afterburner throat
      1. Gas velocities of 15-25 fps in throat req'd for sufficient turbulent mixing (Contaminants injected into throat)
      2. Type and arrangement of gas burner (positioning of burner ports) important in determining degree of mixing.
      3. Efficiency affected by degree of mixing.
   b. Gas residence time req'd = 0.3 - 0.5 sec.
      1. Upper limit practical = 0.5 - 0.7 sec. due to size and construction cost limitations.
      2. Combustion chamber volume: 1 ft^3/15 - 20,000 BTU/hr. heat liberated.
   c. Combustion temperature req'd between 850°F - 1600°F
      1. Depends on nature of contaminants, T residence, turbulence, $[O_2]$
      2. Affects type and mtl. of construction
      3. May be varied to affect
         (a) efficiency
         (b) reaction rate
   d. Gas burner
      1. Fuel and primary air may be pre-mixed or may enter in separate ports (no pre-mixing)
      2. Primary air may be partially or completely composed of contaminant gas
         (a) results in fuel savings
      3. Locate burner in chamber throat (near entrance of contaminant gases)

E. Safety Precautions: Avoid Fire and Explosion Hazards by:
1. Diluting Vapor Concentration below L.E.L.
   a. Use of recirculated flue gas results in fuel saving
2. Use of flame arrestors
   a. Packed bed
   b. Metal tower packing
   c. Metal gridwork
   d. Use of above methods w/ pressure release device effects
      1. Vel. thru bed $>$ flame propagation velocities
      2. Pressure drop
      3. Cooling of flame below combustion temp.
3. Restriction in duct to increase V to $>$ Vflame propagation
   $V_{fo} \approx 20$ fpm
4. Installation of a water spray leg
   a. May serve dual purpose of scrubbing out particulates
   b. Cooling and humidifying gas results in greater fuel use.
5. Flame safety devices (low response time req'd.)
6. Safety shutoff valves

F. Heat Recovery
1. Used to reduce fuel input to combustor by pre-heating exhaust fumes
2. Used to reduce fuel requirements in an industrial process (dryer preheating, etc.), or to provide heated factory supply air.
3. Combination of (1) and (2)

G. Materials of construction
1. Corrosion resistance req'd.
2. Temp. resistance req'd.
   a. Use heat resistant steels
   b. Use refractory material (increases efficiency)(SO_2 causes spalling)
3. Insulating properties important (minimize heat losses)
4. Stress resistant material and proper construction important

4. Long-luminous flames result in highest efficiency
   (a) best mixing of contaminant & burner combustion gases
   (b) large radiative heat transfer
   (c) achieve by slow gas-air mixing
   (d) more rapid combustion of particulate matter
5. Short intense flames (more economical fuel use.)

Injection of contaminated gases
1. Inject contaminants near burner ports and in throat
2. Tangential injection

Types of controls
1. Flame failure controls
2. Constant T -- chamber or stack control by use of sensing element which actuates burner input control.
   (a) valuable cohere Q or contaminant concentration variable during a process cycle
   (b) results in considerable fuel saving
   (c) response rate to temp. changes possible
3. Safety pilot to shut off burner if contaminant gas flow interrupted or malfunction occurs.
4. High temperature limiting control to shut off fuel supply if gas flow (contaminant) interrupted.

g. Design calculations
See ref. A4, A9, B2

B. Catalytic Combustion
1. Usefulness and adaptability
   a. Limited to use for disposal of combustible, residue-free gaseous or vaporized materials.
   b. Where no large amount of dust, fly ash or solid inorganic mfl. present in gas.
   c. Greatest use has been in control of solvent & organic vapors from industrial ovens.
   d. Material to be oxidized must yield innocuous products
   e. Efficiencies of 80% for particulate matter, 98% for HC & organic vapors
2. Advantages
   a. Lower fud requirements than direct-fired method
   b. Reduced operating temperature
      1. Reduced insulation
      2. Reduced fire hazards
   c. Oxides of nitrogen not produced
3. Disadvantages
   a. High capital cost
   b. Sensitivity to catalyst poisoning
   c. Pretreatment requirements
      1. Combustibles must be vaporized
      2. Particulate matter (inorganics must be removed)
   d. Reactivation of catalyst may be frequent
   e. Efficiency low at usual operating temperature
4. Principles of catalytic oxidation
   a. Catalysis involves 5 steps
      1. Diffusion of reacting molecules to adsorption surface
      2. Adsorption of reactants on surface
      3. Chemical reaction on the surface
      4. Desorption of combustion products
      5. Diffusion of products from adsorption surface to gas stream.

b. Diffusion to adsorption surface usually the rate-limiting step
   1. Diffusion a function of temperature, OC $1/\sqrt{MW_{reactants}}$, OC 1/Distance.
   2. Rate can be increased by system design which
      a. Provides for small clearance between adsorption surfaces
      b. Promotes turbulent flow in catalyst bed
      c. Operates at increased T
c. Catalyst may be operated at lower T than direct incineration and at a reactant [C] < L.E.L. since catalytic adsorption energy is substituted for thermal activation energy and [C] of reactants is (cont
reased at adsorption face. ($T_{cat} < T_{air}$)
d. Since adsorption is a surface mechanism, the capacity of the adsorption catalyst is increased by increasing its surface area. (total surface area replaces time factor in direct combustion) Normally 0.2 - 0.5 ft^2/SCFM Provided. (left (margin
e. General adsorption requirements
   1. Reactants must be in gaseous or vapor phase
   2. Combustion products must be volatile for desorption to occur.
   3. Minimum temperatures are required for the initiation of catalytic oxidation of various compounds.
   4. Flame not required for combustion.
   5. Only a stoichiometric quantity of air required (efficiency increases where excess O_2 exists, however)
f. Catalyst poisons and interferents
   1. Non-volatile products are not desorbed from catalyst surface
      a. This includes organometallic or metallic vapors (e.g., Hg, As, Pb, Zn)
   2. Substances which form solid oxides
   3. Catalysis suppressants (halogen & sulfur compounds)
   4. Materials leaving carbonaceous, oily, or resinous deposits on surface
   5. Abrasive erosion of catalytic surface coating by particulate matter.
      (Use of expanded catalyst elements minimizing filtration of particulates and loss of active sites, may result in successful operating w/ frequent cleaning.)
g. Metals which may be used as catalysts to promote combustion
   1. Metals of platinum family
   2. Copper chromite, oxides of copper
   3. Oxides of chromium, vanadium, mangamese, nickel cobalt
h. Metal catalysts are costly
   1. Use only in proportion to quantity of gas handled
   2. Prevent loss of catalyst by erosion
   3. Reactivate poisoned catalysts periodically by washing in acid solutions.
      (a) frequency of req'd, reactivation governs much of operating cost of unit.
   4. Eventual catalyst replacement necessary
i. Design of catalyst bed
   1. Minimize bed depth to minimize pressure drop across bed (usually negligible)
   2. Catalyst element must be designed to permit even and equal flow over catalyst surface and through bed.
   3. Catalytic agent
      (a) Must be applied uniformly to carrier

(b) Must be extremely active
(c) Degree of activity determines ability to withstand contaminating agents, prevents carbon aceous buildup due to fast burning rate.

Reaction rate will determine face velocity allowable and bed depth allowable; rate determined by chemical and physical characteristics of catalytic agent.

Example of catalyst design - oxycat
(a) Platinum and alumina catalyst mixture
(b) High-grade porcelain carrier
(c) Catalyst metal and porcelain have same coeff. c expansion
(d) Carrier design creates flow pottem which prevents clogging or small particle impingement at low Vel.

5. Operation of Catalytic Combustors
   a. Components of system
      (1) Pre-heat burner (if needed)
      (2) Chamber
      (3) Catalyst elements
      (4) Fan (if needed)
      (5) Air Recirculation Ducts (if needed)
      (6) Heat exchanger (if needed)

      Thermodynamics of system
      (1) If $T_{effluent} > T_{cat.combustion}$, duct enlargement to accommodate catalytic units required only. ($650^{o} < T_{cat.comb} < 1000^{o}F$ usually)
      (2) If $T_{effluent} < T_{cat.comb}$, preheat required
         (a) Separate structure needed to house combustion units.
         (b) Provide preheat by use of fuel fired burner
) Amount of external pre-heater fuel used $= f(T_{effluent}, T_{combustion}, T_{exhaust})$
            (1) T_{comb}, $T_{exhaust}$ are in turn f (type and energy [C] of contaminant)
            (2) Example: T_{in}, [C] energy low and $T_{comb} >> T_{in}$ ∴ heat rise due to combustion negligible, $T_{exhaust} \doteq T_{comb}$. Even use of recycled combustion air or heat exchanger may be insufficient to raise $T_{influent}$ to $T_{combustion}$; ∴ Use pre-heat burner continuously.
            If T_{in} near T_{comb}, [C] energy high, then $T_{exhaust} >> T_{comb}$
            Recycle part of combustion gas or use heat exchanger (or both) to raise T_{in} to T_{comb}.
            ∴ Preheat burner only req'd for start-up, and system requires no external fuel during operation and is self-sustaining.
         (d) Effluent gas may be recycled to process system directly (as in industrial oven) as a means of supplying heat and thus supplementing process preheat system (explosion hazard w/ system malfunction may result, however)
         (e) Effluent gas may be recycled to process system using heat exchanger.

(f) Effluent gas may be recycled to external processes (water drying operations, waste-heat or steam boilers, heating of building make-up Zir)

(g) The greater the F.E.C., the more economical the system; it is practical to recycle gas for preheating when F.E.C. $\geq$ 10 BTU/SCF ($\approx$ 25% L.E.L.)
When [C] energy low, use heat exchangers for preheating. $1 \leq 10$ BTU/SCF

(h) Once combustion initiated, if F.E.C. large, then ΔT_{comb} great
(1) Self-sustaining system may be achieved, and
(2) Catalyst surface temp. increases greatly requiring substantially lower T_{in}; $\therefore$ preheat requirements $<$ initial preheat requirements.
(3) Pre-heat fuel then OC 1/[C] energy if modulating burner control used.

(i) Some combustion gas may have to be recycled to effluent prior to introduction to heat exchanger, e.g., to percent condensation of corrosive acids by maintaining $T_{exhaust} > T_{condensation}$.

(j) Fuel consumption can be reduced from 10 $\rightarrow$ 4 BTU/SCF w/ use of heat exchangers.

(k) Catalyst should not be exposed to contaminant gas below operating, temp. due to effects of poisoning, deposition; $\therefore$ use by-pass arrangement temporarily.

c. Fan
(1) Fan exhausting process equipment may be used to deliver air to catalyst
(2) Fan may be located in preheat chamber between burner and catalyst:
(a) Serves to thoroughly mix combustion products & exhaust gas ← or use baffles, elbows
(b) Operates in region where $T > T_{condensation}$, no condensates occur in fan.
(c) Distributes gas evenly over catalyst ← or use perforated baffle plate, or splitting vanes
(d) Fan must be heat resistant

d. Pre-heat burner
(1) Preheat burner multipurpose:
(a) Preheats gas to desired T_{comb}.
(b) Combusts some materials in pre-heat chamber
(c) Vaporizes condensed combustibles prior to catalysis
(2) Use pre-mix burner when burner located on discharge side of fan due to positive chamber P.
(3) Use atmospheric burner when fan between burner and catalyst bed due to negative pressure.
(4) Size burner to meet required $T_{effluent}$) $T_{effluent}$=950° for burner sizing.
(5) Use modulating controls regulated by $T_{exhaust}$. When [C] energy varies greatly.
(6) High temp. limiting control used to prevent overheating of system.

e. Afterburner Chamber
(1) Construct of black iron, heat resisting or stainless steel or refractory.
(a) $750 < T < 1100$: Heat resisting steel
(b) $1100 < T < 1300°F$: Stainless
(c) $1300° < T$: Refractory

(2) 4-6" thermal insulation req'd if refractory not used
(3) Mild steel outer sheet and structural steel frame
(4) Chamber gas velocities of 20 fps satisfactory
(5) Provide thermal expansion joints
(6) Catalyst units must be accessible for cleaning and replacement.

f. Automatic safety controls req'd when FEC >25% LEL.
g. Gas flow variations of 50% tolerable w/o affecting efficiency
h. Filters to remove particulate matter, if needed should be placed downstream of pre-heat burner to allow vaporized contaminants to pass through.
i. Costs
   (1) $3 - 10.00/ SCFM (Cost of catalyst element itself = $1/SCFM)
   (2) Operating cost from preheat fuel, catalyst deaning
   (3) Maintenance costs
      (a) Inspect 6 months min. interval

6. Design calculations
   See engr. manual, pp. 184

Flare Combustion

1. Applicability
   a. Incinerate gases which cannot be used for other purposes due to variable emission rate
   b. Incinerate toxic or dangerous gases subject to emergency conditions
      1. Immediate release of large volume of such gases req'd (e.g., hydrocarbons, NH_3, hydrogen cyanide)
      2. Volume and gas [C] subject to large variation
   c. Most economical combustion method where fume energy concentration w/in or greater than flammable limits.
      1. Gases cannot be burned in enclosed chamber since an explosion hazard would result.
   d. Gases whose combustion products may be hazardous to health should not be burned in a flare.
2. Design Considerations
   a. Achieve good combusion by providing adequate mixing, or fuel-Air
      1. Use steam jets to provide mixing.
      2. High pressure air jets too costly.
   b. Steam injection effects
      1. Inspirates air into the combustion zone
      2. Reacts w/ hydrocarbons forming compounds which burn at low T
      3. Lowers partial pressure of fuel which causes greater separation of molecules.
         (a) Inhibits polymerization
         (b) thus, elimination of smoke-forming mechanism
      4. Creates blue-flame combustion
         (a) Water-gas reaction removes unburned carbon
            $C + H_2O \rightarrow CO + H_2 \xrightarrow{O_2} CO_2 + H_2O$
         (b) Blue flame more pleasing aesthetically
   c. Quantity of steam added is important
      1. 1/20 - 1/3 lb. steam/lb. combustible gas usually req'd. to prevent smoke formation.

2. Quantity added depends on composition of gas
   (a) Usually measured by carbon/hydrogen ratio
   (b) Degree of unsaturation important
   (c) Steam to gas ratio (by weight) increases as degree of unsaturation increases, or C/H decreases, or MW increases (aromatics, e.g., require high ratio)
      (1) Side-reactions (polymerization, e.g.) increase w/ increase in MW, degree of unsaturation: side-reactions result in smoke formation.
3. Minimum amt. of steam req'd produces luminous flame
4. Excess steam results in steam plume w/ dissappearance of flame.
   (a) Flame may be extinguished
   (b) Use of automatic controls will eliminate this hazard.

d. Flare stack height must be great enough to provide heat, flame protection

e. Pilot flame required
   1. Multiple pilot burner tips usually provided
   2. If energy [C] of fume $<$ L.E.L., ring burner may be used to provide energy concentration sufficient to support combustion; ignited by same pilot system.

f. Prevent flash-back explosion hazard
   1. Use did leg and water seal when O_2 present in gas
   2. Remove oil-mist at stack base for safe operation

g. General
   1. Collect pressure relief valve discharges in storage surge tanks and meter contents to plare
      (a) Peak flow to flare reduced
      (b) Required height, diameter, cost of flare stack reduced
   2. Protect top of flare stack w/ a few feet of refractory lining and a stainless steel shell.
   3. Maintenance and operating costs of flare negligible

3. Components of a flare
   a. burner
   b. stack
   c. seal
   d. liquid trap
   e. controls
   f. pilot burner
   g. ignition system

4. Types of flares
   a. elevated
   b. ground level
   c. burning pits

COMBUSTION BIBLIOGRAPHY

A. General

1. "Control of Gaseous Emissions" Training Course Manual, USDHEW, PHS Cincinnati, Ohio. May, 1967.
2. Stern, A. C. Air Pollution, Vol. III, Ch. 48 Academic Press, N.Y. 1970
3. Strauss, W. Industrial Gas Cleaning 1st Ed., Pergamon Press, N.Y. (1966)
4. Danielson, J. A. ed. Air Pollution Engineering Manual, USDHEW, PHS Publication 999-AP-40, 1967.
5. Control Techniques for Hydrocarbons and Organic Solvent Emissions from Stationary Sources, USDHEW, PHS, Washington, D.C. March, 1970.
6. Magill, P.L. et al, ed. Air Pollution Handbook, McGraw-Hill Book Co. 1956.
7. Summer, W. Methods of Air Deodorization, Elsevier, 1963.
8. Gilpin, A. Control of Air Pollution, Butterworths, London 1963.
9. The North American Combustion Handbook, North American Manufacturing Co., Cleveland, Ohio (1965).
10. Air Pollution Manual, Part II--Control Equipment, American Industrial Hygiene Association, 1968.

B. Combustion by Direct Flame Incineration

1. Meyers, F. D. "Fume Incineration with Combustion Air at Elevated Temperature", JAPCA 16, No. 7. (1966).
2. Ingels, R. M. "The Afterburner Route to Air Pollution Control" Air Engr., No. 6, pp. 39-42, (6/64)
3. Sandomirsky, A. G. et al, "Fume Control in Rubber Processing by Direct Flame Incineration" JAPCA, 11 No. 12, (12/66)
4. Benforado, D. M. et al "Economics of Heat Recovery in Direct-Flame Fume Incineration" Air Engr., 9 pp. 29-32 (3/67).
5. Mills, J. L. et al "Design of Afterburners for Varnish Cookers" JAPCA 10 No. 2, 1960.
6. Sullivan J. L. et al "An Evaluation of Catalytic and Direct Fired Afterburners for Coffee and Chicory Roasting Odors" JAPCA. 15 No 12, (12/65).

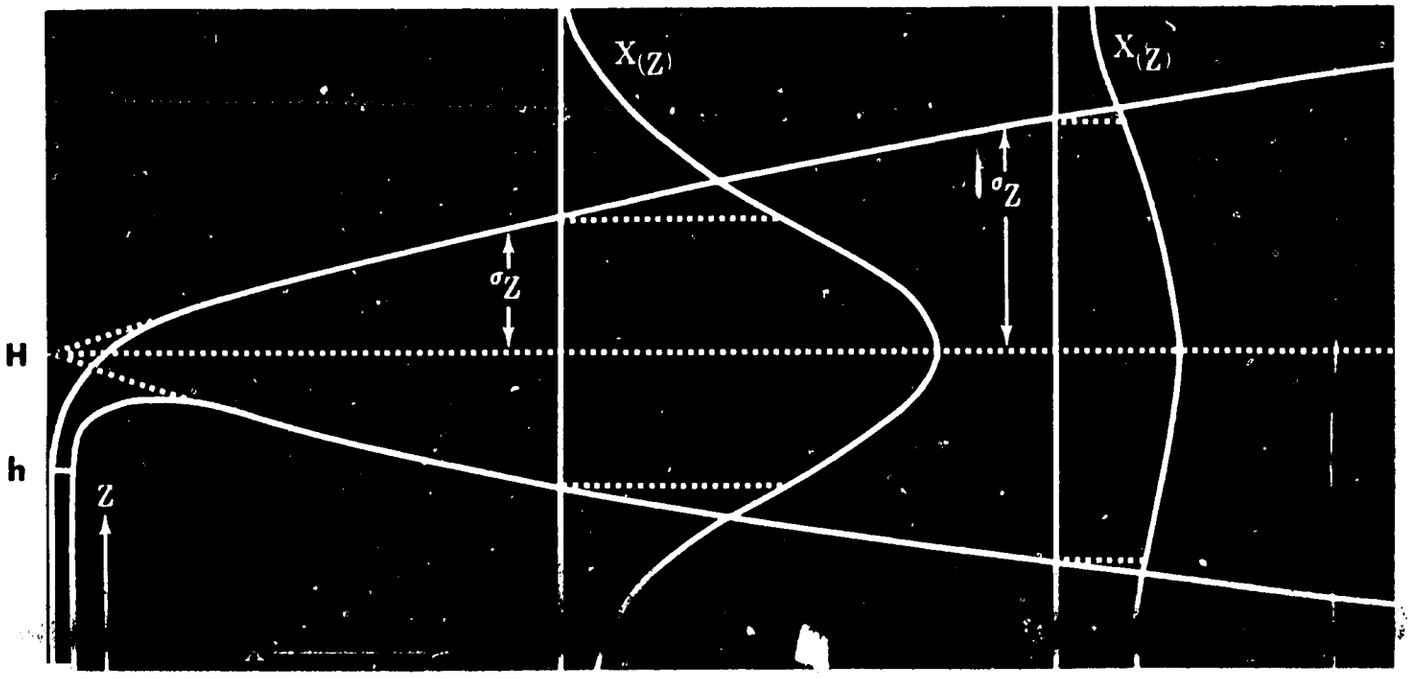
C. Catalytic Afterburning

1. Suter, H. R. "Range of Applicability of Catalytic Fume Burners" JAPCA, 5, No. 3 pp. 173 (1955)
2. Houdry, J. H., Hayes, C. T. "Versatility of Oxidation Catalysts for Industrial Air Pollution Control" JAPCA, 7 No. 3 (195[illegible])
3. Goodell, P. H. "Industrial Ovens Designed for Air Pollution Control" JAPCA, 10 No. 3 (1960)
4. Donahue, J. L. "System Designs for the Catalytic Decomposition of Nitrogen Oxides" JAPCA, 8 No. 3 (1958).

D. Flare Combustion

1. Bodurthz, F. H. "Flare Stacks--How Tall" Chem. Engr. Progress. pp. 177-180 (12/15/58).
2. Mellor, J. F. "A Multi-Purpose Flare Stack for Control of Chemical Process Wastes" JAPCA, 10 No. 6 (Nov. 1960).

WORKBOOK OF ATMOSPHERIC DISPERSION ESTIMATES



U.S. ENVIRONMENTAL PROTECTION AGENCY

WORKBOOK OF ATMOSPHERIC DISPERSION ESTIMATES

D. BRUCE TURNER

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Environmental Science Services Administration

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Office of Air Programs
Research Triangle Park, North Carolina
Revised 1970

3091198

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7th printing January 1974

Office of Air Programs Publication No. AP-26

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price $1.00
Stock Number 5503-0015

3-1120

PREFACE

This workbook presents some computational techniques currently used by scientists working with atmospheric dispersion problems. Because the basic working equations are general, their application to specific problems usually requires special care and judgment; such considerations are illustrated by 26 example problems. This workbook is intended as an aid to meteorologists and air pollution scientists who are required to estimate atmospheric concentrations of contaminants from various types of sources. It is not intended as a complete do-it-yourself manual for atmospheric dispersion estimates; all of the numerous complications that arise in making best estimates of dispersion cannot be so easily resolved. Awareness of the possible complexities can enable the user to appreciate the validity of his "first approximations" and to realize when the services of a professional air pollution meteorologist are required.

Since the initial publication of this workbook, air pollution meteorologists affiliated with the Environmental Protection Agency have turned to using the method of Briggs to determine plume rise in most cases rather than using the plume-rise equation of Holland as set forth in Chapter 4. The reader is directed to:

> Briggs, Gary A. 1971: "Some Recent Analyses of Plume Rise Observations." In: Proceedings of the Second International Clean Air Congress. Academic Press, New York, N. Y. pp 1029 - 1032
>
> and modified by
>
> Briggs, Gary A. 1972: "Discussion, Chimney Plumes in Neutral and Stable Surroundings." Atmospheric Environment, 6:507-510.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to Robert A. McCormick, Paul A. Humphrey, and other members of the Field Research Office for their helpful discussions and review; to Jean J. Schueneman, Chief, Criteria and Standards Development, National Center for Air Pollution Control, who suggested this workbook; to Phyllis Polland and Frank Schiermeier, who checked the problem solutions; to Ruth Umfleet and Edna Beasley for their aid; and to the National Center for Air Pollution Control, Public Health Service, and Air Resources Laboratory, Environmental Science Services Administration, for their support.

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ABSTRACT

This workbook presents methods of practical application of the binormal continuous plume dispersion model to estimate concentrations of air pollutants. Estimates of dispersion are those of Pasquill as restated by Gifford. Emphasis is on the estimation of concentrations from continuous sources for sampling times of 10 minutes. Some of the topics discussed are determination of effective height of emission, extension of concentration estimates to longer sampling intervals, inversion break-up fumigation concentrations, and concentrations from area, line, and multiple sources. Twenty-six example problems and their solutions are given. Some graphical aids to computation are included.

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Chapter 1 — INTRODUCTION

NOTE: SEE PREFACE TO THE SIXTH PRINTING ON PAGE iii.

During recent years methods of estimating atnospheric dispersion have undergone considerable 'evision, primarily due to results of experimental nesurements. In most dispersion problems the 'elevant atmospheric layer is that nearest the ;round, varying in thickness from several hundred o a few thousand meters. Variations in both hermal and mechanical turbulence and in wind 'elocity are greatest in the layer in contact with he surface. Turbulence induced by buoyancy forces n the atmosphere is closely related to the vertical temperature structure. When temperature decreases with height at a rate higher than 5.4°F per 1000 ft (1°C per 100 meters), the atmosphere is in unstable equilibrium and vertical motions are enhanced. When temperature decreases at a lower rate or increases with height (inversion), vertical motions are damped or reduced. Examples of typical variations in temperature and wind speed with height for daytime and nighttime conditions are illustrated in Figure 1-1.

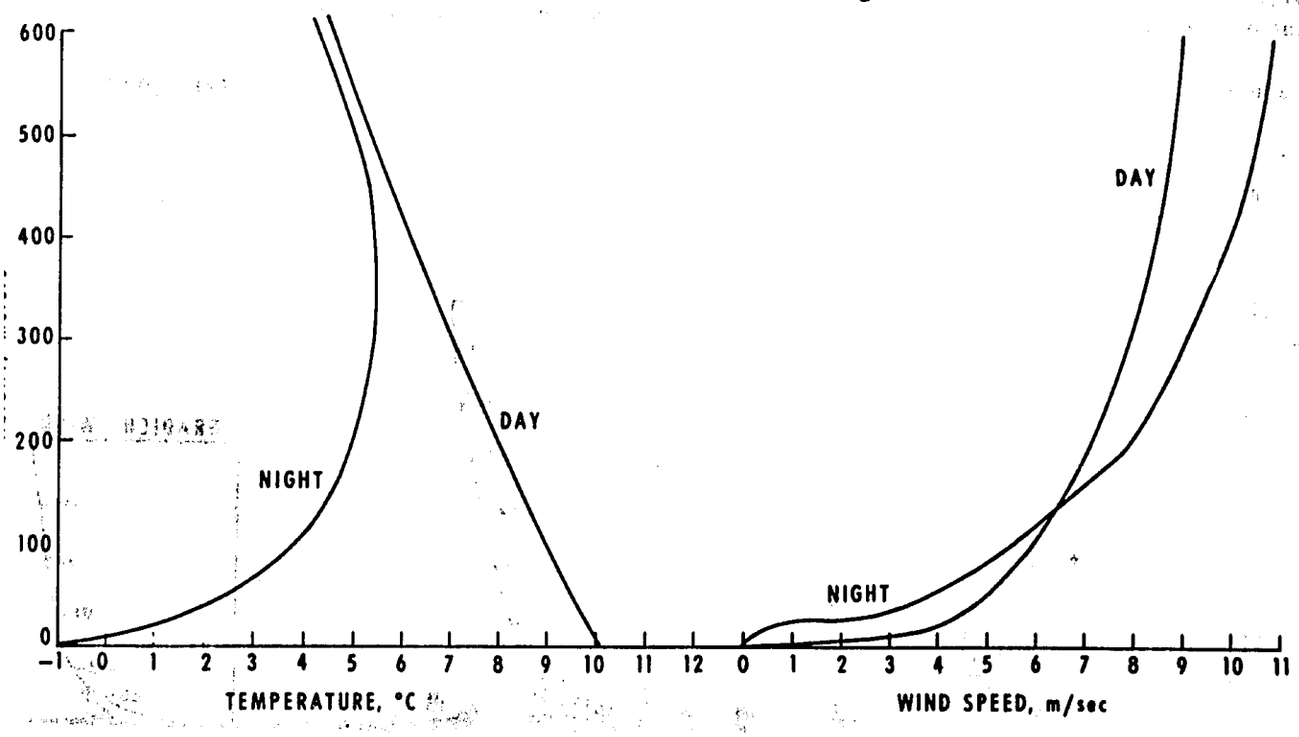

Figure 1-1. Examples of variation of temperature and wind speed with height (after Smith, 1963).

The transfer of momentum upward or downward in the atmosphere is also related to stability; 'hen the atmosphere is unstable, usually in the aytime, upward motions transfer the momentum deficiency" due to eddy friction losses near the arth's surface through a relatively deep layer, ausing the wind speed to increase more slowly ;ith height than at night (except in the lowest few ieters). In addition to thermal turbulence, roughess elements on the ground engender mechanical urbulence, which affects both the dispersion of naterial in the atmosphere and the wind profile variation of wind with height). Examples of these ffects on the resulting wind profile are shown in 'igure 1-2.

As wind speed increases, the effluent from a continuous source is introduced into a greater volume of air per unit time interval. In addition to this dilution by wind speed, the spreading of the material (normal to the mean direction of transport) by turbulence is a major factor in the dispersion process.

The procedures presented here to estimate atmospheric dispersion are applicable when mean wind speed and direction can be determined, but measurements of turbulence, such as the standard deviation of wind direction fluctuations, are not available. If such measurements are at hand, techniques such as those outlined by Pasquill (1961) are likely to give more accurate results. The diffusion param-

eters presented here are most applicable to ground-level or low-level releases (from the surface to about 20 meters), although they are commonly applied at higher elevations without full experimental validation. It is assumed that stability is the same throughout the diffusing layer, and no turbulent transfer occurs *through* layers of dissimilar stability characteristics. Because mean values for wind directions and speeds are required, neither the variation of wind speed nor the variation of wind direction with height in the mixing layer are taken into account. This usually is not a problem in neutral or unstable (e.g., daytime) situations, but can cause over-estimations of downwind concentrations in stable conditions.

REFERENCES

Davenport, A. G., 1963: The relationship of wind structure to wind loading. Presented at Int. Conf. on The Wind Effects on Buildings and Structures, 26-28 June 63, Natl. Physical Laboratory, Teddington, Middlesex, Eng.

Pasquill, F., 1961: The estimation of the dispersion of wind borne material. Meteorol. Mag. *90*, 1063, 33-49.

Smith, M. E., 1963: The use and misuse of the atmosphere, 15 pp., Brookhaven Lecture Series, No. 24, 13 Feb 63, BNL 784 (T-298) Brookhaven National Laboratory.

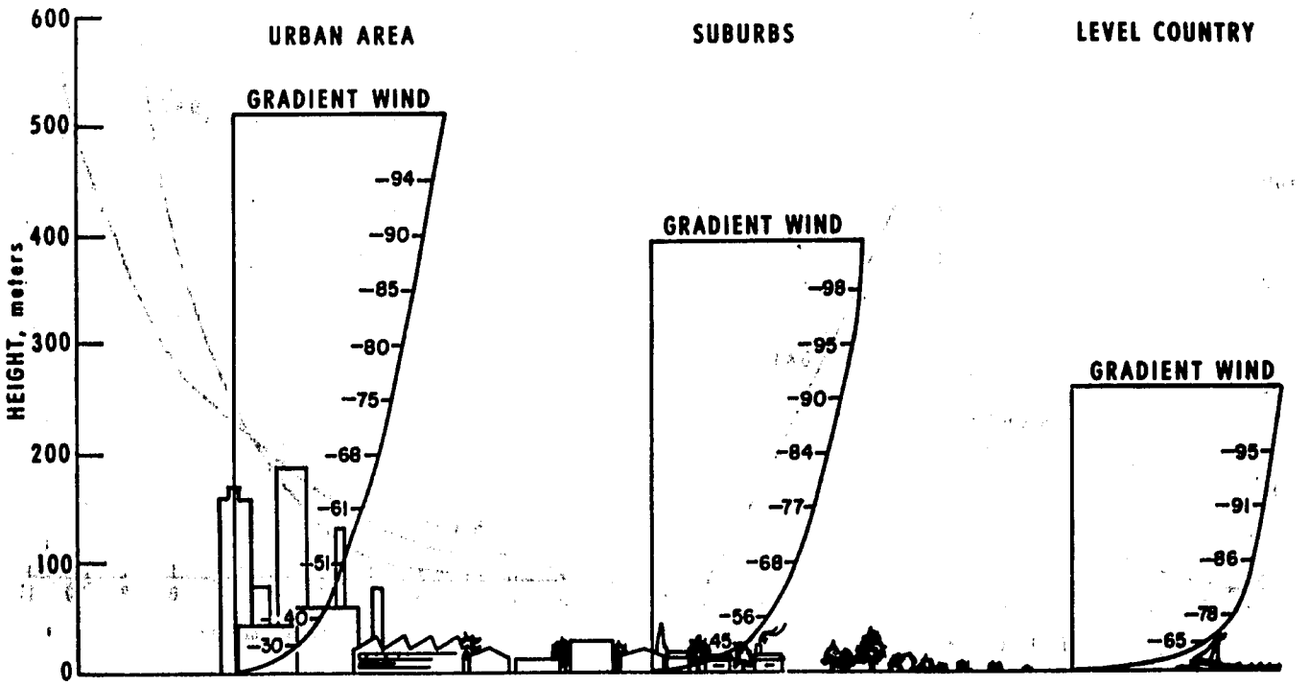

Figure 1-2. Examples of variation of wind with height over different size roughness elements (figures are percentages of gradient wind); (from Davenport, 1963).

Chapter 2 — BACKGROUND

For a number of years estimates of concentrations were calculated either from the equations of Sutton (1932) with the atmospheric dispersion parameters C_y, C_z, and n, or from the equations of Bosanquet (1936) with the dispersion parameters p and q.

Hay and Pasquill (1957) have presented experimental evidence that the vertical distribution of spreading particles from an elevated point is related to the standard deviation of the wind elevation angle, σ_E, at the point of release. Cramer (1957) derived a diffusion equation incorporating standard deviations of Gaussian distributions: σ_y for the distribution of material in the plume across wind in the horizontal, and σ_z for the vertical distribution of material in the plume. (See Appendix 2 for properties of Gaussian distributions.) These statistics were related to the standard deviations of azimuth angle, σ_A, and elevation angle, σ_E, calculated from wind measurements made with a bi-directional wind vane (bivane). Values for diffusion parameters based on field diffusion tests were suggested by Cramer, et al. (1958) (and also in Cramer 1959a and 1959b). Hay and Pasquill (1959) also presented a method for deriving the spread of pollutants from records of wind fluctuation. Pasquill (1961) has further proposed a method for estimating diffusion when such detailed wind data are not available. This method expresses the height and angular spread of a diffusing plume in terms of more commonly observed weather parameters. Suggested curves of height and angular spread as a function of distance downwind were given for several "stability" classes. Gifford (1961) converted Pasquill's values of angular spread and height into standard deviations of plume concentration distribution, σ_y and σ_z. Pasquill's method, with Gifford's conversion incorporated, is used in this workbook (see Chapter 3) for diffusion estimates.

Advantages of this system are that (1) only two dispersion parameters are required and (2) results of most diffusion experiments are now being reported in terms of the standard deviations of plume spread. More field dispersion experiments are being conducted and will be conducted under conditions of varying surface roughness and atmospheric stability. If the dispersion parameters from a specific experiment are considered to be more representative than those suggested in this workbook, the parameter values can be used with the equations given here.

REFERENCES

Bosanquet, C. H., and J. L. Pearson, 1936: The spread of smoke and gases from chimneys. Trans. Faraday Soc., *32*, 1249-1263.

Cramer, H. E., 1957: A practical method for estimating the dispersion of atmospheric contaminants. Proc. 1st Natl. Conf. on Appl. Meteorol. Amer. Meterol. Soc.

Cramer, H. E., F. A. Record, and H. C. Vaughan, 1958: The study of the diffusion of gases or aerosols in the lower atmosphere. Final Report Contract AF 19(604)-1058 Mass. Inst. of Tech., Dept. of Meteorol.

Cramer, H. E., 1959a: A brief survey of the meteorological aspects of atmospheric pollution. Bull. Amer. Meteorol. Soc., *40*, 4, 165-171.

Cramer, H. E., 1959b: Engineering estimates of atmospheric dispersal capacity. Amer. Ind. Hyg. Assoc. J., *20*, 3, 183-189.

Gifford, F. A., 1961: Uses of routine meteorological observations for estimating atmospheric dispersion. Nuclear Safety, *2*, 4, 47-51.

Hay, J. S., and F. Pasquill, 1957: Diffusion from a fixed source at a height of a few hundred feet in the atmosphere. J. Fluid Mech., *2*, 299-310.

Hay, J. S., and F. Pasquill, 1959: Diffusion from a continuous source in relation to the spectrum and scale of turbulence. pp 345-365 in *Atmospheric Diffusion and Air Pollution*, edited by F. N. Frenkiel and P. A. Sheppard, Advances in Geophysics, *6*, New York, Academic Press, 471 pp.

Pasquill, F., 1961: The estimation of the dispersion of windborne material. Meteorol. Mag., *90*, 1063, 33-49.

Sutton, O. G., 1932: A theory of eddy diffusion in the atmosphere. Proc. Roy. Soc., A, *135*, 143-165.

Chapter 3 — ESTIMATES OF ATMOSPHERIC DISPERSION

This chapter outlines the basic procedures to be used in making dispersion estimates as suggested by Pasquill (1961) and modified by Gifford (1961).

COORDINATE SYSTEM

In the system considered here the origin is at ground level at or beneath the point of emission, with the x-axis extending horizontally in the direction of the mean wind. The y-axis is in the horizontal plane perpendicular to the x-axis, and the z-axis extends vertically. The plume travels along or parallel to the x-axis. Figure 3-1 illustrates the coordinate system.

DIFFUSION EQUATIONS

The concentration, χ, of gas or aerosols (particles less than about 20 microns diameter) at x,y,z from a continuous source with an effective emission height, H, is given by equation 3.1. The notation used to depict this concentration is χ (x,y,z;H). [illegible] the plume centerline when it becomes essentially level, and is the sum of the physical stack height, h, and the plume rise, ΔH. The following assumptions are made: the plume spread has a Gaussian distribution (see Appendix 2) in both the horizontal and vertical planes, with standard deviations of plume concentration distribution in the horizontal and vertical of σ_y and σ_z, respectively; the mean wind speed affecting the plume is u; the uniform emission rate of pollutants is Q; and total reflection of the plume takes place at the earth's surface, i.e., there is no deposition or reaction at the surface (see problem 9).

$$\chi(x,y,z;H) = \frac{Q}{2\pi\,\sigma_y\,\sigma_z\,u}\,\exp^{*}\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right]+\exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\} \tag{3.1}$$

*Note: exp $-a/b = e^{-a/b}$ where e is the base of natural logarithms and is approximately equal to 2.7182

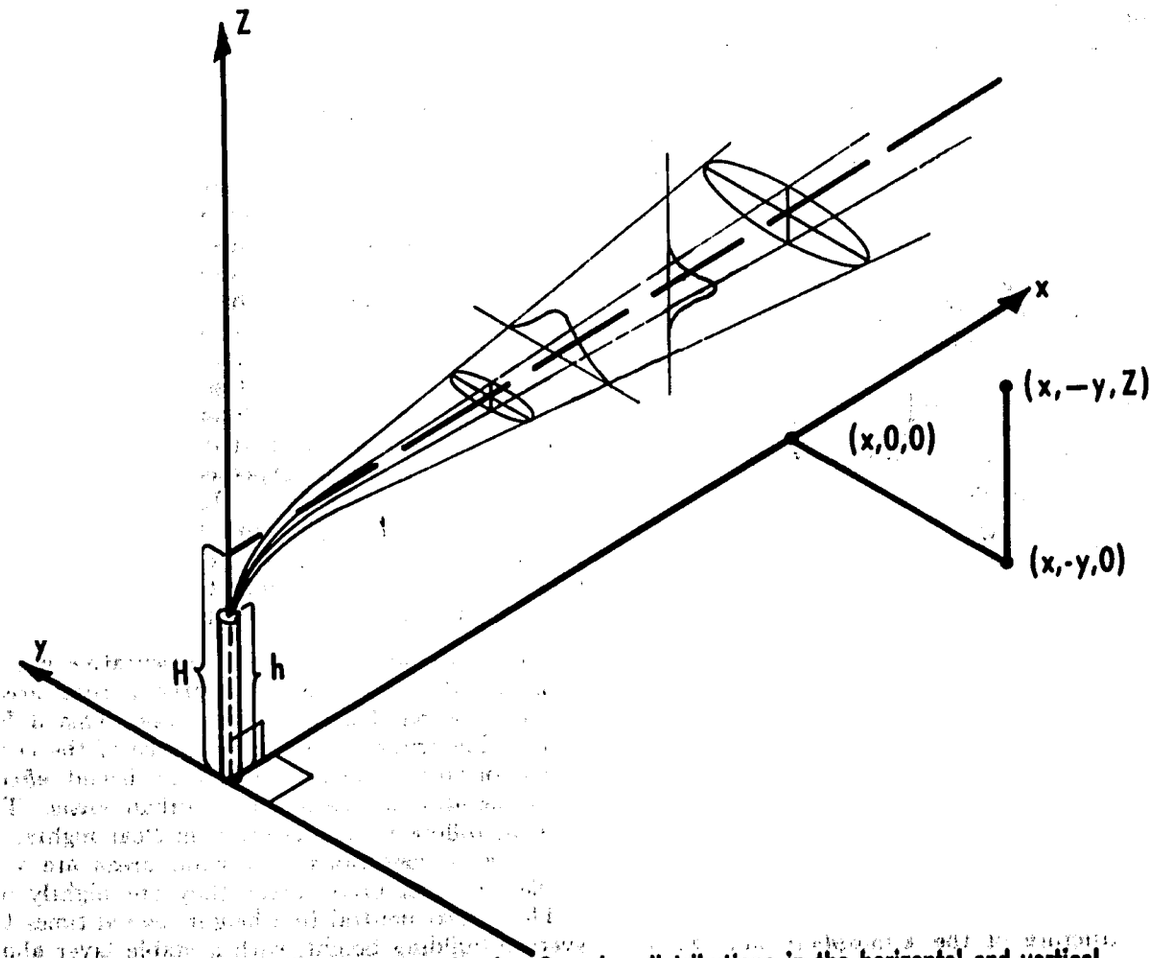

Figure 3-1. Coordinate system showing Gaussian distributions in the horizontal and vertical.

Any consistent set of units may be used. The most common is:

χ (g m^{-3}) or, for radioactivity (curies m^{-3})
Q (g sec^{-1}) or (curies sec^{-1})
u (m sec^{-1})
σ_y, σ_z, H, x, y, and z (m)

This equation is the same as equation (8.35) p. 293 of Sutton (1953) when σ's are substituted for Sutton's parameters through equations like (8.27) p. 286. For evaluations of the exponentials found in Eq. (3.1) and those that follow, see Appendix 3. χ is a mean over the same time interval as the time interval for which the σ's and u are representative. The values of both σ_y and σ_z are evaluated in terms of the downwind distance, x.

Eq. (3.1) is valid where diffusion in the direction of the plume travel can be neglected, that is, no diffusion in the x direction.

This may be assumed if the release is continuous or if the duration of release is equal to or greater than the travel time (x/u) from the source to the location of interest.

For concentrations calculated at ground level, i.e., z = 0, (see problem 3) the equation simplifies to:

$$\chi\,(x,y,0;H) = \frac{Q}{\pi\,\sigma_y\,\sigma_z\,u}\,\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \qquad (3.2)$$

Where the concentration is to be calculated along the centerline of the plume (y = 0), (see problem 2) further simplification results:

$$\chi\,(x,0,0;H) = \frac{Q}{\pi\,\sigma_y\,\sigma_z\,u}\,\exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \qquad (3.3)$$

For a ground-level source with no effective plume rise (H = 0), (see problem 1):

$$\chi\,(x,0,0;0) = \frac{Q}{\pi\,\sigma_y\,\sigma_z\,u} \qquad (3.4)$$

EFFECTS OF STABILITY

The values of σ_y and σ_z vary with the turbulent structure of the atmosphere, height above the surface, surface roughness, sampling time over which concentration is to be estimated, wind speed, and distance from the source. For the parameter values given here, the sampling time is assumed to be about 10 minutes, the height to be the lowest few hundred meters of the atmosphere, and the surface to be relatively open country. The turbulent structure of the atmosphere and wind speed are considered in the stability classes presented, and the effect of distance from the source is considered in the graphs determining the parameter values. Values for σ_y and σ_z are estimated from the stability of the atmosphere, which is in turn estimated from the wind speed at a height of about 10 meters and, during the day, the incoming solar radiation or, during the night, the cloud cover (Pasquill, 1961). Stability categories (in six classes) are given in Table 3-1. Class A is the most unstable, class F the most stable class considered here. Night refers to the period from 1 hour before sunset to 1 hour after sunrise. Note that the neutral class, D, can be assumed for overcast conditions during day or night, regardless of wind speed.

Table 3-1 KEY TO STABILITY CATEGORIES

Surface Wind Speed (at 10 m), m sec^{-1}	Day: Incoming Solar Radiation			Night	
	Strong	Moderate	Slight	Thinly Overcast or ≥4/8 Low Cloud	≤3/8 Cloud
< 2	A	A-B	B		
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
> 6	C	D	D	D	D

The neutral class, D, should be assumed for overcast conditions during day or night.

"Strong" incoming solar radiation corresponds to a solar altitude greater than 60° with clear skies; "slight" insolation corresponds to a solar altitude from 15° to 35° with clear skies. Table 170, Solar Altitude and Azimuth, in the Smithsonian Meteorological Tables (List, 1951) can be used in determining the solar altitude. Cloudiness will decrease incoming solar radiation and should be considered along with solar altitude in determining solar radiation. Incoming radiation that would be strong with clear skies can be expected to be reduced to moderate with broken (5/8 to 7/8 cloud cover) middle clouds and to slight with broken low clouds. An objective system of classifying stability from hourly meteorological observations based on the above method has been suggested (Turner, 1961).

These methods will give representative indications of stability over open country or rural areas, but are less reliable for urban areas. This difference is due primarily to the influence of the city's larger surface roughness and heat island effects upon the stability regime over urban areas. The greatest difference occurs on calm clear nights; on such nights conditions over rural areas are very stable, but over urban areas they are slightly unstable or near neutral to a height several times the average building height, with a stable layer above (Duckworth and Sandberg, 1954; DeMarrais, 1961).

Some preliminary results of a dispersion experiment in St. Louis (Pooler, 1965) showed that the dispersion over the city during the daytime behaved somewhat like types B and C; for one night experiment σ_y varied with distance between types D and E.

ESTIMATION OF VERTICAL AND HORIZONTAL DISPERSION

Having determined the stability class from Table 3-1, one can evaluate the estimates of σ_y and σ_z as a function of downwind distance from the source, x, using Figures 3-2 and 3-3. These values of σ_y and σ_z are representative for a sampling time of about 10 minutes. For estimation of concentrations for longer time periods see Chapter 5. Figures 3-2 and 3-3 apply strictly only to open level country and probably underestimate the plume dispersion potential from low-level sources in built-up areas. Although the vertical spread may be less than the values for class F with very light winds on a clear night, quantitative estimates of concentrations are nearly impossible for this condition. With very light winds on a clear night for ground-level sources free of topographic influences, frequent shifts in wind direction usually occur which serve to spread the plume horizontally. For elevated sources under these extremely stable situations, significant concentrations usually do not reach ground level until the stability changes.

A stable layer existing above an unstable layer will have the effect of restricting the vertical diffusion. The dispersion computation can be modified for this situation by considering the height of the base of the stable layer, L. At a height 2.15 σ_z above the plume centerline the concentration is one-tenth the plume centerline concentration at the same distance. When one-tenth the plume centerline concentration extends to the stable layer, at height L, it is reasonable to assume that the distribution starts being affected by the "lid." The following method is suggested to take care of this situation. Allow σ_z to increase with distance to a value of L/2.15 or 0.47 L. At this distance x_L, the plume is assumed to have a Gaussian distribution in the vertical. Assume that by the time the plume travels twice this far, 2 x_L, the plume has become uniformly distributed between the earth's surface and the height L, i.e., concentration does not vary with height (see Figure 3-4). For the distances greater than 2 x_L, the concentration for any height between the ground and L can be calculated from:

$$\chi\,(x,y,z;H) = \frac{Q}{\sqrt{2\pi}\,\sigma_y\,L\,u}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \qquad (3.5)$$

from any z from 0 to L
for $x > 2\,x_L$; x_L is where $\sigma_z = 0.47$ L

(see problem 6). Note that Eq. (3.5) assumes normal or Gaussian distribution of the plume *only* in the horizontal plane. The same result can be obtained from the following equation where σ_{zL} is an effective dispersion parameter because $\sqrt{2\pi}$ L = 2.5066 L and 0.8 πL = 2.51 L.

$$\chi\,(x,y,z;H) = \frac{Q}{\pi\,\sigma_y\,\sigma_{zL}\,u}\left[\exp -\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \qquad (3.6)$$

for any z from 0 to L
for $x > 2_{xL}$; x_L is where $\sigma_z = 0.47$ L
The value of $\sigma_{zL} = 0.8$ L

EVALUATION OF WIND SPEED

For the wind speed, u, a mean through the vertical extent of the plume should be used. This would be from the height H — 2 σ_z through H + 2 σ_z. Of course, if 2 σ_z is greater than H then the wind can be averaged from the ground to H + 2 σ_z. However, the "surface wind" value may be all that is available. The surface wind is most applicable to surface or low-level emissions, especially under stable conditions.

PLOTS OF CONCENTRATIONS AGAINST DISTANCE

To gain maximum insight into a diffusion problem it is often desirable to plot centerline concentrations against distance downwind. A convenient procedure is to determine the ground-level centerline concentrations for a number of downwind distances and plot these values on log-log graph paper. By connecting the points, one may estimate concentrations for intermediate downwind distances (see problem 6).

ACCURACY OF ESTIMATES

Because of a multitude of scientific and technical limitations the diffusion computation method presented in this manual may provide *best estimates* but not infallible predictions. In the unstable and stable cases, severalfold errors in estimate of σ_z can occur for the longer travel distances. In some cases the σ_z may be expected to be correct within a factor of 2, however. These are: (1) all stabilities for distance of travel out to a few hundred meters; (2) neutral to moderately unstable conditions for distances out to a few kilometers; and (3) unstable conditions in the lower 1000 meters of the atmosphere with a marked inversion above for distances out to 10 km or more. Uncertainties in the estimates of σ_y are in general less than those of σ_z. The ground-level centerline concentrations for these

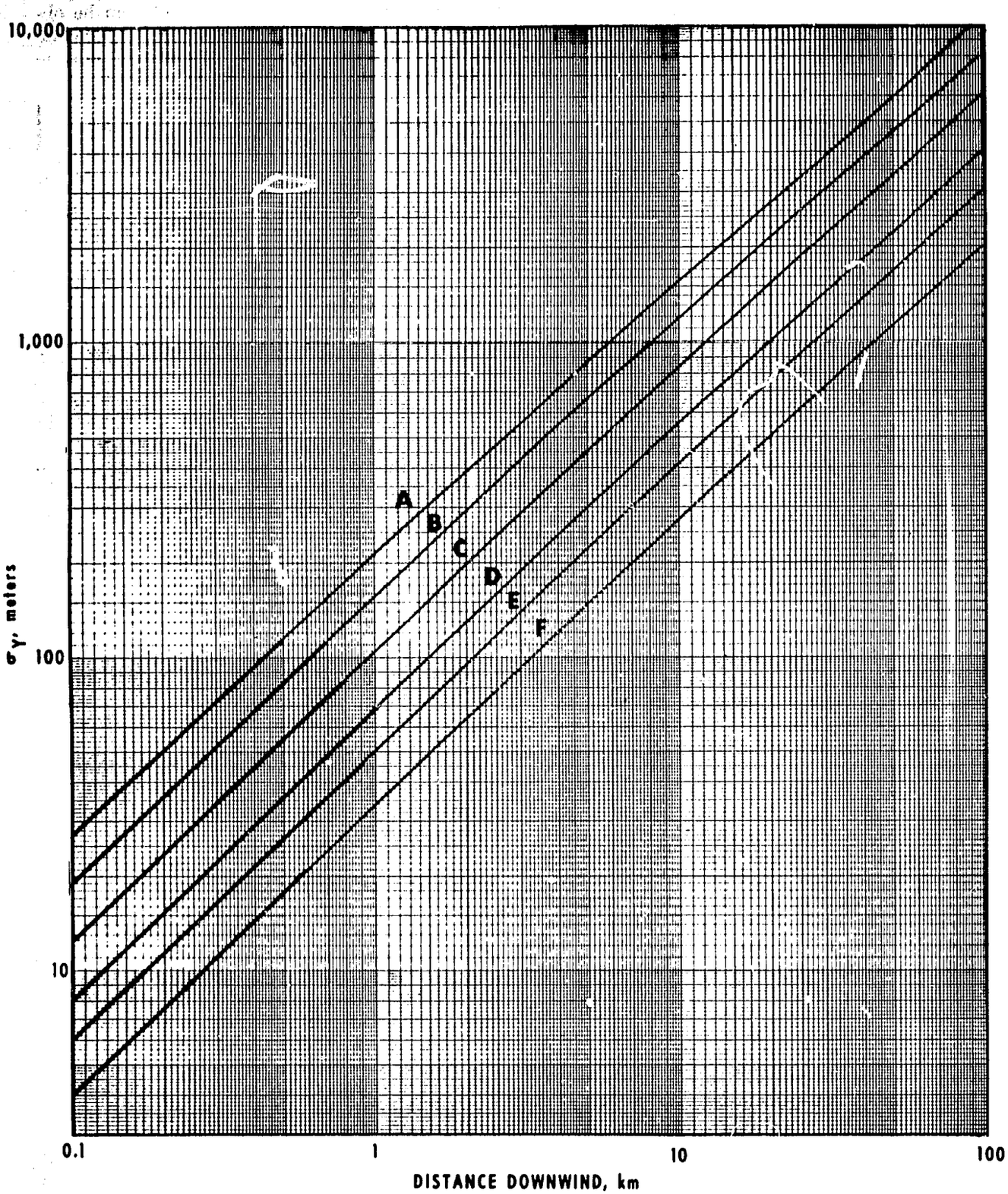

Figure 3-2. Horizontal dispersion coefficient as a function of downwind distance from the source.

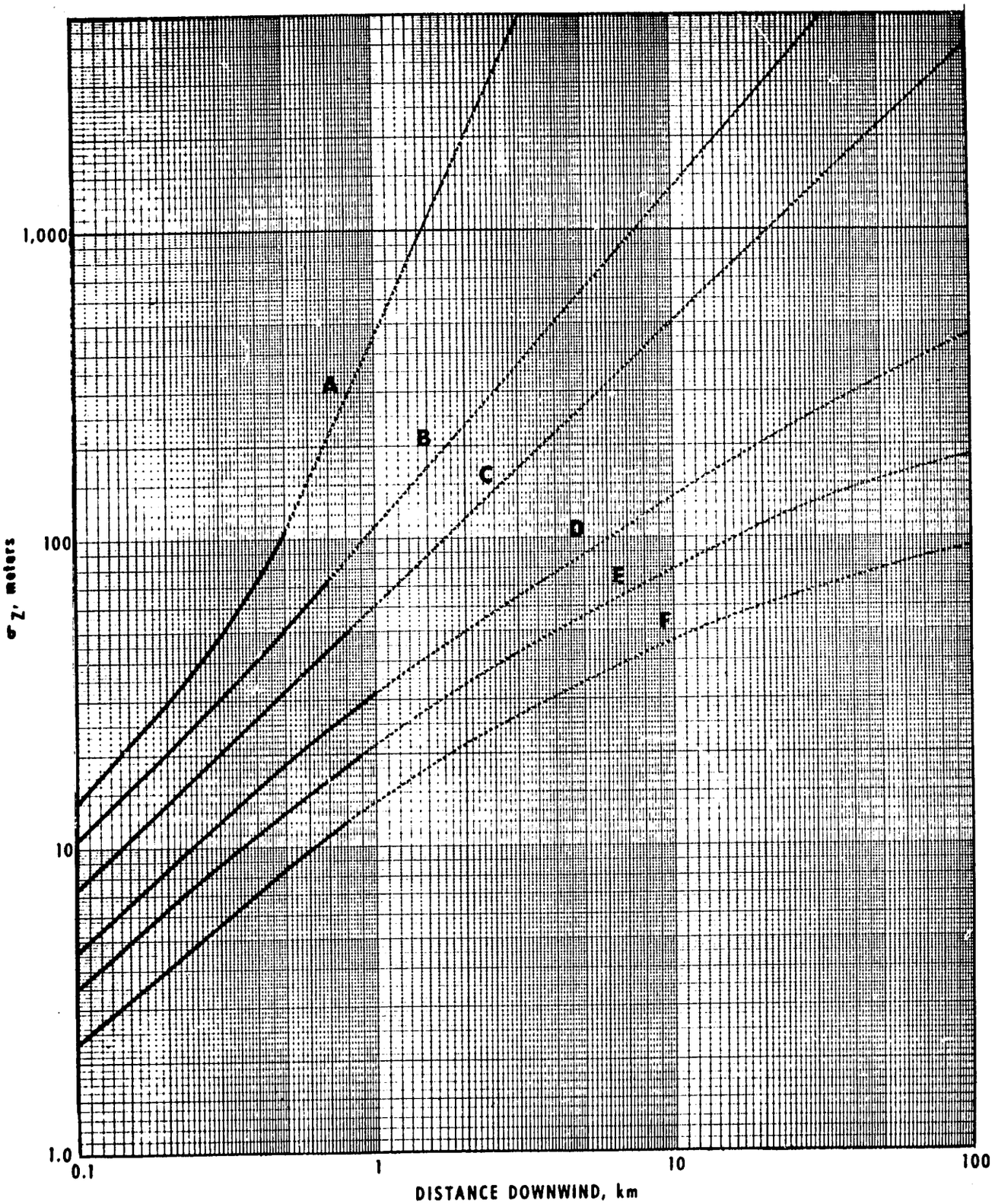

Figure 3-3. Vertical dispersion coefficient as a function of downwind distance from the source.

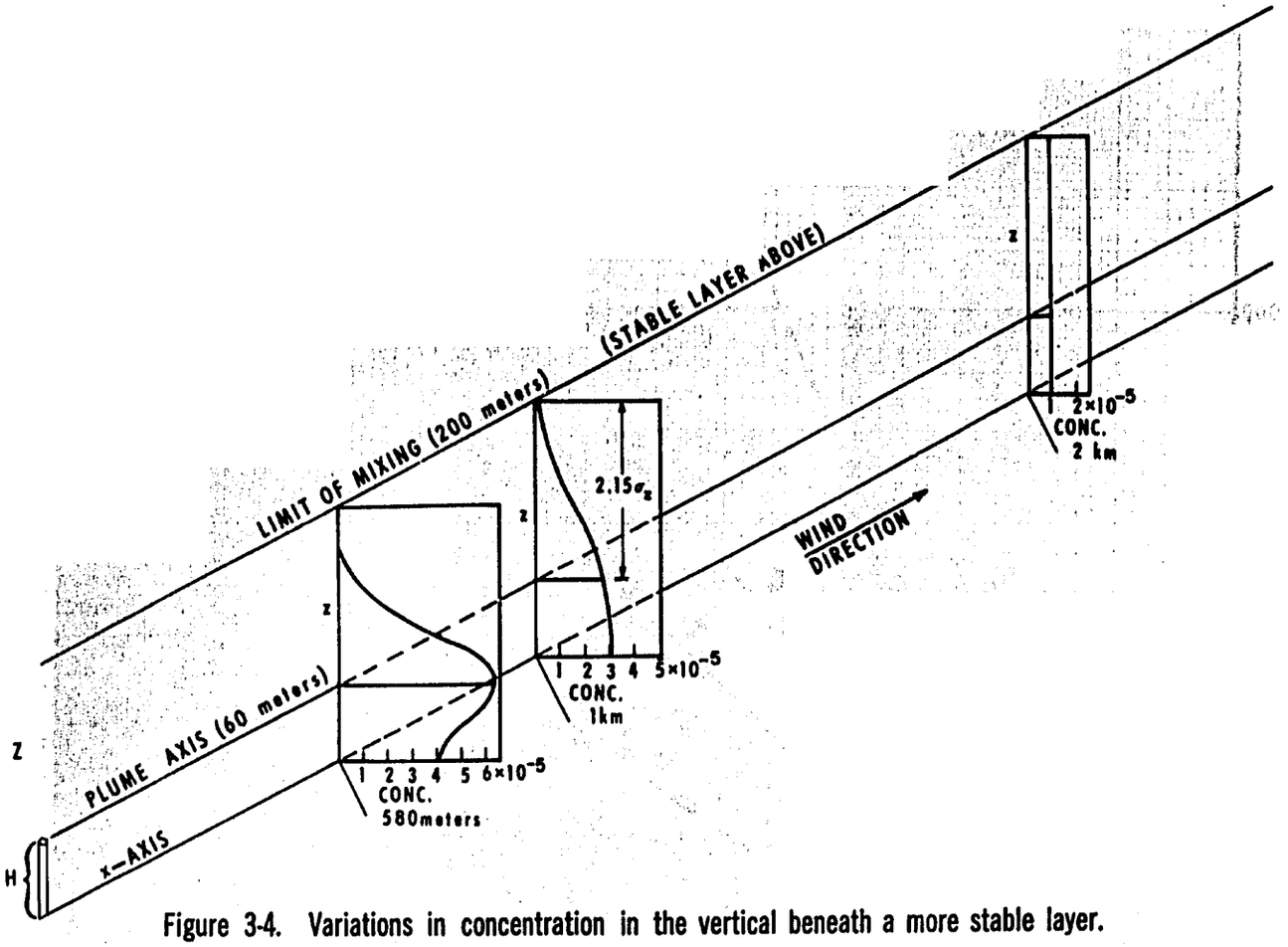

Figure 3-4. Variations in concentration in the vertical beneath a more stable layer.

three cases (where σ_z can be expected to be within a factor of 2) should be correct within a factor of 3, including errors in σ_y and u. The relative confidence in the σ's (in decreasing order) is indicated by the heavy lines and dashed lines in Figures 3-2 and 3-3.

Estimates of H, the effective height of the plume, may be in error because of uncertainties in the estimation of ΔH, the plume rise. Also, for problems that require estimates of concentration at a specific point, the difficulty of determining the mean wind over a given time interval and consequently the location of the x-axis can cause considerable uncertainty.

GRAPHS FOR ESTIMATES OF DIFFUSION

To avoid repetitious computations, Figure 3-5 (A through F) gives relative ground-level concentrations times wind speed (χ u/Q) against downwind distances for various effective heights of emission and limits to the vertical mixing for each stability class (1 figure for each stability). Computations were made from Eq. (3.3), (3.4), and (3.5). Estimates of actual concentrations may be determined by multiplying ordinate values by Q/u.

PLOTTING GROUND-LEVEL CONCENTRATION ISOPLETHS

Often one wishes to determine the locations where concentrations equal or exceed a given magnitude. First, the axial position of the plume must be determined by the mean wind direction. For plotting isopleths of ground-level concentrations, the relationship between ground-level centerline concentrations and ground-level off-axis concentrations can be used:

$$\frac{\chi\,(x,y,0;H)}{\chi\,(x,0,0;H)} = \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \qquad (3.7)$$

The y coordinate of a particular isopleth from the x-axis can be determined at each downwind distance, x. Suppose that one wishes to know the off-axis distance to the 10^{-3} g m^{-3} isopleth at an x of 600 m, under stability type B, where the ground-level centerline concentration at this distance is 2.9 x 10^{-3} g m^{-3}.

$$\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] = \frac{\chi\,(x,y,0;H)}{\chi\,(x,0,0;H)} = \frac{10^{-3}}{2.9 \times 10^{-3}} = 0.345$$

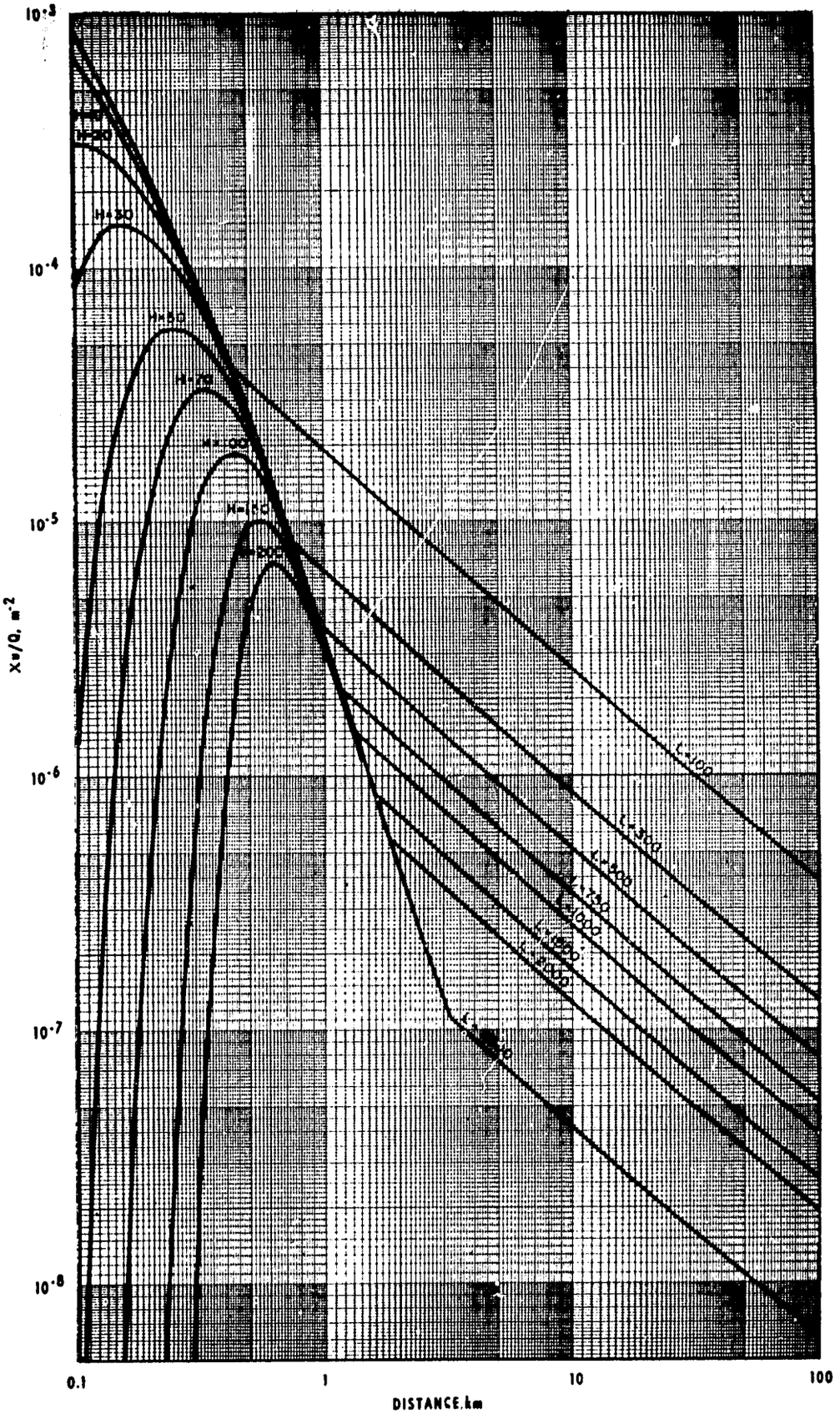

Figure 3-5A. xu/Q with distance for various heights of emission (H) and limits to vertical dispersion (L), A stability.

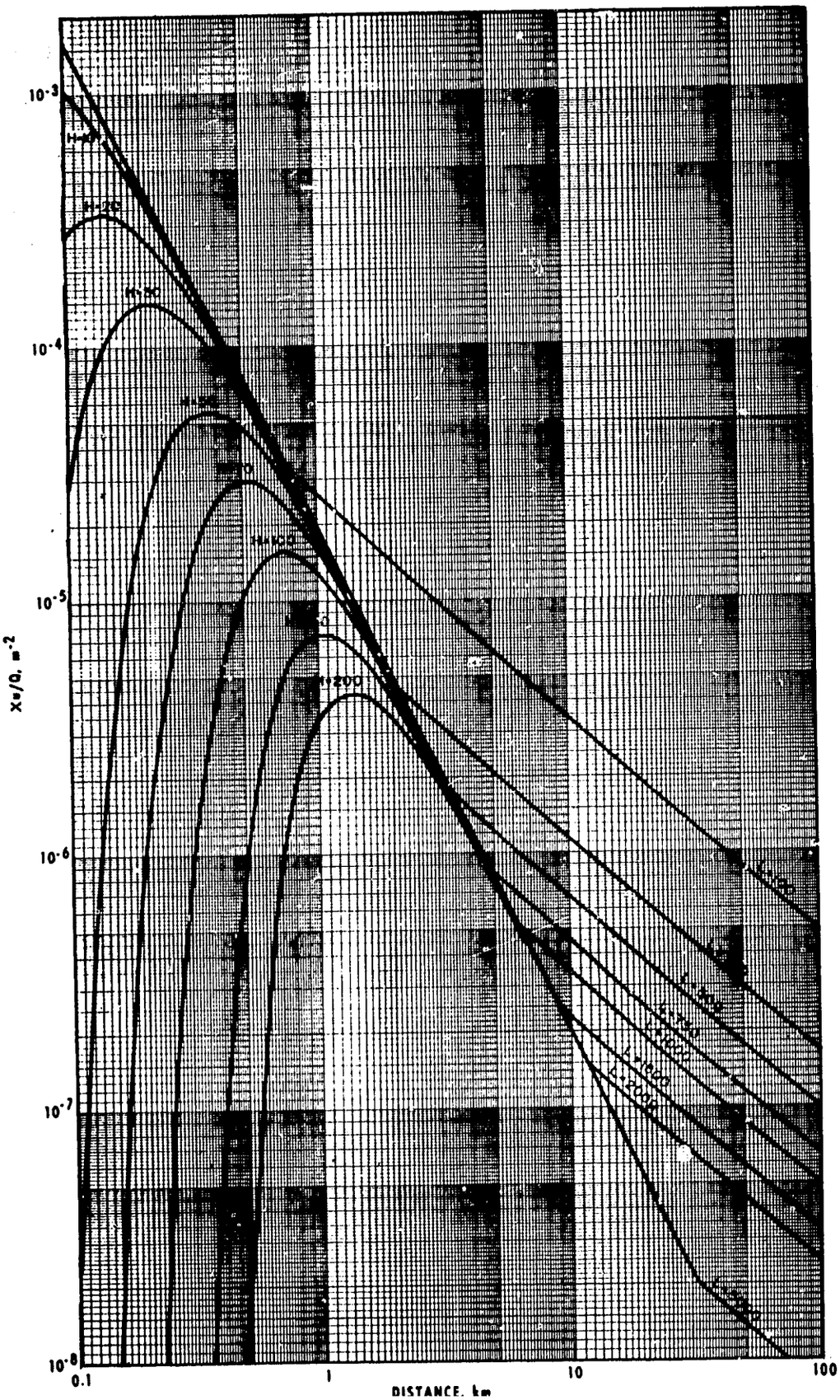

Figure 3-5B. xu/Q with distance for various heights of emission (H) and limits to vertical dispersion (L), B stability.

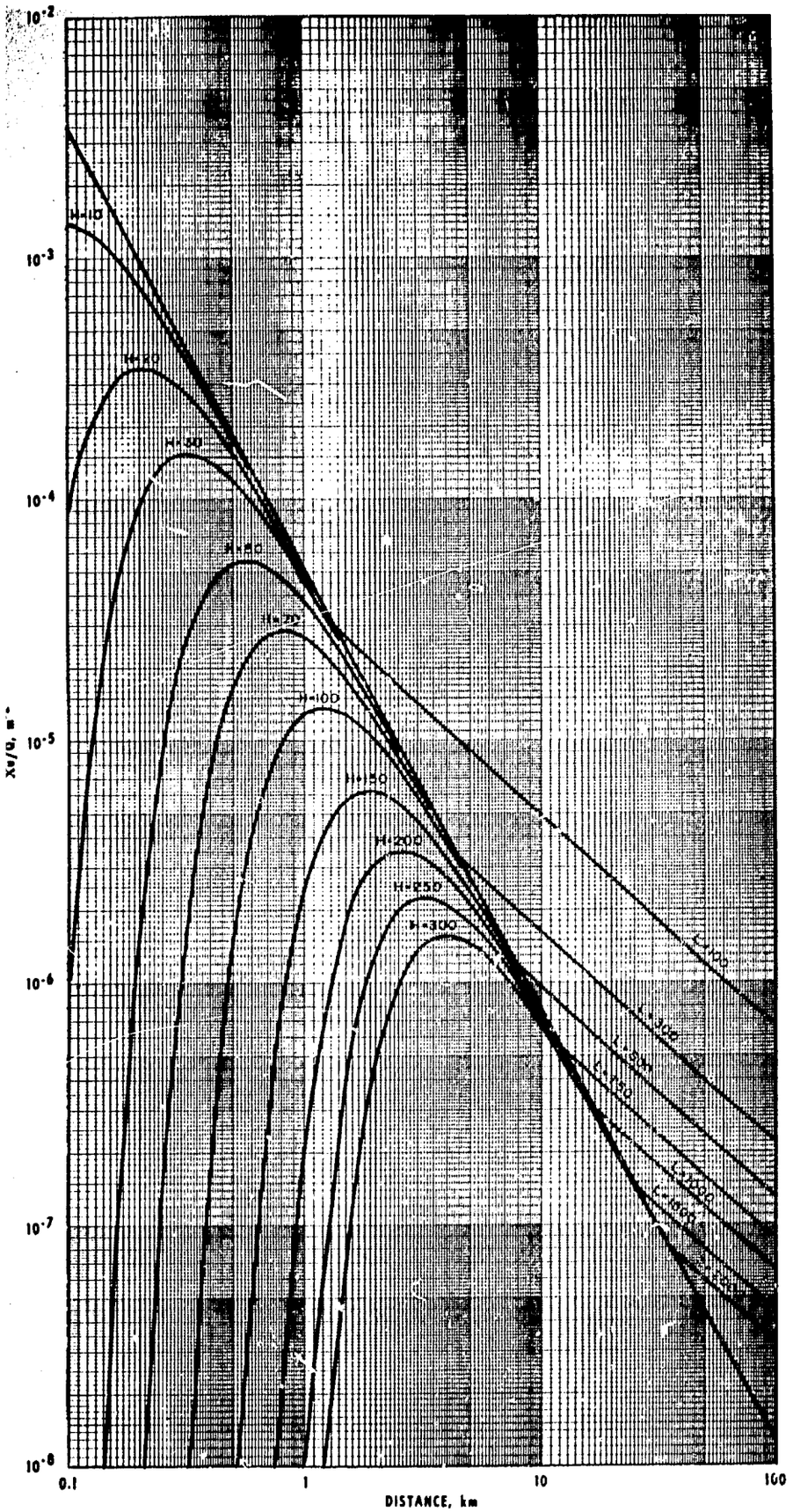

Figure 3-5C. xu/Q with distance for various heights of emission (H) and limits to vertical dispersion (L), C stability.

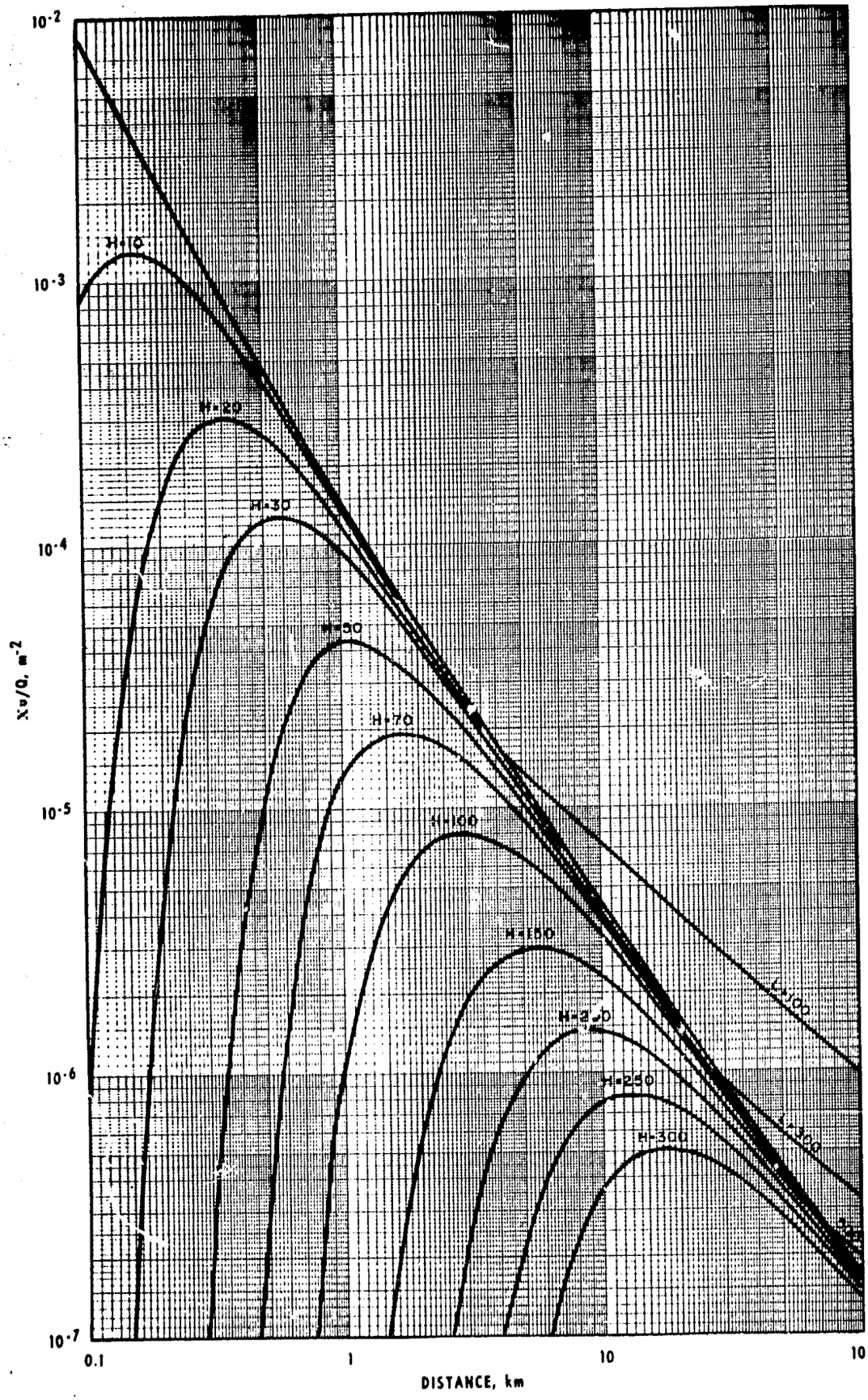

Figure 3-5D. xu Q with distance for various heights of emission (H) and limits to vertical dispersion (L), D stability.

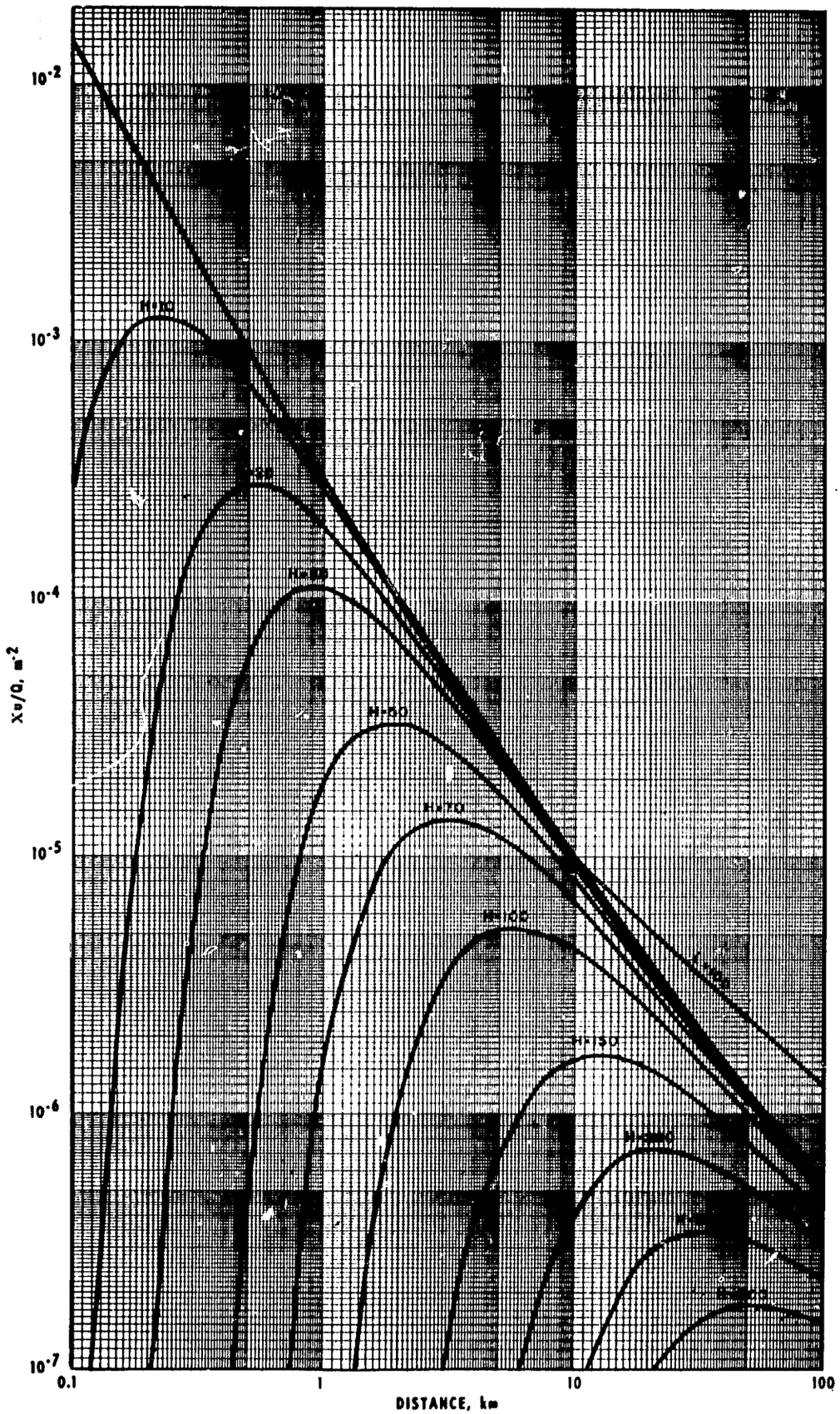

Figure 3-5E. xu/Q with distance for various heights of emission (H) and limits to vertical dispersion (L), E stability.

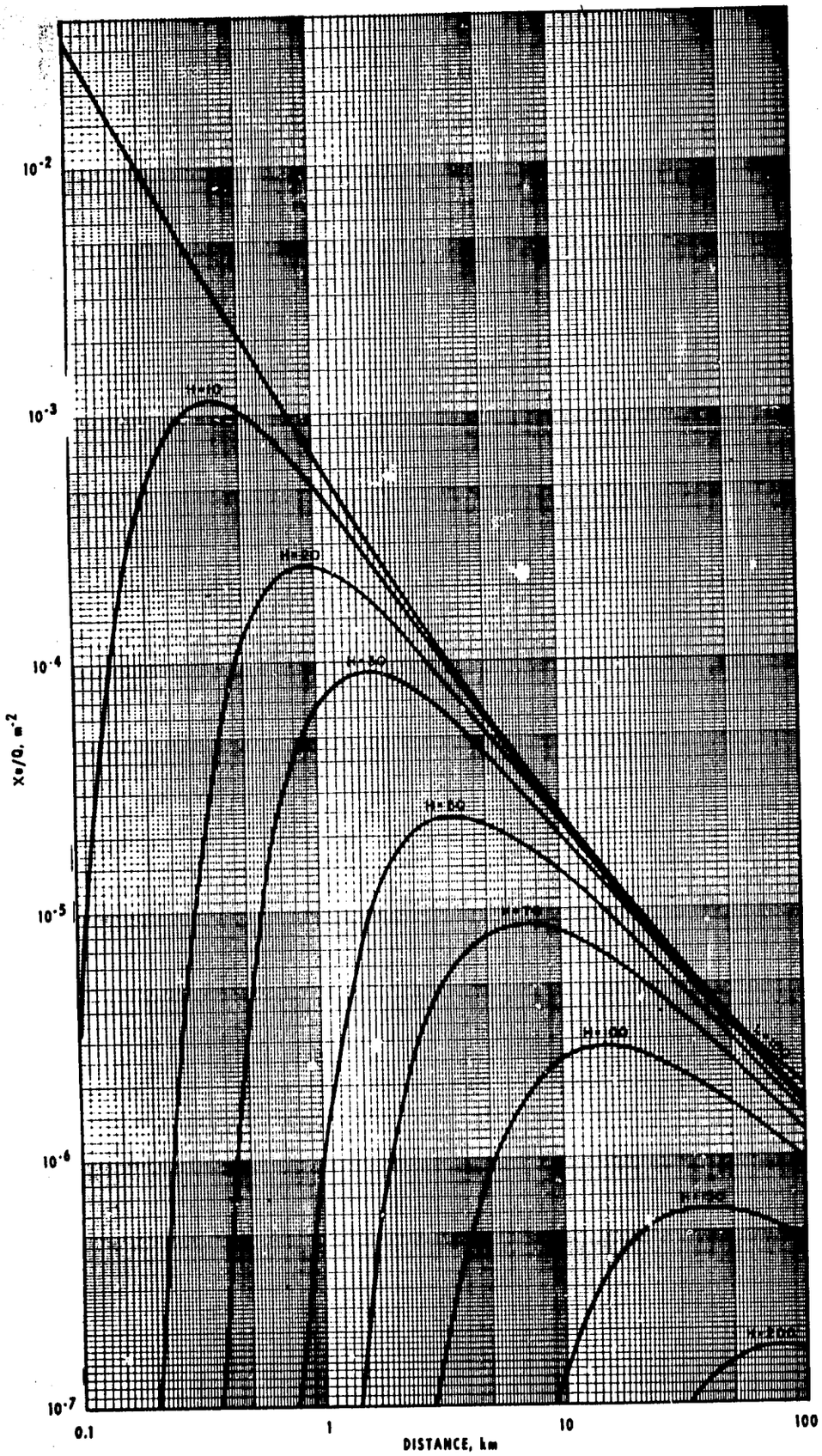

Figure 3-5F. xu/Q with distance for various heights of emission (H) and limits to vertical dispersion (L), F stability.

From Table A-1 (Appendix 3) when exp

$$\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] = 0.345,\ y/\sigma_y = 1.46$$

From Figure 3-2, for stability B and x = 600 m, σ_y = 92. Therefore y = (1.46) (92) = 134 meters. This is the distance of the 10^{-3} isopleth from the x-axis at a downwind distance of 600 meters.

This can also be determined from:

$$y = \left\{2 \ln^* \left[\frac{\chi\,(x,0,0;H)}{\chi\,(x,y,0;H)}\right]\right\}^{1/2} \sigma_y \qquad (3.8)$$

The position corresponding to the downwind distance and off-axis distance can then be plotted. After a number of points have been plotted, the concentration isopleth may be drawn (see problems 8 and 26). Figures 3-6 and 3-7 give ground-level isopleths of $\chi u/Q$ for various stabilities for sources at H = 0 and H = 100 meters. For example, to locate the 10^{-3} g m^{-3} isopleth resulting from a ground-level source of 20 g sec^{-1} under B stability conditions with wind speed 2 m sec^{-1}, one must first determine the corresponding value of $\chi u/Q$ since this is the quantity graphed in Figure 3-6. $\chi u/Q = 10^{-3} \times 2/20 = 10^{-4}$. Therefore the $\chi u/Q$ isopleth in Figure 3-6B having a value of 10^{-4} m^{-2} corresponds to a χ isopleth with a value of 10^{-3} g m^{-3}

AREAS WITHIN ISOPLETHS

Figure 3-8 gives areas within isopleths of ground-level concentration in terms of χ u/Q for a ground-level source for various stability categories (Gifford, 1962; Hilsmeier and Gifford, 1962). For the example just given, the area of the 10^{-3} g m^{-3} isopleth (10^{-4} m^{-2} χ u/Q isopleth) is about 5 x 10^4 $meter^2$.

CALCULATION OF MAXIMUM GROUND-LEVEL CONCENTRATIONS

Figure 3-9 gives the distance to the point of maximum concentration, x_{max}, and the relative maximum concentration, χ u/Q_{max}, as a function of effective height of emission and stability class (Martin, 1965). This figure was prepared from graphs of concentration versus distance, as in Figure 3-5. The maximum concentration can be determined by finding χ u/Q as a function of effective emission height and stability and multiplying by Q/u. In using Figure 3-9, the user must keep in mind that the dispersion at higher levels may differ considerably from that determined by the σ_y's and σ_z's used here. As noted, however, since σ_y generally decreases with height and u increases with height, the product u σ_y σ_z will not change appreciably. The greater the effective height, the more likely it is that the stability may not be the same from the ground to this height. With the longer travel distances such as the points of maximum concentrations for stable conditions (Types E or F), the stability may change before the plume travels the entire distance.

*"ln" denotes natural logarithms, i.e., to the base e.

REVIEW OF ASSUMPTIONS

The preceding has been based on these assumptions, which should be clearly understood:

(i) Continuous emission from the source or emission times equal to or greater than travel times to the downwind position under consideration, so that diffusion in the direction of transport may be neglected.

(ii) The material diffused is a stable gas or aerosol (less than 20 microns diameter) which remains suspended in the air over long periods of time.

(iii) The equation of continuity:

$$Q = \int_0^{+\infty} \int_{-\infty}^{+\infty} \chi\, u\, dy\, dz \qquad (3.9)$$

is fulfilled, i.e., none of the material emitted is removed from the plume as it moves downwind and there is complete reflection at the ground.

(iv) The mean wind direction specifies the x-axis, and a mean wind speed representative of the diffusing layer is chosen.

(v) Except where specifically mentioned, the plume constituents are distributed normally in both the cross-wind and vertical directions.

(vi) The σ's given in Figures 3-2 and 3-3 represent time periods of about 10 minutes.

REFERENCES

DeMarrais, G. A., 1961: Vertical temperature difference observed over an urban area. Bull. Amer. Meteorol. Soc., *42*, 8, 548-554.

Duckworth, F. S., and J. S. Sandberg, 1954: The effect of cities upon horizontal and vertical temperature gradients. Bull. Amer. Meteorol. Soc., *35*, 5, 198-207.

Gifford, F. A., 1961: Use of routine meteorological observations for estimating atmospheric dispersion. Nuclear Safety, *2*, 4, 47-51.

Gifford, F. A., 1962: The area within ground-level dosage isopleths. Nuclear Safety, *4*, 2, 91-92.

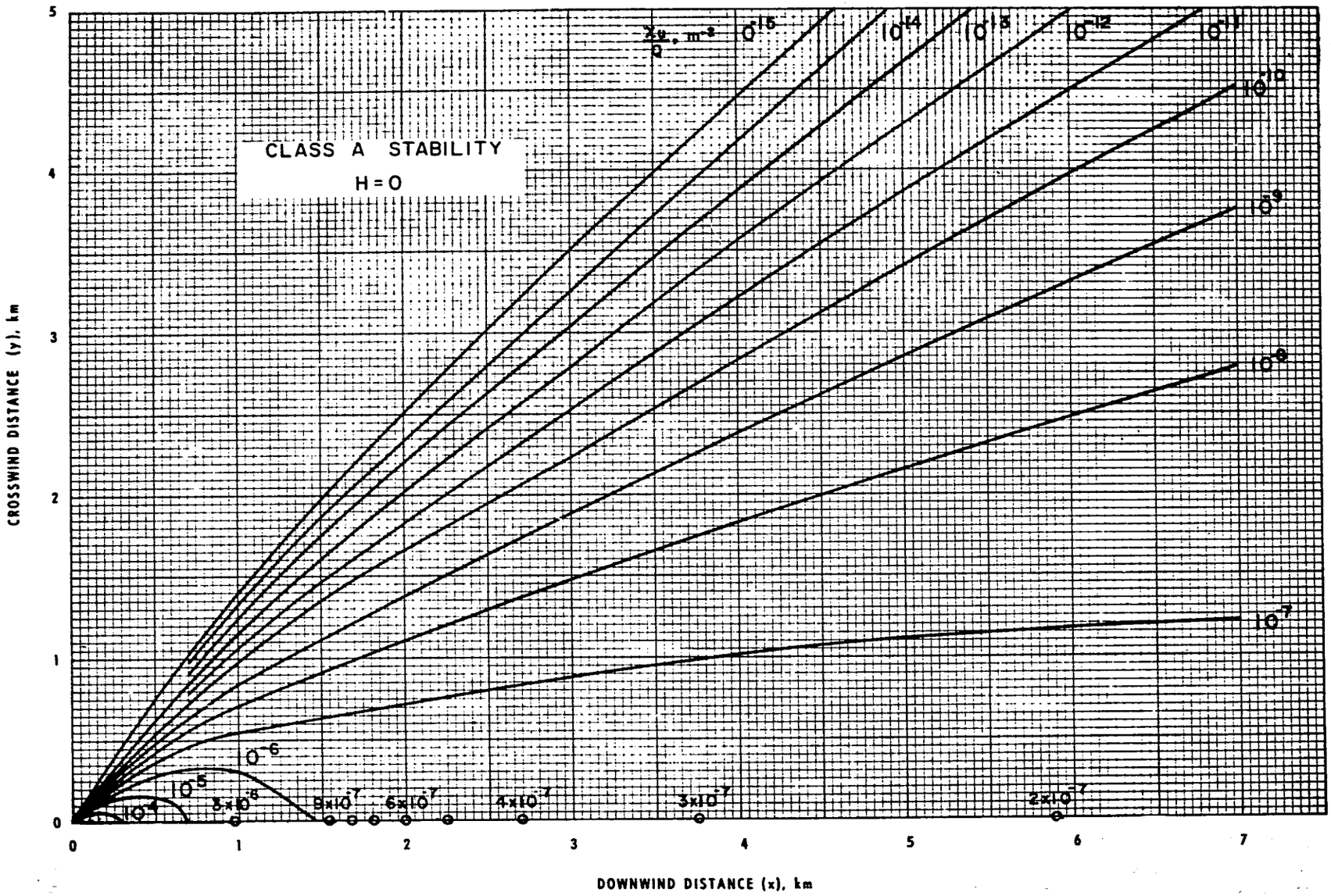

Figure 3-6A. Isopleths of xu/Q for a ground-level source, A stability.

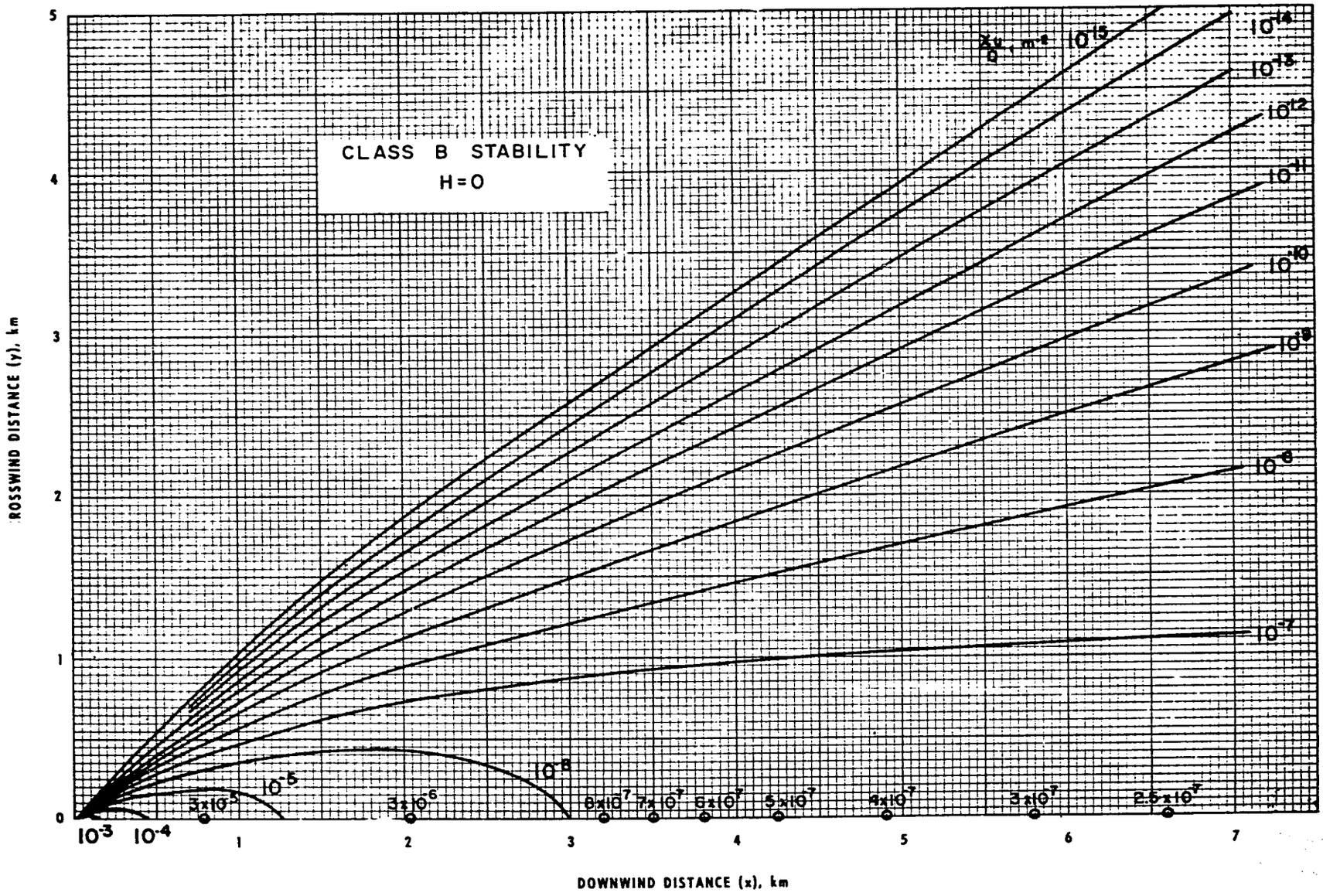

Figure 3-6B. Isopleths of xu/Q for a ground-level source, B stability.

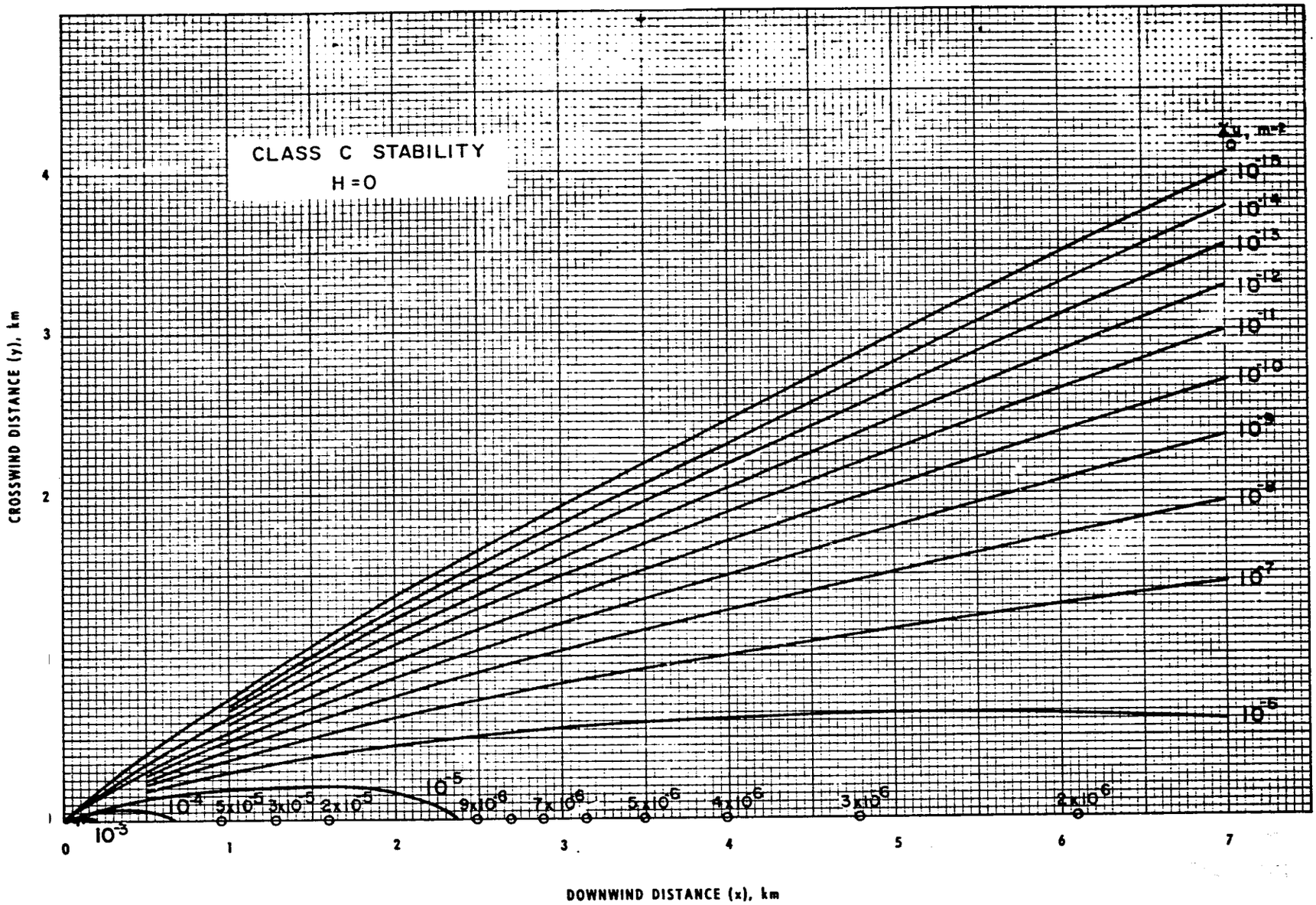

Figure 3-6C. Isopleths of xu/Q for a ground-level source, C stability.

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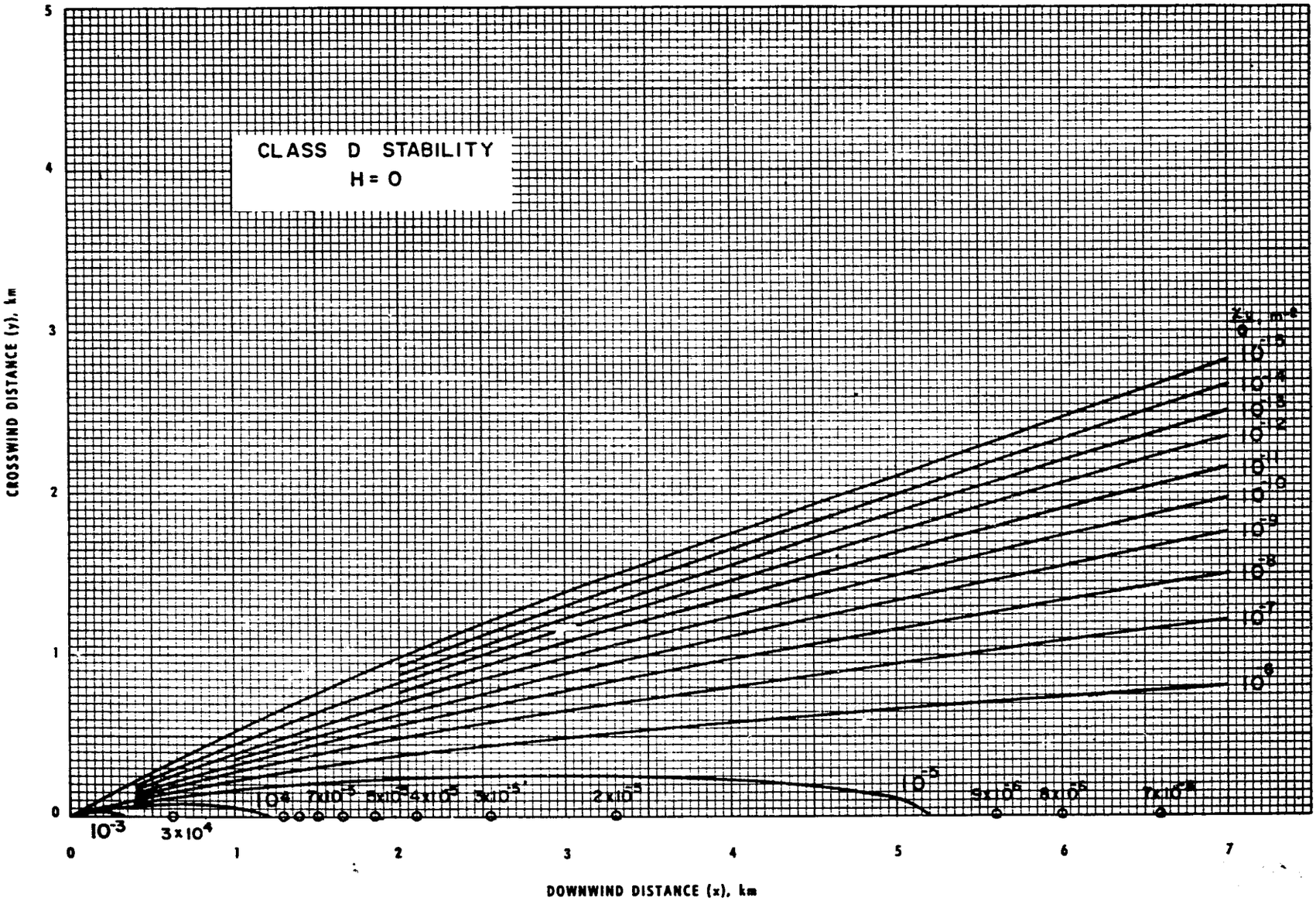
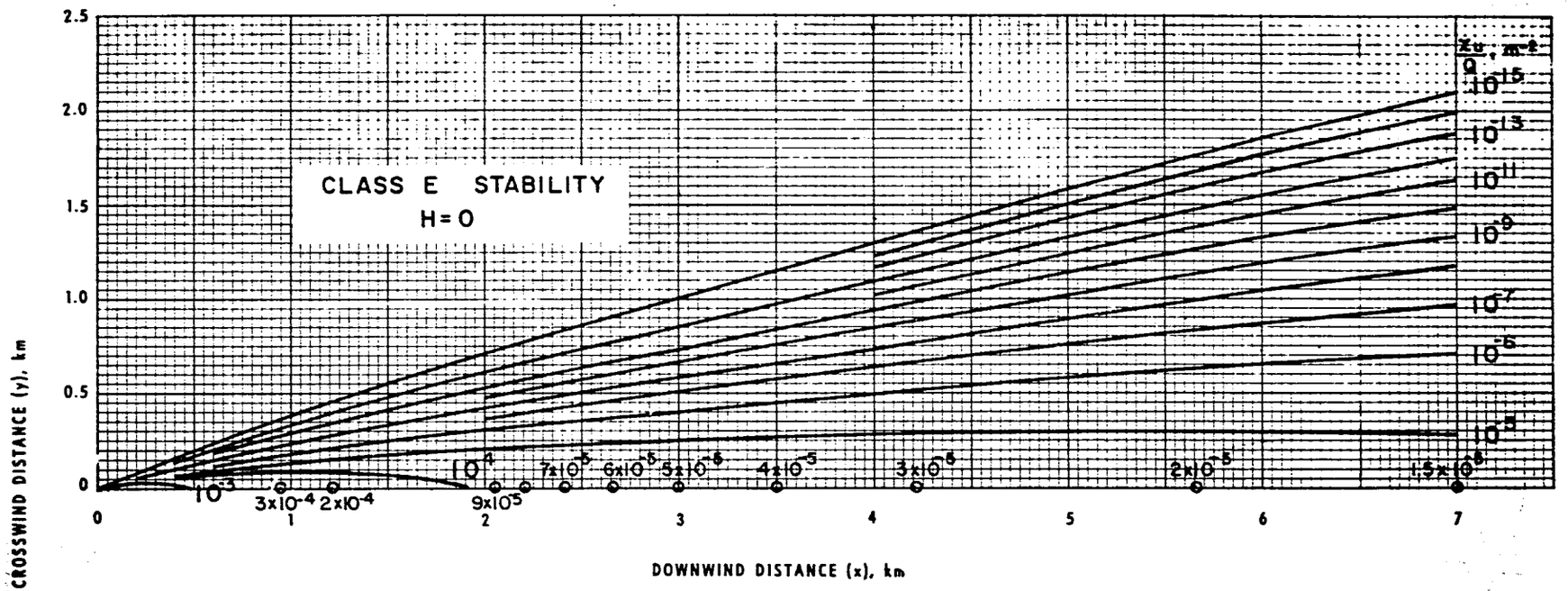


Figure 3-6D. Isopleths of xu/Q for a ground-level source, D stability.



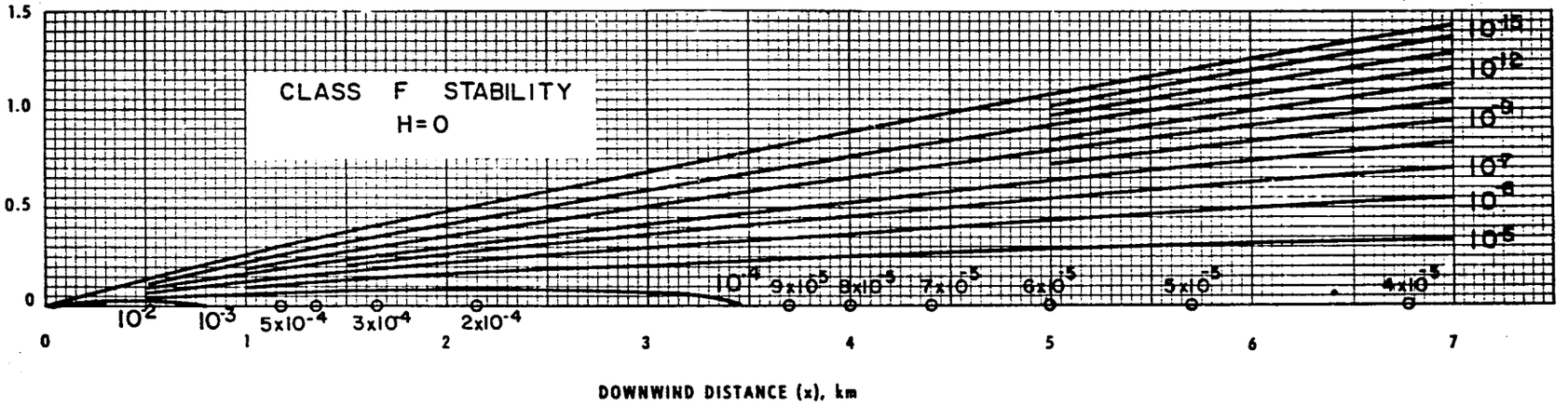


Figure 3-6E, F. Isopleths of xu/Q for a ground-level source, E and F stabilities.

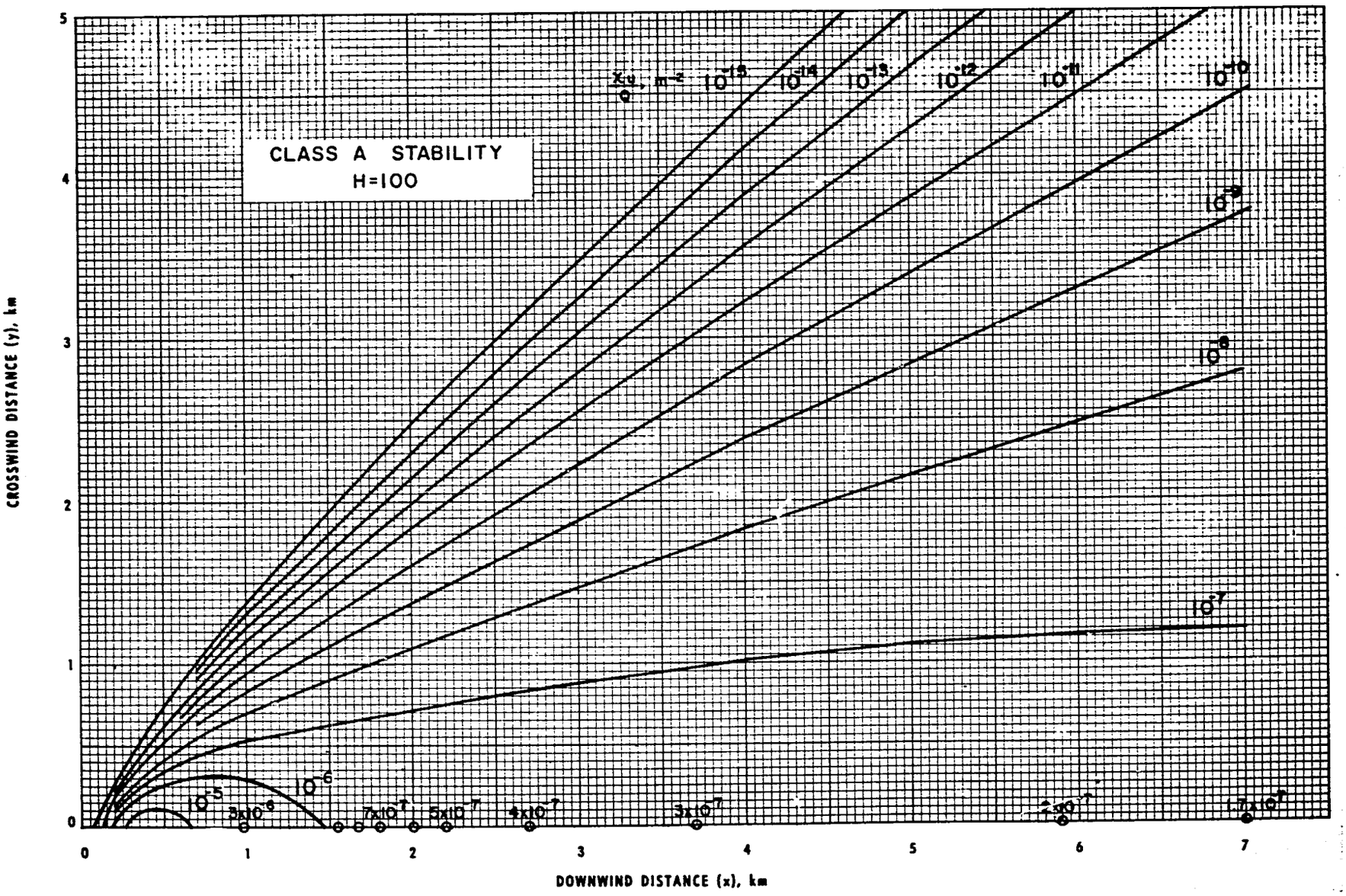


Figure 3-7A. Isopleths of χu/Q for a source 100 meters high, A stability.

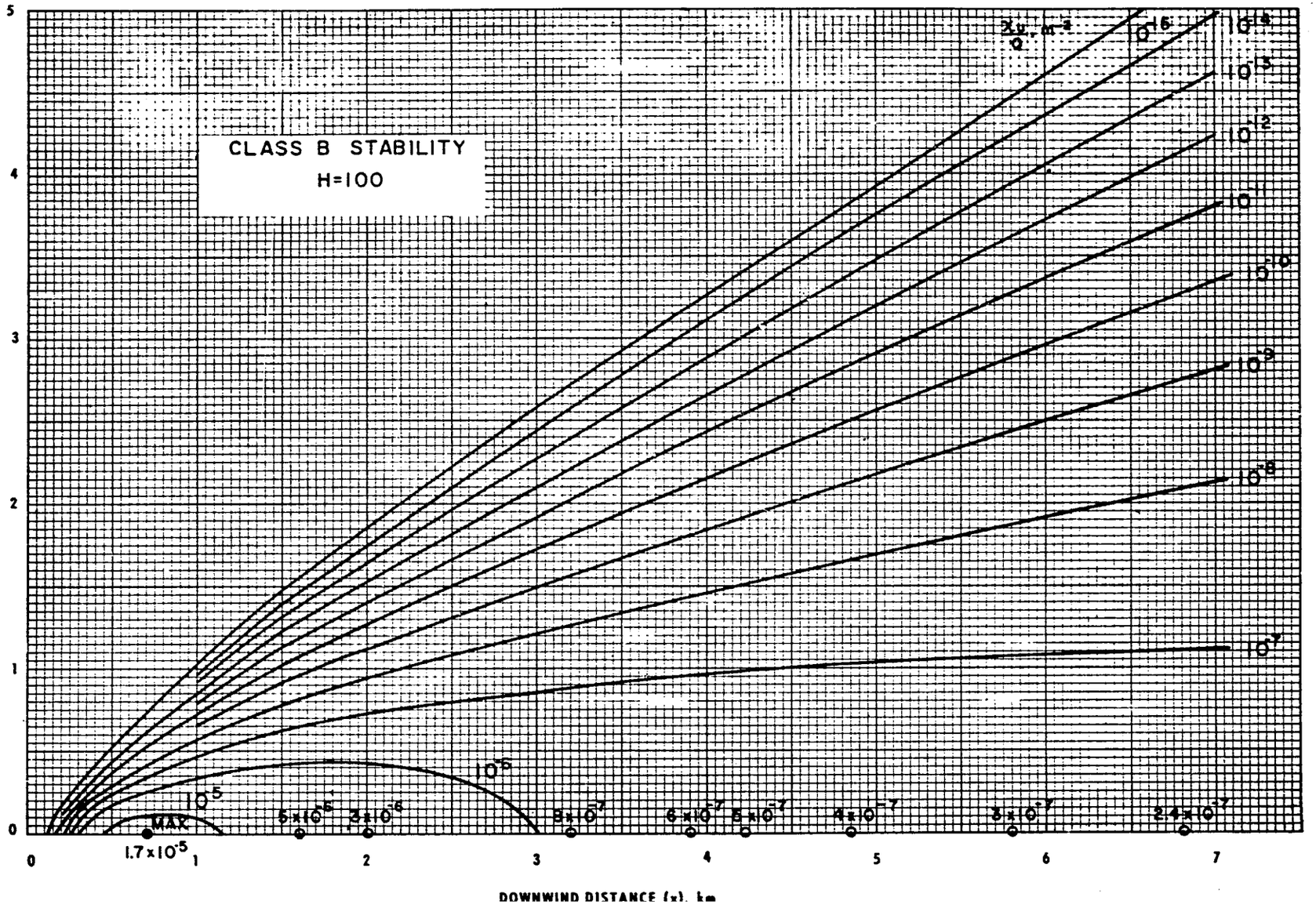


Figure 3-7B. Isopleths of $\chi u/Q$ for a source 100 meters high, B stability.

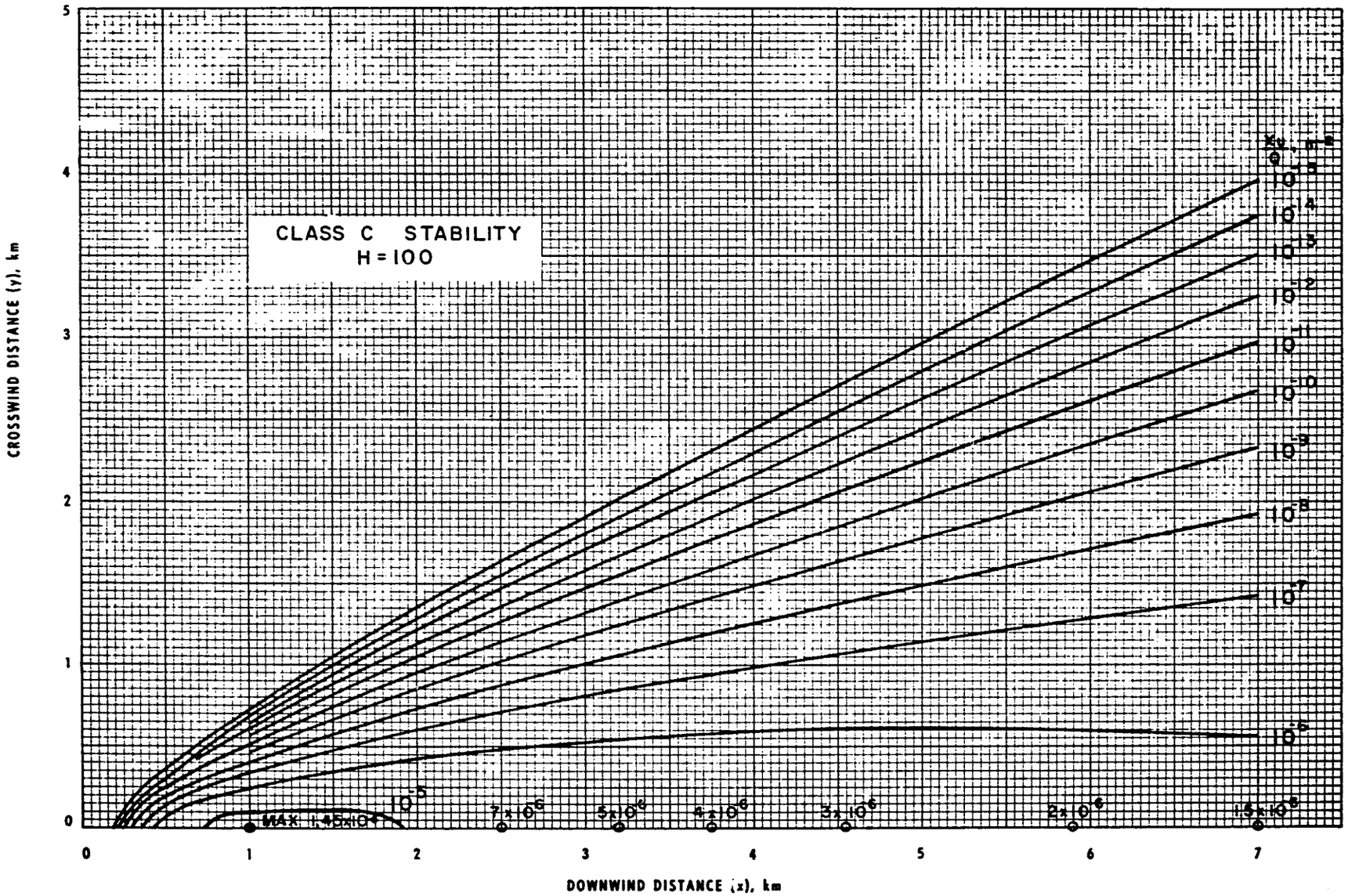


Figure 3-7C. Isopleths of xu/Q for a source 100 meters high, C stability.

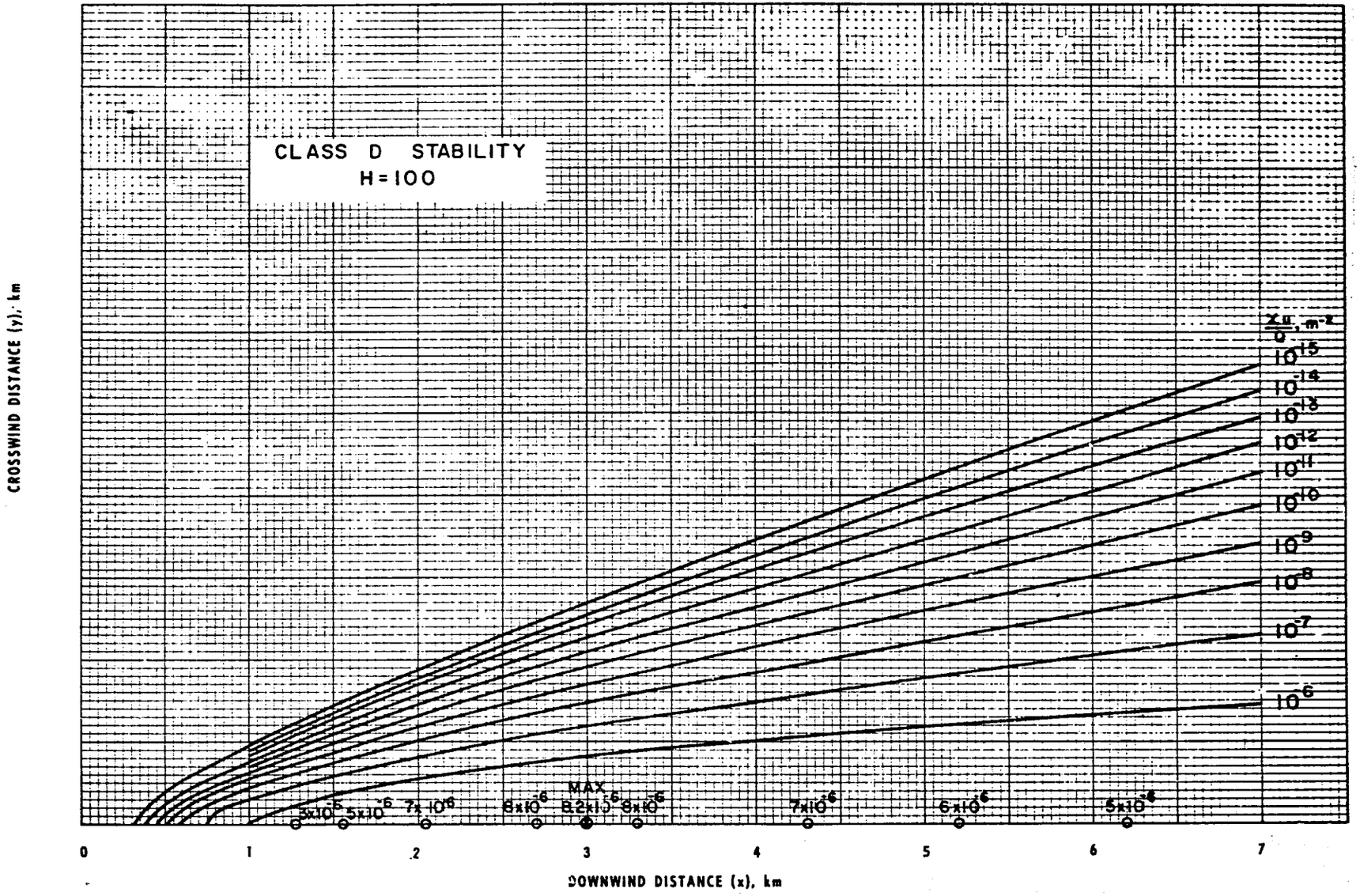


Figure 3-7D. Isopleths of xu/Q for a source 100 meters high, D stability.

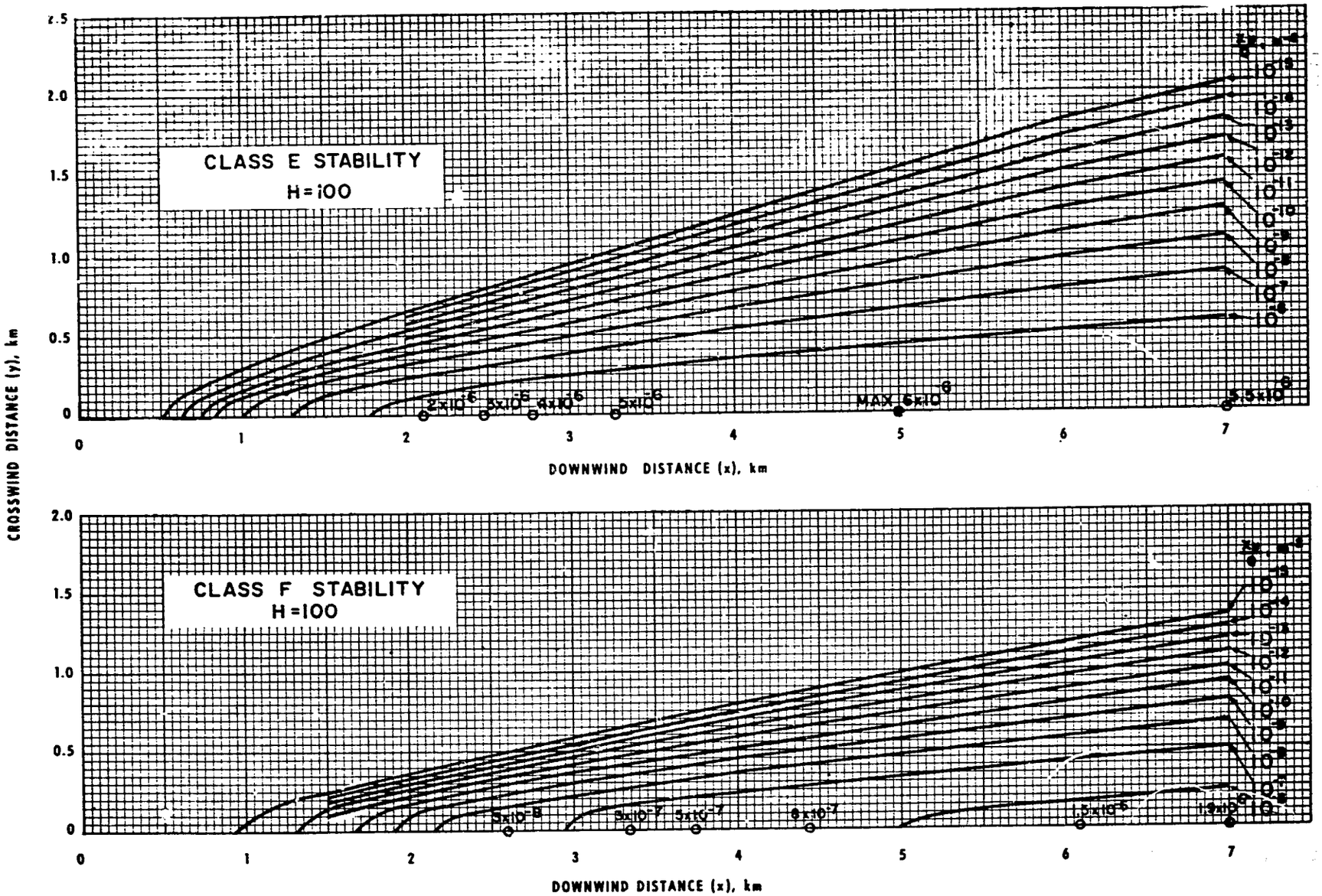


Figure 3-7E, F. Isopleths of xu/Q for a source 100 meters high, E and F stabilities.

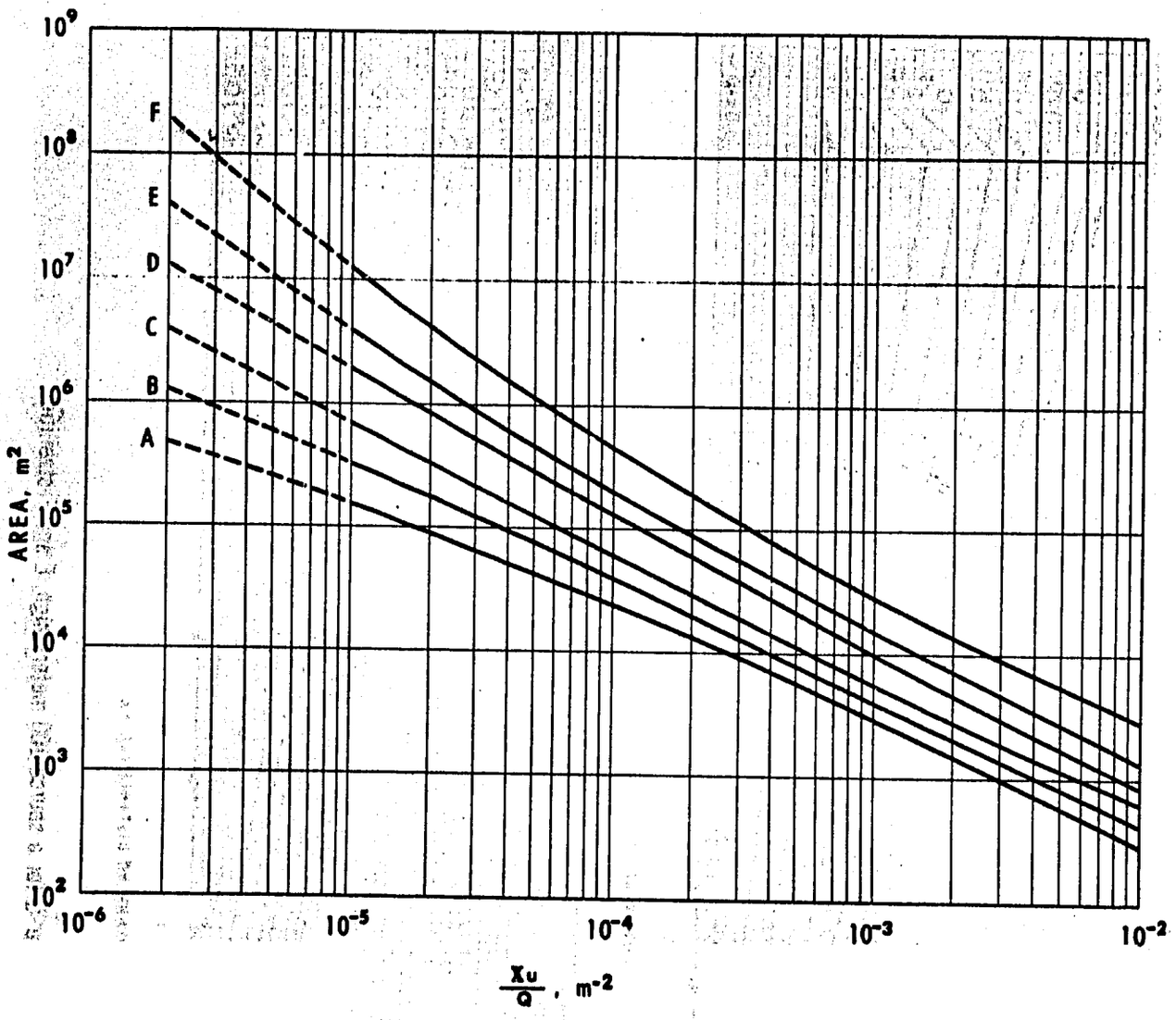


Figure 3-8. Area within isopleths for a ground-level source (from Hilsmeier and Gifford).

Hilsmeier, W. F., and F. A. Gifford, 1962: Graphs for estimating atmospheric diffusion. ORO-545, Oak Ridge, Tenn. Atomic Energy Commission, 10 pp.

List, R. J., 1951: *Smithsonian Meteorological Tables*, Sixth Revised Edition, 497-505, Washington, D. C., Smithsonian Institution, 527 pp.

Martin, D. O., 1965: Personal communication.

Pasquill, F., 1961: The estimation of the dispersion of windborne material. Meteorol. Mag., *90*, 1063, 33-49.

Pooler, F., 1965: Personal communication.

Sutton, O. G., 1953: *Micrometeorology*, New York, McGraw-Hill. 333 pp.

Turner, D. B., 1961: Relationships between 24-hour mean air quality measurements and meteorological factors in Nashville, Tennessee. J. Air Poll. Cont. Assoc., *11*, 483-489.

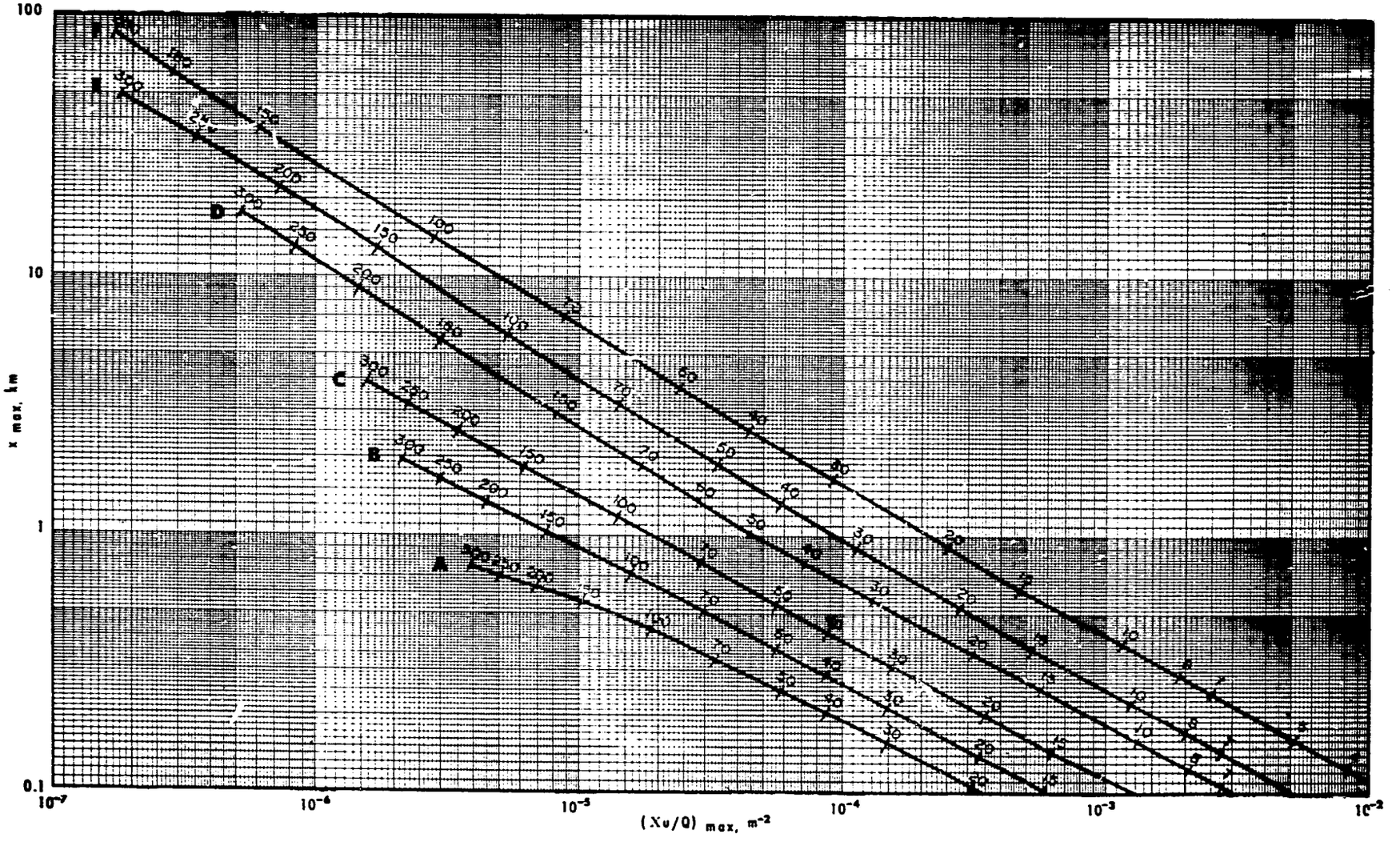


Figure 3-9. Distance of maximum concentration and maximum xu/Q as a function of stability (curves) and effective height (meters) of emission (numbers).

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Chapter 4 — EFFECTIVE HEIGHT OF EMISSION

GENERAL CONSIDERATIONS

In most problems one must estimate the effective stack height, H, at which the plume becomes essentially level. Rarely will this height correspond to the physical height of the stack, h. If the plume is caught in the turbulent wake of the stack or of buildings in the vicinity of the stack, the effluent will be mixed rapidly downward toward the ground (aerodynamic downwash). If the plume is emitted free of these turbulent zones, a number of emission factors and meteorological factors influence the rise of the plume. The emission factors are: velocity of the effluent at the top of the stack, v_s; temperature of the effluent at the top of the stack, T_s; and diameter of the stack opening, d. The meteorological factors influencing plume rise are wind speed, u; temperature of the air, T_a; shear of the wind speed with height, du/dz; and atmospheric stability. No theory on plume rise takes into account all of these variables; even if such a theory were available, measurements of all of the parameters would seldom be available. Most of the equations that have been formulated for computing the effective height of emission are semi-empirical. For a recent review of equations for effective height of emission see Moses, Strom, and Carson (1964).

Moses and Strom (1961), having compared actual and calculated plume heights by means of six plume rise equations, report "There is no one formula which is outstanding in all respects." The formulas of Davidson-Bryant (1949), Holland (1953), Bosanquet-Carey-Halton (1950), and Bosanquet (1957) all give generally satisfactory results in the test situations. The experiments conducted by Moses and Strom involved plume rise from a stack of less than 0.5 meter diameter, stack gas exit velocities less than 15 m sec^{-1}, and effluent temperature not more than 35°C higher than that of the ambient air.

The equation of Holland was developed with experimental data from larger sources than those of Moses and Strom (stack diameters from 1.7 to 4.3 meters and stack temperatures from 82 to 204°C); Holland's equation is used in the solution of the problems given in this workbook. This equation frequently underestimates the effective height of emission; therefore its use often provides a slight "safety" factor.

Holland's equation is:

$$\Delta H = \frac{v_s d}{u} \left(1.5 + 2.68 \times 10^{-3} p \frac{T_s - T_a}{T_s} d\right) \quad (4.1)$$

where:

ΔH = the rise of the plume above the stack, m

v_s = stack gas exit velocity, m sec^{-1}

d = the inside stack diameter, m

u = wind speed, m sec^{-1}

p = atmospheric pressure, mb

T_s = stack gas temperature, °K

T_a = air temperature, °K

and 2.68×10^{-3} is a constant having units of mb^{-1} m^{-1}.

Holland (1953) suggests that a value between 1.1 and 1.2 times the ΔH from the equation should be used for unstable conditions; a value between 0.8 and 0.9 times the ΔH from the equation should be used for stable conditions.

Since the plume rise from a stack occurs over some distance downwind, Eq. (4.1) should not be applied within the first few hundred meters of the stack.

EFFECTIVE HEIGHT OF EMISSION AND MAXIMUM CONCENTRATION

If the effective heights of emission were the same under all atmospheric conditions, the highest ground-level concentrations from a given source would occur with the lightest winds. Generally, however, emission conditions are such that the effective stack height is an inverse function of wind speed as indicated in Eq. (4.1). The maximum ground-level concentration occurs at some intermediate wind speed, at which a balance is reached between the dilution due to wind speed and the effect of height of emission. This critical wind speed will vary with stability. In order to determine the critical wind speed, the effective stack height as a function of wind speed should first be determined. The maximum concentration for each wind speed and stability can then be calculated from Figure 3-9 as a function of effective height of emission and stability. When the maximum concentration as a function of wind speed is plotted on log-log graph paper, curves can be drawn for each stability class; the critical wind speed corresponds to the point of highest maximum concentration on the curve (see problem 14).

ESTIMATES OF REQUIRED STACK HEIGHTS

Estimates of the stack height required to produce concentrations below a given value may be made through the use of Figure 3-9 by obtaining solutions for various wind speeds. Use of this figure considers maximum concentrations at any distance from the source.

In some situations high concentrations upon the property of the emitter are of little concern, but

maximum concentrations beyond the property line are of the utmost importance. For first approximations it can be assumed that the maximum concentration occurs where $\sqrt{2}\,\sigma_z = H$ and that at this distance the σ's are related to the maximum concentration by:

$$\sigma_y\,\sigma_z \sim \frac{Q}{\pi\,u\,e\,\chi_{max}} \simeq \frac{0.117\,Q}{u\,\chi_{max}} \qquad (4.2)$$

Knowing the source strength, Q, and the concentration not to be exceeded χ_{max}, one can determine the necessary $\sigma_y\,\sigma_z$ for a given wind speed. Figure 4-1 shows $\sigma_y\,\sigma_z$ as a function of distance for the various stability classes. The value of $\sigma_y\,\sigma_z$ and a design distance, x_d (the distance beyond which χ is less than some pre-determined value), will determine a point on this graph yielding a stability class or point between classes. The σ_z for this stability (or point between stabilities) can then be determined from Figure 3-3. The required effective stack height for this wind speed can then be approximated by $H = \sqrt{2}\,\sigma_z$ (see problem 15). Since Eq. (4.2) is an approximation, the resulting height should be used with Eq. (3.3) to ensure that the maximum concentration is sufficiently low. If enough is known about the proposed source to allow use of an equation for effective height of emission, the relation between ΔH and u can be determined. The physical stack height required at the wind speed for which H was determined is $H - \Delta H$. The same procedure, starting with the determination of $\sigma_y\,\sigma_z$, must be used with other wind speeds to determine the maximum required physical stack height (see problem 16).

EFFECT OF EVAPORATIVE COOLING

When effluent gases are washed to absorb certain constituents prior to emission, the gases are cooled and become saturated with water vapor. Upon release of the gases from the absorption tower, further cooling due to contact with cold surfaces of ductwork or stack is likely. This cooling causes condensation of water droplets in the gas stream. Upon release of the gases from the stack, the water droplets evaporate, withdrawing the latent heat of vaporization from the air and cooling the plume. The resulting negative buoyancy reduces the effective stack height (Scorer, 1959).

EFFECT OF AERODYNAMIC DOWNWASH

The influence of mechanical turbulence around a building or stack can significantly alter the effective stack height. This is especially true with high winds, when the beneficial effect of high stack-gas velocity is at a minimum and the plume is emitted nearly horizontally. The region of disturbed flow surrounds an isolated building, generally to at least twice its height and extends downwind 5 to 10 times its height. Building the stack 2.5 times the height of the highest building adjacent to the stack usually overcomes the effects of building turbulence (Hawkins and Nonhebel, 1955). Ensuring that the exit velocity of the stack gas is more than 1.5 times the wind speed will usually prevent downwash in the wake of the stack. Most of the knowledge about the turbulent wakes around stacks and buildings has been gained through wind tunnel studies (Sherlock and Lesher, 1954; Strom, 1955-1956; Strom, et al, 1957; and Halitsky, 1962). By use of models of building shapes and stacks, one may determine the wind speeds required to cause downwash for various wind directions. With a wind tunnel the meteorological variables most easily accounted for are wind speed and wind direction (by rotation of the model within the tunnel). The emission factors that may be considered are the size and shape of the plant building; the shape, height, and diameter of the stack; the amount of emission; and the stack-gas velocity.

Through wind tunnel studies, the critical wind speeds that will cause downwash from various directions can be determined for a given set of plant factors. The average number of hours of downwash per year can then be calculated by determining the frequency of wind speeds greater than the critical speeds for each direction (Sherlock and Lesher, 1954) if climatological data representative of the site are available.

Maximum downwash about a rectangular structure occurs when the direction of the wind is at an angle of 45 degrees from the major axis of the structure; minimum downwash occurs with wind flow parallel to the major axis of the structure (Sherlock and Lesher, 1954).

Halitsky (1961, 1963) has shown that the effluent from flush openings on flat roofs frequently flows in a direction opposite to that of the free atmospheric wind, owing to counter-flow along the roof in the turbulent wake above the building. In addition to the effect of aerodynamic downwash upon the release of air pollutants from stacks and buildings, one must also consider the effects of aerodynamic downwash when exposing meteorological instruments near or upon buildings.

Where the pollution is emitted from a vent or opening on a building and is immediately influenced by the turbulent wake of the building, the pollution is rapidly distributed within this turbulent wake. To account for mixing in the turbulent wake, one may assume binormal distributions of concentrations at the source, with horizontal and vertical standard deviations of σ_{y0} and σ_{z0}. The standard deviations are related to the width and height of the building, for example, letting 4.3 σ_{y0} equal the width of the building and 2.15 σ_{z0} equal

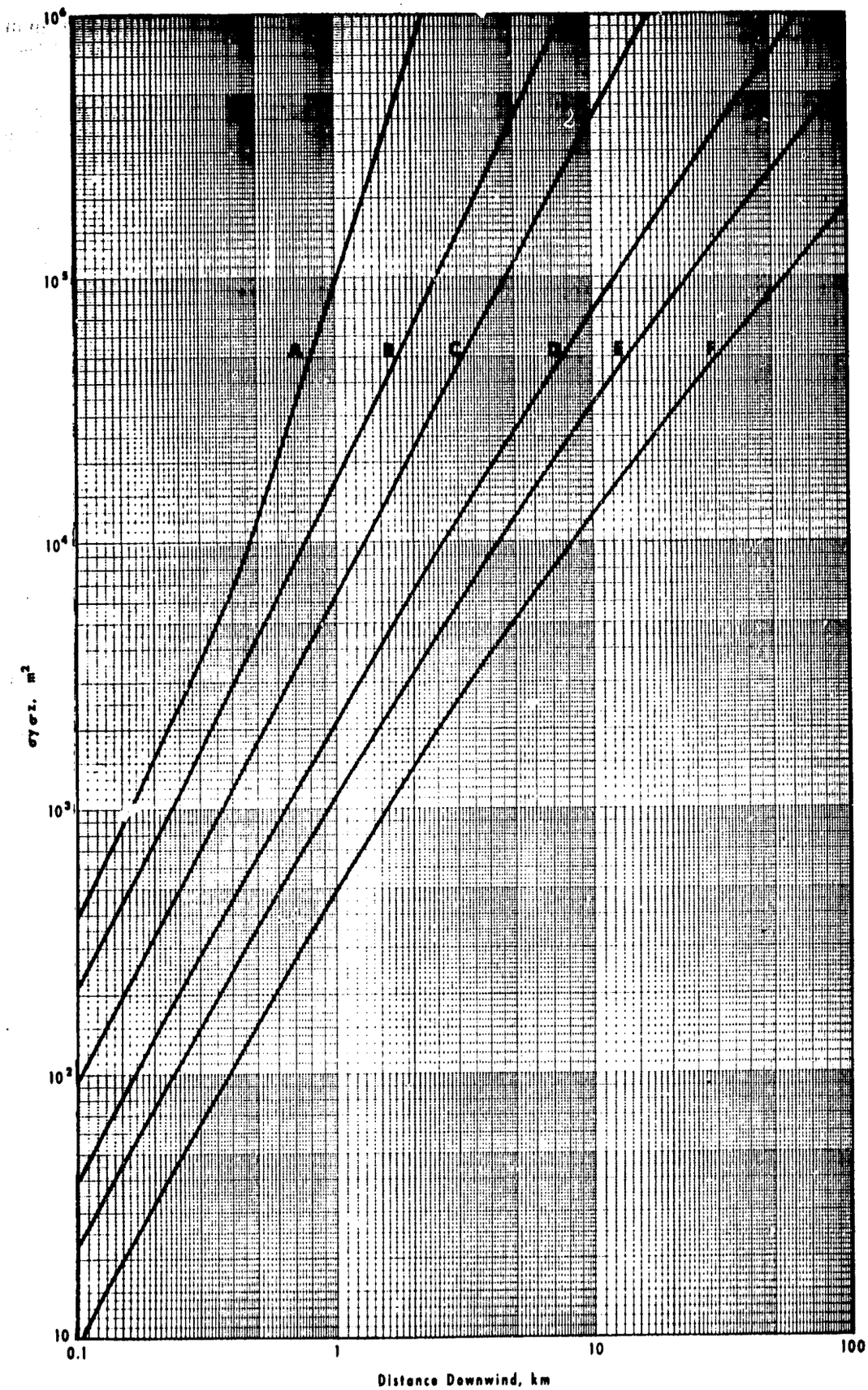

Figure 4-1. The product of $\sigma_y \sigma_z$ as a function of downwind distance from the source.

the height. Values other than 4.3 and 2.15 can be used. When these values are used 97% of the distribution is included within these limits. Virtual distances x_y and x_z can be found such that at x_y, $\sigma_y = \sigma_{y_0}$ and at x_z, $\sigma_z = \sigma_{z_0}$. These x's will differ with stability. Equations applicable to point sources can then be used, determining σ_y as a function of $x + x_y$ and σ_z as a function of $x + x_z$.

REFERENCES

Bosanquet, C. H., W. F. Carey, and E. M. Halton, 1950: Dust from chimney stacks. Proc. Inst. Mech. Eng., *162*, 355-367.

Bosanquet, C. H., 1957: The rise of a hot waste gas plume. J. Inst. Fuel, *30*, 197, 322-328.

Davidson, W. F., 1949: The dispersion and spreading of gases and dust from chimneys. Trans. Conf. on Ind. Wastes, 14th Ann. Meeting, Ind. Hygiene Found. Amer., 38-55.

Halitsky, J., 1961: Wind tunnel model test of exhaust gas recirculation at the NIH Clinical Center. Tech. Rep. No. 785.1, New York Univ.

Halitsky, J., 1962: Diffusion of vented gas around buildings. J. Air Poll. Cont. Assoc., *12*, 2, 74-80.

Halitsky, J., 1963: Gas diffusion near buildings, theoretical concepts and wind tunnel model experiments with prismatic building shapes. Geophysical Sciences Lab. Rep. No. 63-3. New York Univ.

Hawkins, J. E., and G. Nonhebel, 1955: Chimneys and the dispersal of smoke. J. Inst. Fuel, *28*, 530-546.

Holland, J. Z., 1953: A meteorological survey of the Oak Ridge area. 554-559 Atomic Energy Comm., Report ORO-99, Washington, D.C., 584 pp.

Moses, H., and G. H. Strom, 1961: A comparison of observed plume rises with values obtained from well-known formulas. J. Air Poll. Cont. Assoc., *11*, 10, 455-466.

Moses, H., G. H. Strom, and J. E. Carson, 1964: Effects of meteorological and engineering factors on stack plume rise. Nuclear Safety, *6*, 1, 1-19.

Scorer, R. S., 1959: The behavior of plumes. Int. J. Air Poll., *1*, 198-220.

Sherlock, R. H., and E. J. Lesher, 1954: Role of chimney design in dispersion of waste gases. Air Repair, *4*, 2, 1-10.

Strom, G. H., 1955-1956: Wind tunnel scale model studies of air pollution from industrial plants. Ind. Wastes, Sept. - Oct. 1955, Nov. - Dec. 1955, and Jan. - Feb. 1956.

Strom, G. H., M. Hackman, and E. J. Kaplin, 1957: Atmospheric dispersal of industrial stack gases determined by concentration measurements in scale model wind tunnel experiments. J. Air Poll. Cont. Assoc., *7*, 3, 198-203.

CONCENTRATIONS IN AN INVERSION BREAK-UP FUMIGATION

A surface-based inversion may be eliminated by the upward transfer of sensible heat from the ground surface when that surface is warmer than the overlying air. This situation occurs when the ground is being warmed by solar radiation or when air flows from a cold to a relatively warm surface. In either situation pollutants previously emitted above the surface into the stable layer will be mixed vertically when they are reached by the thermal eddies, and ground-level concentrations can increase. This process, called "fumigation" was described by Hewson and Gill (1944) and Hewson (1945). Equations for estimating concentrations with these conditions have been given by Holland (1953), Hewson (1955), Gifford (1960a), Bierly and Hewson (1962), and Pooler (1965).

To estimate ground-level concentrations under inversion break-up fumigations, one assumes that the plume was initially emitted into a stable layer. Therefore, σ_y and σ_z characteristic of stable conditions must be selected for the particular distance of concern. An equation for the ground-level concentration when the inversion has been eliminated to a height h_i is:

$$\chi_F(x,y,0;H) = \frac{Q\left[\int_{-\infty}^{p} \frac{1}{\sqrt{2\pi}} \exp(-0.5\,p^2)\,dp\right]}{\sqrt{2\pi}\,\sigma_{yF}\,u\,h_i} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_{yF}}\right)^2\right] \qquad (5.1)$$

where $p = \frac{h_i - H}{\sigma_z}$

and σ_{yF} is discussed below.

Values for the integral in brackets can be found in most statistical tables. For example, see pages 273-276, Burington (1953). This factor accounts for the portion of the plume that is mixed downward. If the inversion is eliminated up to the effective stack height, half of the plume is presumed to be mixed downward, the other half remaining in the stable air above. Eq. (5.1) can be approximated when the fumigation concentration is near its maximum by:

$$\chi_F(x,y,0;H) = \frac{Q}{\sqrt{2\pi}\,u\,\sigma_{yF}\,h_i} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_{yF}}\right)^2\right] \qquad (5.2)$$

$$h_i = H + 2\,\sigma_z = h + \Delta H + 2\,\sigma_z \qquad (5.3)$$

A difficulty is encountered in estimating a reasonable value for the horizontal dispersion since in mixing the stable plume through a vertical depth some additional horizontal spreading occurs (see problem 12). If this spreading is ignored and the σ_y for stable conditions used, the probable result would be estimated concentrations higher than actual concentrations. Or, using an approximation suggested by Bierly and Hewson (1962) that the edge of the plume spreads outward with an angle of 15°, the σ_{yF} for the inversion break-up fumigation equals the σ_y for stable conditions plus one-eighth the effective height of emission. The origin of this concept can be seen in Figure 5-1 and the following equation, where the edge of the plume is the point at which the concentration falls to 1/10 that at the centerline (at a distance of 2.15 σ_y from the plume center).

$$\sigma_{yF} = \frac{2.15\,\sigma_y\,(\text{stable}) + H\tan 15^\circ}{2.15}$$

$$= \sigma_y\,(\text{stable}) + H/8 \qquad (5.4)$$

A Gaussian distribution in the horizontal is assumed.

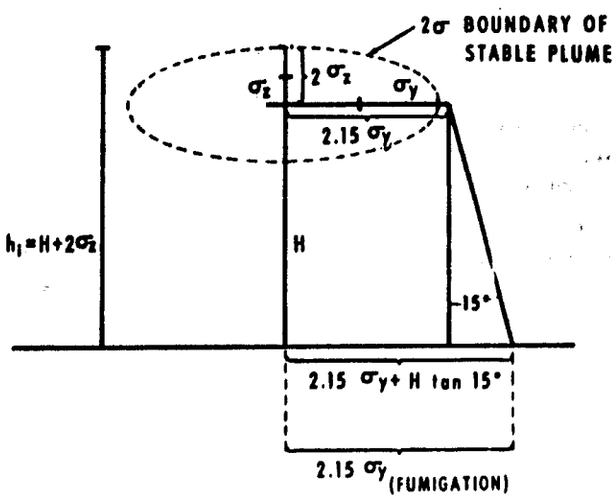

Figure 5-1. Diagram showing assumed height, h_i and σ_y during fumigation, for use in equation (5.2).

Eq. (5.4) should not be applied near the stack, for if the inversion has been eliminated to a height sufficient to include the entire plume, the emission is taking place under unstable not stable conditions. Therefore, the nearest downwind distance to be considered for an estimate of fumigation concentrations must be great enough, based on the time required to eliminate the inversion, that this portion of the plume was initially emitted into stable air. This distance is $x = ut_m$, where u is the mean

wind in the stable layer and t_m is the time required to eliminate the inversion from h, the physical height of the stack to h_i (Eq. 5.3).

t_m is dependent upon both the strength of the inversion and the rate of heating at the surface. Pooler (1965) has derived an expression for estimating this time:

$$t_m = \frac{\rho_a c_p}{R} \frac{\delta\Theta}{\delta z} (h_i - h) \left(\frac{h + h_i}{2}\right) \quad (5.5)$$

where t_m = time required for the mixing layer to develop from the top of the stack to the top of the plume, sec

ρ_a = ambient air density, g m^{-3}

c_p = specific heat of air at constant pressure, cal g^{-1} $°K^{-1}$

R = net rate of sensible heating of an air column by solar radiation, cal m^{-2} sec^{-1}

$\frac{\delta\Theta}{\delta_z}$ = vertical potential temperature gradient, $°K\ m^{-1} \sim \frac{\delta T}{\delta z} + \Gamma$ (the adiabatic lapse rate)

h_i = height of base of the inversion sufficient to be above the plume, m

h = physical height of the stack, m

Note that $h_i - h$ is the thickness of the layer to be heated and $\left(\frac{h + h_i}{2}\right)$ is the average height of the layer. Although R depends on season, and cloud cover and varies continuously with time, Pooler has used a value of 67 cal m^{-2} sec^{-1} as an average for fumigation.

Hewson (1945) also suggested a method of estimating the time required to eliminate an inversion to a height z by use of an equation of Taylor's (1915, p. 8):

$$t = \frac{z^2}{4\ K} \quad (5.6)$$

where: t = time required to eliminate the inversion to height z, sec

z = height to which the inversion has been eliminated, m

K = eddy diffusivity for heat, m^2 sec^{-1}

Rewriting to compare with Eq. (5.5),

$$t_m = \frac{h_i^2 - h^2}{4\ K} \quad (5.7)$$

Hewson (1945) has suggested a value of 3 m^2 sec^{-1} for K.

PLUME TRAPPING

Plume trapping occurs when the plume is trapped between the ground surface and a stable layer aloft. Bierly and Hewson (1962) have suggested the use of an equation that accounts for the multiple eddy reflections from both the ground and the stable layer:

$$\chi(x,0,z;H) = \frac{Q}{2\pi u \sigma_y \sigma_z} \left\{ \exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right] + \sum_{N=1}^{N=J} \left[\exp -\frac{1}{2}\left(\frac{z-H-2\ NL}{\sigma_z}\right)^2 + \exp -\frac{1}{2}\left(\frac{z+H-2\ NL}{\sigma_z}\right)^2 + \exp -\frac{1}{2}\left(\frac{z-H+2\ NL}{\sigma_z}\right)^2 + \exp -\frac{1}{2}\left(\frac{z+H+2\ NL}{\sigma_z}\right)^2 \right] \right\} \quad (5.8)$$

where L is the height of the stable layer and J = 3 or 4 is sufficient to include the important reflections. A good approximation of this lengthy equation can be made by assuming no effect of the stable layer until $\sigma_z = 0.47$ L (see Chapter 3). It is assumed that at this distance, x_L, the stable layer begins to affect the vertical distribution so that at the downwind distance, 2 x_L, uniform vertical mixing has taken place and the following equation can be used:

$$\chi(x,y,z;H) = \frac{Q}{\sqrt{2\pi}\ \sigma_y L u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \quad (5.9)$$

For distances between x_L and 2 x_L the best approximation to the ground-level centerline concentration is that read from a straight line drawn between the concentrations for points x_L and 2 x_L on a log-log plot of ground-level centerline concentration as a function of distance.

CONCENTRATIONS AT GROUND LEVEL COMPARED TO CONCENTRATIONS AT THE LEVEL OF EFFECTIVE STACK HEIGHT FROM ELEVATED CONTINUOUS SOURCES

There are several interesting relationships between ground-level concentrations and concentrations at the level of the plume centerline. One of

these is at the distance of maximum concentration at the ground. As a rough approximation the maximum ground-level concentration occurs at the distance where $\sigma_z = \frac{1}{\sqrt{2}} H$. This approximation is much better for unstable conditions than for stable conditions. With this approximation, the ratio of concentration at plume centerline to that at the ground is:

$$\frac{\chi(x,0,H)}{\chi(x,0,0)} = \frac{\frac{1}{2}\left[1.0 + \exp - \frac{1}{2}\left(\frac{2H}{\sigma_z}\right)^2\right]}{\exp - \frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2}$$

$$= \frac{\frac{1}{2}\left[1.0 + \exp - 0.5\,(2\sqrt{2})^2\right]}{\exp - 0.5\,(\sqrt{2})^2}$$

$$= \frac{\frac{1}{2}\,(1.0 + 0.0182)}{0.368}$$

$$= 1.38$$

This calculation indicates that at the distance of maximum ground-level concentration the concentration at plume centerline is greater by about one-third.

It is also of interest to determine the relationship between σ_z and H such that the concentration at ground-level at a given distance from the source is the same as the concentration at plume level. This condition should occur where:

$$\exp - \frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2 = \frac{1}{2}\left[1.0 + \exp - \frac{1}{2}\left(\frac{2H}{\sigma_z}\right)^2\right]$$

The value $H/\sigma_z = 1.10$ satisfies this expression, which can be written as $\sigma_z = 0.91$ H (see problem 10).

TOTAL DOSAGE FROM A FINITE RELEASE

The total dosage, which is the integration of concentration over the time of passage of a plume or puff, can be obtained from:

$$D_T\,(x,y,0;H) = \frac{Q_T}{\pi\,\sigma_y\,\sigma_z\,u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \qquad (5.10)$$

where D_T = total dosage, g sec m^{-3}
and Q_T = total release, g

The σ's should be representative of the time period over which the release takes place, and care should be taken to consider the x-axis along the trajectory or path of the plume or puff travel. Large errors can easily occur if the path is not known accurately. The estimate of this path is usually increasingly difficult with shorter release times. D_T can also be given in curie sec m^{-3} if Q_T is in curies.

CROSSWIND-INTEGRATED CONCENTRATION

The ground-level crosswind-integrated concentration is often of interest. For a continuous elevated source this concentration is determined from Eq. (3.2) integrated with respect to y from $-\infty$ to $+\infty$ (Gifford 1960a) giving:

$$\chi_{CWI} = \frac{2\,Q}{\sqrt{2\pi}\,\sigma_z\,u} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \qquad (5.11)$$

In diffusion experiments the ground-level crosswind-integrated concentration is often determined at particular downwind distances from a crosswind line or arc of sampling measurements made at this distance. When the source strength, Q, and average wind speed, u, are known, σ_z can be estimated indirectly even though no measurements were made in the vertical. If any of the tracer is lost through reaction or deposition, the resulting σ_z from such estimates will not represent the vertical dispersion (see problem 18).

ESTIMATION OF CONCENTRATIONS FOR SAMPLING TIMES LONGER THAN A FEW MINUTES

Concentrations directly downwind from a source decrease with sampling time mainly because of a larger σ_y due to increased meander of wind direction. Stewart, Gale, and Crooks (1958) reported that this decrease in concentration follows a one-fifth power law with the sampling time for sampling periods from about 3 minutes to about half an hour. Cramer (1959) indicates that this same power law applies for sampling times from 3 seconds to 10 minutes. Both of these studies were based on observations taken near the height of release. Gifford (1960b) indicates that ratios of peak to mean concentrations are much higher than those given by the above power law where observations of concentrations are made at heights considerably different from the height of release or considerably removed from the plume axis. He also indicates that for increasing distances from an elevated source, the ratios of peak to average concentrations observed at ground level approach unity. Singer (1961) and Singer, et al. (1963) show that ratios of peak to mean concentrations depend also on the stability of the atmosphere and the type of terrain that the plume is passing over. Nonhebel (1960) reports that Meade deduced a relation between calculated concentrations at ground level and the sampling time from "a study of published data on lateral and vertical diffusion coefficients in steady winds." These relations are shown in Table 5-1.

Table 5-1 VARIATION OF CALCULATED CONCENTRATION WITH SAMPLING TIME

Sampling Time	Ratio of Calculated Concentration to 3-minute Concentration
3 minutes	1.00
15 minutes	0.82
1 hour	0.61
3 hours	0.51
24 hours	0.36

This table indicates a power relation with time: $\chi \propto t^{-0.17}$. Note that these estimates were based upon published dispersion coefficients rather than upon sampling results. Information in the references cited indicates that effects of sampling time are exceedingly complex. If it is necessary to estimate concentrations from a single source for the time intervals greater than a few minutes, the best estimate apparently can be obtained from:

$$\chi_n = \chi_k \left(\frac{t_k}{t_n}\right)^p \qquad (5.12)$$

where χ_n is the desired concentration estimate for the sampling time, t_n; χ_k is the concentration estimate for the shorter sampling time, t_k, (probably about 10 minutes); and p should be between 0.17 and 0.2. Eq. (5.12) probably would be applied most appropriately to sampling times less than 2 hours (see problem 19).

ESTIMATION OF SEASONAL OR ANNUAL AVERAGE CONCENTRATIONS AT A RECEPTOR FROM A SINGLE POLLUTANT SOURCE

For a source that emits at a constant rate from hour to hour and day to day, estimates of seasonal or annual average concentrations can be made for any distance in any direction if stability wind "rose" data are available for the period under study. A wind rose gives the frequency of occurrence for each wind direction (usually to 16 points) and wind speed class (9 classes in standard Weather Bureau use) for the period under consideration (from 1 month to 10 years). A stability wind rose gives the same type of information for each stability class.

If the wind directions are taken to 16 points and it is assumed that the wind directions within each sector are distributed randomly over a period of a month or a season, it can further be assumed that the effluent is uniformly distributed in the horizontal within the sector (Holland, 1953, p. 540). The appropriate equation for average concentration is then either:

$$\bar{\chi} = \frac{2\,Q}{\sqrt{2\pi}\,\sigma_z\,u\left(\frac{2\pi x}{16}\right)} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right]$$

$$= \frac{2.03Q}{\sigma_z\,ux} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \qquad (5.13)$$

or

$$\bar{\chi} = \frac{Q}{L\,u\left(\frac{2\pi x}{16}\right)} = \frac{2.55\,Q}{L\,u\,x} \qquad (5.14)$$

depending upon whether a stable layer aloft is affecting the distribution.

The estimation of χ for a particular direction and downwind distance can be accomplished by choosing a representative wind speed for each speed class and solving the appropriate equation (5.13 or 5.14) for all wind speed classes and stabilities. Note that a SSW wind affects a receptor to the NNE of a source. One obtains the average concentration for a given direction and distance by summing all the concentrations and weighting each one according to its frequency for the particular stability and wind speed class. If desired, a different effective height of emission can be used for various wind speeds. The average concentration can be expressed by:

$$\chi(x,\theta) = \sum_S \sum_N \left\{ \frac{2\,Q\,f(\theta,S,N)}{\sqrt{2\pi}\,\sigma_{zS}\,u_N\left(\frac{2\pi x}{16}\right)} \exp\left[-\frac{1}{2}\left(\frac{H_u}{\sigma_{zS}}\right)^2\right]\right\} \qquad (5.15)$$

where $f(\theta, S, N)$ is the frequency during the period of interest that the wind is from the direction θ, for the stability condition, S, and wind speed class N.

σ_{zS} is the vertical dispersion parameter evaluated at the distance x for the stability condition S.

u_N is the representative wind speed for class N.

H_u is the effective height of release for the wind speed u_N.

Where stability wind rose information cannot be obtained, a first-order approximation may be made of seasonal or annual average concentrations by using the appropriate wind rose in the same manner, and assuming the neutral stability class, D, only.

METEOROLOGICAL CONDITIONS ASSOCIATED WITH MAXIMUM GROUND-LEVEL CONCENTRATIONS

1. For ground-level sources maximum concentrations occur with stable conditions.

2. For elevated sources maximum "*instantaneous*" concentrations occur with unstable conditions when portions of the plume that have undergone little dispersion are brought to the ground. These occur close to the point of emission (on the order of 1 to 3 stack heights). These concentrations are usually of little general interest because of their very short duration; they *cannot* be estimated from the material presented in this workbook.

3. For elevated sources maximum concentrations for time periods of a few minutes occur with unstable conditions; although the concentrations fluctuate considerably under these conditions, the concentrations averaged over a few minutes are still high compared to those found under other conditions. The distance of this maximum concentration occurs near the stack (from 1 to 5 stack heights downwind) and the concentration drops off rapidly downwind with increasing distance.

4. For elevated sources maximum concentrations for time periods of about half an hour can occur with fumigation conditions when an unstable layer increases vertically to mix downward a plume previously discharged within a stable layer. With small ΔH, the fumigation can occur close to the source but will be of relatively short duration. For large ΔH, the fumigation will occur some distance from the stack (perhaps 30 to 40 km), but can persist for a longer time interval. Concentrations considerably lower than those associated with fumigations, but of significance can occur with neutral or unstable conditions when the dispersion upward is severely limited by the existence of a more stable layer above the plume, for example, an inversion.

5. Under stable conditions the maximum concentrations at ground-level from elevated sources are less than those occurring under unstable conditions and occur at greater distances from the source. However, the difference between maximum ground-level concentrations for stable and unstable conditions is only a factor of 2 for effective heights of 25 meters and a factor of 5 for H of 75 m. Because the maximum occurs at greater distances, concentrations that are below the maximum but still significant can occur over large areas. This becomes increasingly significant if emissions are coming from more than one source.

CONCENTRATIONS AT A RECEPTOR POINT FROM SEVERAL SOURCES

Sometimes, especially for multiple sources, it is convenient to consider the receptor as being at the origin of the diffusion coordinate system. The source-receptor geometry can then be worked out merely by drawing or visualizing an x-axis oriented upwind from the receptor and determining the crosswind distances of each source in relation to this x-axis. As pointed out by Gifford (1959), the concentration at (0, 0, 0) from a source at (x, y, H) on a coordinate system with the x-axis oriented upwind is the same as the concentration at (x, y, 0) from a source at (0, 0, H) on a coordniate system with the x-axis downwind (Figure 5-2). The total concentration is then given by summing the individual contributions from each source (see problem 20).

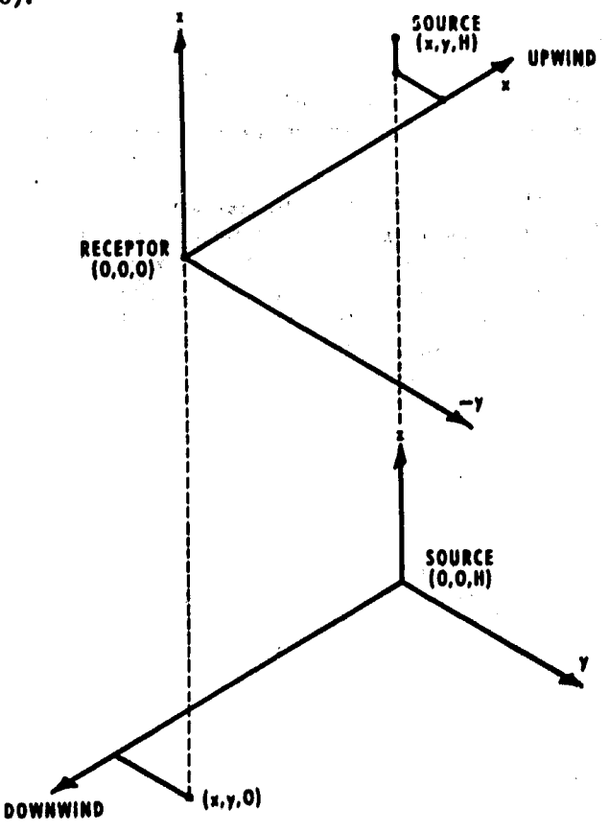

Figure 5-2. Comparison of source-oriented and receptor-oriented coordinate systems.

It is often difficult to determine the atmospheric conditions of wind direction, wind speed, and stability that will result in the maximum combined concentrations from two or more sources; drawing iscpleths of concentration for various wind speeds and stabilities and orienting these according to wind direction is one approach.

AREA SOURCES

In dealing with diffusion of air pollutants in areas having large numbers of sources, e.g., as in urban areas, there may be too many sources of most atmospheric contaminants to consider each source

individually. Often an approximation can be made by combining all of the emissions in a given area and treating this area as a source having an initial horizontal standard deviation, σ_{yo}. A virtual distance, x_y, can then be found that will give this standard deviation. This is just the distance that will yield the appropriate value for σ_y from Figure 3-2. Values of x_y will vary with stability. Then equations for point sources may be used, determining σ_y as a function of $x + x_y$, a slight variation of the suggestion by Holland (1953). This procedure treats the area source as a cross-wind line source with a normal distribution, a fairly good approximation for the distribution across an area source. The initial standard deviation for a square area source can be approximated by $\sigma_{yo} \simeq s/4.3$, where s is the length of a side of the area (see problem 22).

If the emissions within an area are from varying effective stack heights, the variation may be approximated by using a σ_{zo}. Thus H would be the *mean* effective height of release and σ_{zo} the standard deviation of the initial vertical distribution of sources. A virtual distance, x_z, can be found, and point source equations used for estimating concentrations, determining σ_z as a function of $x + x_z$.

TOPOGRAPHY

Under conditions of irregular topography the direct application of a standard dispersion equation is often invalid. In some situations the best one may be able to do without the benefit of *in situ* experiments is to estimate the upper limit of the concentrations likely to occur.

For example, to calculate concentrations on a hillside downwind from and facing the source and at about the effective source height, the equation for concentrations at ground-level from a ground-level source (Eq. 3.4) will yield the highest expected concentrations. This would closely approximate the situation under stable conditions, when the pollutant plume would be most likely to encounter the hillside. Under unstable conditions the flow is more likely to rise over the hill (see problem 21).

With downslope flow when the receptor is at a lower elevation than the source, a likely assumption is that the flow parallels the slope; i.e., no allowance is made for the difference between ground-level elevations at the source and at the receptor.

Where a steep ridge or bluff restricts the horizontal dispersion, the flow is likely to be parallel to such a bluff. An assumption of complete reflection at the bluff, similar to eddy reflection at the ground from an elevated source, is in order. This may be accomplished by using:

$$\chi(x,y,0;H) = \frac{Q}{\pi \sigma_y \sigma_z u} \left\{ \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{2B-y}{\sigma_y}\right)^2\right] \right\} \left\{ \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \right\} \quad (5.16)$$

B is the distance from the x-axis to the restricting bluff, and the positive y axis is defined to be in the direction of the bluff.

The restriction of horizontal dispersion by valley sides is somewhat analogous to restriction of the vertical dispersion by a stable layer aloft. When the σ_y becomes great enough, the concentrations can be assumed to be uniform across the width of the valley and the concentration calculated according to the following equation, where in this case Y is the width of the valley.

$$\chi = \frac{2Q}{\sqrt{2\pi}\,\sigma_z Y u} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \quad (5.17)$$

LINE SOURCES

Concentrations downwind of a continuously emitting infinite line source, when the wind direction is normal to the line, can be expressed by rewriting equation (12) p. 154 of Sutton (1932):

$$\chi(x,y,0;H) = \frac{2q}{\sqrt{2\pi}\,\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \quad (5.18)$$

Here q is the source strength per unit distance, for example, g sec^{-1} m^{-1}. Note that the horizontal dispersion parameter, σ_y, does not appear in this equation, since it is assumed that lateral dispersion from one segment of the line is compensated by dispersion in the opposite direction from adjacent segments. Also y does not appear, since concentration at a given x is the same for any value of y (see problem 23).

Concentrations from infinite line sources when the wind is not perpendicular to the line can be approximated. If the angle between the wind direction and line source is ϕ, the equation for concentration downwind of the line source is:

$$\chi(x,y,0;H) = \frac{2q}{\sin\phi\,\sqrt{2\pi}\,\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \quad (5.19)$$

This equation should not be used where ϕ is less than 45°.

When estimating concentrations from finite line sources, one must account for "edge effects" caused by the end of the line source. These effects will of course extend to greater cross-wind distances as the distance from the source increases. For concentrations from a finite line source oriented cross-wind, define the x-axis in the direction of the mean wind and passing through the receptor of interest. The limits of the line source can be defined as extending from y_1 to y_2 where y_1 is less than y_2. The equation for concentration (from Sutton's (1932) equation (11), p. 154), is:

$$\chi(x,0,0;H) = \frac{2\,q}{\sqrt{2\pi}\,\sigma_z\,u} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \int_{p_1}^{p_2} \frac{1}{\sqrt{2\pi}} \exp(-0.5\,p^2)\,dp \qquad (5.20)$$

$$\text{where } p_1 = \frac{y_1}{\sigma_y},\ p_2 = \frac{y_2}{\sigma_y}$$

The value of the integral can be determined from tabulations given in most statistical tables (for example, see Burrington (1953), pp. 273-276; also see problem 24).

INSTANTANEOUS SOURCES

Thus far we have considered only sources that were emitting continuously or for time periods equal to or greater than the travel times from the source to the point of interest. Cases of instantaneous release, as from an explosion, or short-term releases on the order of seconds, are often of practical concern. To determine concentrations at any position downwind, one must consider the time interval after the time of release and diffusion in the downwind direction as well as lateral and vertical diffusion. Of considerable importance, but very difficult, is the determination of the path or trajectory of the "puff." This is most important if concentrations are to be determined at specific points. Determining the trajectory is of less importance if knowledge of the magnitude of the concentrations for particular downwind distances or travel times is required without the need to know exactly at what points these concentrations occur. Rewriting Sutton's (1932) equation (13), p. 155, results in an equation that may be used for estimates of concentration downwind from a release from height, H:

$$\chi(x,y,0;H) = \frac{2\,Q_T}{(2\pi)^{3/2}\,\sigma_x\,\sigma_y\,\sigma_z} \exp\left[-\frac{1}{2}\left(\frac{x-ut}{\sigma_x}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \qquad (5.21)$$

(The numerical value of $(2\pi)^{3/2}$ is 15.75.)

The symbols have the usual meaning, with the important exceptions that Q_T represents the *total mass* of the release and the σ's are *not* those evaluated with respect to the dispersion of a continuous source at a fixed point in space.

In Eq. (5.21) the σ's refer to dispersion statistics following the motion of the expanding puff. The σ_x is the standard deviation of the concentration distribution in the puff in the downwind direction, and t is the time after release. Note that there is no dilution in the downwind direction by wind speed. The speed of the wind mainly serves to give the downwind position of the center of the puff, as shown by examination of the exponential involving σ_x. Wind speed may influence the dispersion indirectly because the dispersion parameters σ_x, σ_y, and σ_z may be functions of wind speed. The σ_y's and σ_z's for an instantaneous source are less than those for a few minutes given in Figure 3-2 and 3-3. Slade (1965) has suggested values for a σ_y and σ_z for quasi-instantaneous sources. These are given in Table 5-2. The problem remains to make best estimates of σ_x. Much less is known of diffusion in the downwind direction than is known of lateral and vertical dispersion. In general one should expect the σ_x value to be about the same as σ_y. Initial dimensions of the puff, i.e., from an explosion, may be approximated by finding a virtual distance to give the appropriate initial standard deviation for each direction. Then σ_y will be determined as a function of $x + x_y$, σ_z as a function of $x + x_z$, and σ_x as a function of $x + x_x$.

Table 5-2 ESTIMATION OF DISPERSION PARAMETERS FOR QUASI-INSTANTANEOUS SOURCES (FROM SLADE, 1965)

	x = 100 m		x = 4 km	
	σ_y	σ_z	σ_y	σ_z
Unstable	10	15	300	220
Neutral	4	3.8	120	50
Very Stable	1.3	0.75	35	7

REFERENCES

Bierly, E. W., and E. W. Hewson, 1962: Some restrictive meteorological conditions to be considered in the design of stacks. J. Appl. Meteorol., *1*, 3, 383-390.

Burington, R. S., 1953: Handbook of Mathematical Tables and Formulas. Sandusky, Ohio, Handbook Publishers, 296 pp.

Cramer, H. E., 1959: Engineering estimates of atmospheric dispersal capacity. Amer. Ind. Hyg. Assoc. J., *20*, 3, 183-189.

Gifford, F. A., 1959: Computation of pollution from several sources. Int. J. Air Poll., 2, 109-110.

Gifford, F. A., 1960a: Atmospheric dispersion calculations using the generalized Gaussian plume model. Nuclear Safety, 2, 2, 56-59, 67-68.

Gifford, F. A., 1960b: Peak to average concentration ratios according to a fluctuating plume dispersion model. Int. J. Air Poll., *3*, 4, 253-260.

Hewson, E. W., and G. C. Gill, 1944: Meteorological investigations in Columbia River Valley near Trail, B. C., pp 23-228 in Report submitted to the Trail Smelter Arbitral Tribunal by R. S. Dean and R. E. Swain, Bur. of Mines Bull 453, Washington, Govt. Print. Off., 304 pp.

Hewson, E. W., 1945: The meteorological control of atmospheric pollution by heavy industry. Quart. J. R. Meteorol. Soc., *71*, 266-282.

Hewson, E. W., 1955: Stack heights required to minimize ground concentrations. Trans. ASME *77*, 1163-1172.

Holland, J. Z., 1953: A meteorological survey of the Oak Ridge area, p. 540. Atomic Energy Comm., Report ORO-99, Washington, D. C., 584 pp.

Nonhebel, G., 1960: Recommendations on heights for new industrial chimneys. J. Inst. Fuel, *33*, 479-513.

Pooler, F., 1965: Potential dispersion of plumes from large power plants. PHS Publ. No. 999-AP-16, 1965. 13 pp.

Singer, I. A., 1961: The relation between peak and mean concentrations. J. Air Poll. Cont. Assoc., *11*, 336-341.

Singer, I. A., K. Imai, and R. G. Del Campos, 1963: Peak to mean pollutant concentration ratios for various terrain and vegetation cover. J. Air Poll. Cont. Assoc., *13*, 40-42.

Slade, D. H., 1965: Dispersion estimates from pollutant releases of a few seconds to 8 hours in duration. Unpublished Weather Bureau Report. Aug. 1965.

Stewart, N. G., H. J. Gale, and R. N. Crooks, 1958: The atmospheric diffusion of gases discharged from the chimney of the Harwell Reactor BEPO. Int. J. Air Poll., *1*, 87-102.

Sutton, O. G., 1932: A theory of eddy diffusion in the atmosphere. Proc. Roy. Soc. London, A, *135*, 143-165.

Taylor, G. I., 1915: Eddy motion in the atmosphere. Phil. Trans. Roy. Soc., A, *215*, 1-26.

Chapter 6 — RELATION TO OTHER DIFFUSION EQUATIONS

Most other widely used diffusion equations are variant forms of the ones presented here. With respect to ground-level concentrations from an elevated source (Eq. 3.2):

$$\chi(x,y,0;H) = \frac{Q}{\pi \sigma_y \sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \tag{3.2}$$

Other well-known equations can be compared:

Bosanquet and Pearson (1936):

$$\chi(x,y,0;H) = \frac{Q}{\sqrt{2\pi}\, pq\, x^2 u} \exp\left[-\frac{1}{2}\left(\frac{y}{qx}\right)^2\right] \exp\left[-\frac{H}{px}\right] \tag{6.1}$$

where p and q are dimensionless diffusion coefficients.

Sutton (1947):

$$\chi(x,y,0;H) = \frac{2\,Q}{\pi C_y C_z x^{2-n} u} \exp\left[-\frac{1}{x^{2-n}}\left(\frac{y^2}{C_y^2} + \frac{H^2}{C_z^2}\right)\right] \tag{6.2}$$

where n is a dimensionless constant and C_y and C_z are diffusion coefficients in $m^{n/2}$.

Calder (1952):

$$\chi(x,y,0;H) = \frac{Q\,u}{2\,k^2 a\, v_x^2 x^2} \exp\left[-\frac{u}{k\, v_x\, x}\left(\frac{y}{a} + H\right)\right] \tag{6.3}$$

where $a = \frac{v'}{w'}$, the ratio of horizontal eddy velocity to vertical eddy velocity, k is von Karman's constant approximately equal to 0.4, and $v_x = \frac{k\,u}{\ln\left(\frac{H}{z_o}\right)}$ where z_o is a roughness parameter, m.

NOTE: Calder wrote the equation for the concentration at (x, y, z) from a ground-level source. For Eq. (6.3) it is assumed that the concentration at ground level from an elevated source is the same as the concentraton at an elevated point from a ground-level source.

Table 6-1 lists the expressions used in these equations that are equivalent to σ_y and σ_z (continuous source) in this paper.

Table 6-1 EXPRESSIONS EQUIVALENT TO σ_y AND σ_z IN VARIOUS DIFFUSION EQUATIONS.

Equation	σ_y	σ_z
Bosanquet and Pearson	$q\,x$	$\sqrt{2}\,p\,x$
Sutton	$\frac{1}{\sqrt{2}} C_y x^{\frac{2-n}{2}}$	$\frac{1}{\sqrt{2}} C_z x^{\frac{2-n}{2}}$
Calder	$\frac{\sqrt{2}\,a\,k\,v_x\,x}{u}$	$\frac{\sqrt{2}\,k\,v_x\,x}{u}$

REFERENCES

Bosanquet, C. H., and J. L. Pearson, 1936: The spread of smoke and gases from chimneys. Trans. Faraday Soc., *32*, 1249-1263.

Calder, K. L., 1952: Some recent British work on the problem of diffusion in the lower atmosphere, 787-792 in *Air Pollution*, Proc. U. S. Tech. Conf. Air Poll., New York, McGraw-Hill, 847 pp.

Sutton, O. G., 1947: The problem of diffusion in the lower atmosphere. Quart. J. Roy. Met Soc., *73*, 257-281.

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Chapter 7 — EXAMPLE PROBLEMS

The following 26 example problems and their solutions illustrate the application of most of the techniques and equations presented in this workbook.

PROBLEM 1: It is estimated that a burning dump emits 3 g sec^{-1} of oxides of nitrogen. What is the concentration of oxides of nitrogen, averaged over approximately 10 minutes, from this source directly downwind at a distance of 3 km on an overcast night with wind speed of 7 m sec^{-1}? Assume this dump to be a point ground-level source with no effective rise.

SOLUTION: Overcast conditions with a wind speed of 7 m sec^{-1} indicate that stability class D is most applicable (Statement, bottom of Table 3-1). For x = 3 km and stability D, $\sigma_y = 190$ m from Figure 3-2 and $\sigma_z = 65$ m from Figure 3-3. Eq. (3.4) for estimation of concentrations directly downwind (y = 0) from a ground-level source is applicable:

$$\chi\,(x,0,0;0) = \frac{Q}{\pi\,\sigma_y\,\sigma_z\,u} = \frac{3}{\pi\,190\,(65)\,7}$$

$$= 1.1 \times 10^{-5}\ g\ m^{-3} \text{ of oxides of nitrogen.}$$

PROBLEM 2: It is estimated that 80 g sec^{-1} of sulfur dioxide is being emitted from a petroleum refinery from an average effective height of 60 meters. At 0800 on an overcast winter morning with the surface wind 6 m sec^{-1}, what is the ground-level concentration directly downwind from the refinery at a distance of 500 meters?

SOLUTION: For overcast conditions, D class stability applies. With D stability at x = 500 m, $\sigma_y = 36$ m, $\sigma_z = 18.5$ m. Using Eq. (3.3):

$$\chi\,(x,0,0;H) = \frac{Q}{\pi\,\sigma_y\,\sigma_z\,u}\exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right]$$

$$= \frac{80}{\pi\,36\,(18.5)\,6}\exp\left[-0.5\,(60/18.5)^2\right]$$

$$= 6.37 \times 10^{-3}\exp\left[-0.5\,(3.24)^2\right]$$

The exponential is solved using Table A-1 (Appendix 3).

$$= 6.37 \times 10^{-3}\,(5.25 \times 10^{-3})$$

$$\chi = 3.3 \times 10^{-5}\ g\ m^{-3} \text{ of } SO_2$$

PROBLEM 3: Under the conditions of problem 2, what is the concentration at the same distance downwind but at a distance 50 meters from the x-axis? That is: $\chi\,(500, 50, 0; 60) = ?$

SOLUTION: Using Eq. (3.2):

$$\chi\,(x,y,0;H) = \frac{Q}{\pi\,\sigma_y\,\sigma_z\,u}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]$$

$$\exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right]$$

All but the exponential involving y has been found in the preceding problem. Therefore:

$$\chi\,(500, 50, 0; 60) = 3.3 \times 10^{-5}$$
$$\exp\left[-0.5\,(50/36)^2\right]$$

$$= 3.3 \times 10^{-5}\,(0.381)$$

$$= 1.3 \times 10^{-5}\ g\ m^{-3} \text{ of } SO_2$$

PROBLEM 4: A power plant burns 10 tons per hour of coal containing 3 percent sulfur; the effluent is released from a single stack. On a sunny summer afternoon the wind at 10 meters above ground is 4 m sec^{-1} from the northeast. The morning radiosonde taken at a nearby Weather Bureau station has indicated that a frontal inversion aloft will limit the vertical mixing to 1500 meters. The 1200-meter wind is from 30° at 5 m sec^{-1}. The effective height of emission is 150 meters. From Figure 3-9, what is the distance to the maximum ground-level concentration and what is the concentration at this point?

SOLUTION: To determine the source strength, the amount of sulfur burned is: 10 tons hr^{-1} x 2000 lb ton^{-1} x 0.03 sulfur = 600 lb sulfur hr^{-1}. Sulfur has a molecular weight of 32 and combines with O_2 with a molecular weight of 32; therefore for every mass unit of sulfur burned, there result two mass units of SO_2.

$$Q = \frac{64\ (\text{molecular weight of } SO_2)}{32\ (\text{molecular weight of sulfur})} \times \frac{600\ lb\ hr^{-1}\ (453.6\ g\ lb^{-1})}{3600\ sec\ hr^{-1}}$$

$$= 151\ g\ sec^{-1} \text{ of } SO_2$$

On a sunny summer afternoon the insolation should be strong. From Table 3-1, strong insolation and 4m sec^{-1} winds yield class-B stability. From Figure 3-9, the distance to the point of maximum concentration is 1 km for class-B stability and effective height of 150 meters. From Figure 3-3 at this distance $\sigma_z = 110$ m. This is much less than 0.47 L. Therefore, at this distance, the limit of mixing of 1500 meters will not affect the ground-level concentration. From Figure 3-9, the maximum $\chi u/Q$ for B stability and this effective height of 150 m is 7.5×10^{-6}.

$$\chi_{max} = \frac{\chi u}{Q_{max}}\,\frac{Q}{u} = \frac{7.5 \times 10^{-6} \times 151}{4}$$

$$= 2.8 \times 10^{-4}\ g\ m^{-3} \text{ of } SO_2$$

PROBLEM 5: For the power plant in problem 4, at what distance does the maximum ground-

level concentration occur and what is this concentration on an overcast day with wind speed 4 m sec^{-1}?

SOLUTION: On an overcast day the stability class would be D. From Figure 3-9 for D stability and H of 150 m, the distance to the point of maximum ground-level concentration is 5.6 km, and the maximum $\chi u/Q$ is 3.0×10^{-6}.

$$\chi_{max} = \frac{3.0 \times 10^{-6} \times 151}{4}$$

$$= 1.1 \times 10^{-4} \text{ g m}^{-3}$$

PROBLEM 6: For the conditions given in problem 4, draw a graph of ground-level centerline sulfur dioxide concentration with distance from 100 meters to 100 km. Use log-log graph paper.

SOLUTION: The frontal inversion limits the mixing to L = 1500 meters. The distance at which $\sigma_z = 0.47$ L = 705 m is $x_L = 5.5$ km. At distances less than this, Eq. (3.3) is used to calculate concentrations:

$$\chi\,(x,0,0;H) = \frac{Q}{\pi\,\sigma_y\,\sigma_z\,u} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right]$$

At distance equal to or greater than 2 x_L, which is 11 km, Eq. (3.5) is used:

$$\chi\,(x,0,0;H) = \frac{Q}{\sqrt{2\pi}\,\sigma_y\,L\,u}$$

Solutions for the equations are given in Table 7-1. The values of concentration are plotted against distance in Figure 7-1.

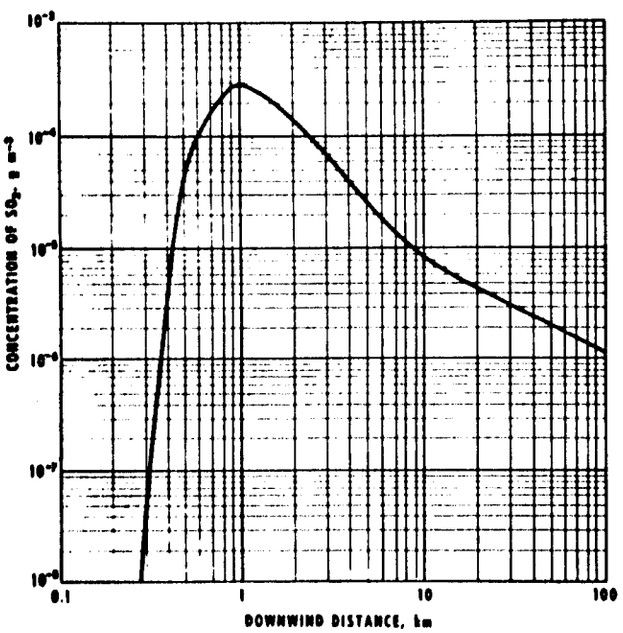

Figure 7-1. Concentration as a function of downwind distance (Problem 6).

Table 7-1 CALCULATION OF CONCENTRATIONS FOR VARIOUS DISTANCES (PROBLEM 6)

x, km	u, m sec^{-1}	σ_y, m	σ_z, m	H/σ_z	$\exp\left[-\frac{1}{2}(H/\sigma_z)^2\right]$	χ, g m^{-3}
0.3	4	52	30	5.0	3.73×10^{-6}	2.9×10^{-6}
0.5	4	83	51	2.94	1.33×10^{-2}	3.8×10^{-5}
0.8	4	129	85	1.77	0.209	2.3×10^{-4}
1.0	4	157	110	1.36	0.397	2.8×10^{-4}
2.0	4	295	230	0.65	0.810	1.4×10^{-4}
3.0	4	425	365	0.41	0.919	7.1×10^{-5}
5.5	4.5	720	705	0.21	0.978	2.1×10^{-5}
x, km	u, m sec^{-1}	σ_y, m	L, m			χ, g m^{-3}
11.0	4.5	1300	1500			6.9×10^{-6}
30	4.5	3000	1500			3.0×10^{-6}
100	4.5	8200	1500			1.1×10^{-6}

PROBLEM 7: For the conditions given in problem 4, draw a graph of ground-level concentration versus crosswind distance at a downwind distance of 1 km.

SOLUTION: From problem 4 the ground-level centerline concentration at 1 km is 2.8×10^{-4} g m^{-3}. To determine the concentrations at distances y from the x-axis, the ground-level centerline concentration must be multiplied by the

$$\text{factor } \exp\left[-\tfrac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]$$

$\sigma_y = 157$ meters at x = 1 km. Values for this computation are given in Table 7-2.

Table 7-2 DETERMINATION OF CROSSWIND CONCENTRATIONS (PROBLEM 7)

y, m	$\frac{y}{\sigma_y}$	$\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]$	$\chi\,(x,y,0)$
± 100	0.64	0.815	2.3×10^{-4}
± 200	1.27	0.446	1.3×10^{-4}
± 300	1.91	0.161	4.5×10^{-5}
± 400	2.55	3.87×10^{-2}	1.1×10^{-5}
± 500	3.18	6.37×10^{-3}	1.8×10^{-6}

These concentrations are plotted in Figure 7-2.

PROBLEM 8: For the conditions given in problem 4, determine the position of the 10^{-5} g m^{-3} ground level isopleth, and determine its area.

SOLUTION: From the solution to problem 6, the graph (Figure 7-1) shows that the 10^{-5} g m^{-3} isopleth intersects the x-axis at approximately x = 350 meters and x = 8.6 kilometers.

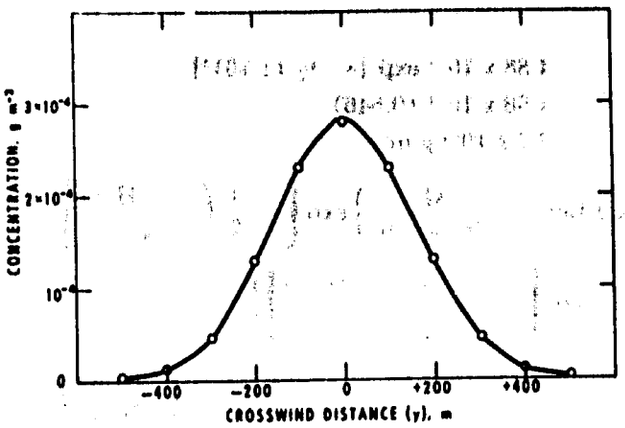

Figure 7-2. Concentration as a function of crosswind distance (Problem 7).

The values necessary to determine the isopleth half widths, y, are given in Table 7-3.

Table 7-3 DETERMINATION OF ISOPLETH WIDTHS (PROBLEM 8)

x, km	σ_y, m	χ (centerline), g m^{-3}	$\frac{\chi \text{ (isopleth)}}{\chi \text{ (centerline)}}$	y/σ_y	y, m
0.5	83	3.8×10^{-5}	0.263	1.64	136
0.8	129	2.3×10^{-4}	4.35×10^{-2}	2.50	323
1.0	157	2.8×10^{-4}	3.53×10^{-2}	2.59	407
2.0	295	1.4×10^{-4}	7.14×10^{-2}	2.30	679
3.0	425	7.1×10^{-5}	1.42×10^{-1}	1.98	842
4.0	540	4.0×10^{-5}	0.250	1.67	902
5.0	670	2.4×10^{-5}	0.417	1.32	884
6.0	780	1.8×10^{-5}	0.556	1.08	842
7.0	890	1.4×10^{-5}	0.714	0.82	730
8.0	980	1.1×10^{-5}	0.909	0.44	432

The orientation of the x-axis will be toward 225° close to the source, curving more toward 210° to 215° azimuth at greater distances because of the change of wind direction with height. The isopleth is shown in Figure 7-3.

Since the isopleth approximates an ellipse, the area may be estimated by π ab where a is the semimajor axis and b is the semiminor axis.

$$a = \frac{8600 - 350}{2} = 4125 \text{ m}$$

$$b = 902$$

$$A \text{ (m}^2) = \pi (4125)(902)$$

$$= 11.7 \times 10^6 \text{ m}^2$$

$$\text{or } A = 11.7 \text{ km}^2$$

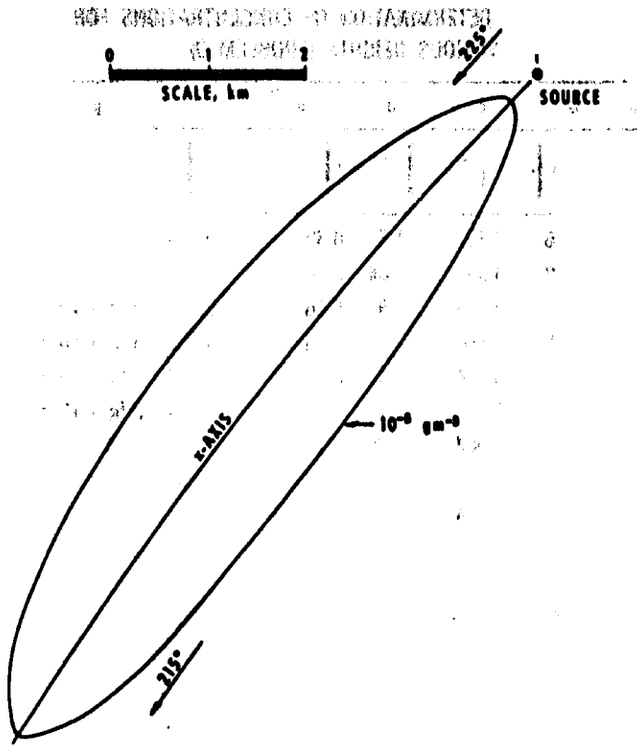

Figure 7-3. Location of the 10^{-6} g m^{-3} ground-level isopleth (Problem 8).

PROBLEM 9: For the conditions given in problem 4, determine the profile of concentration with height from ground level to z = 450 meters at x = 1 km, y = 0 meters, and draw a graph of concentration against height above ground.

SOLUTION: Eq. (3.1) is used to solve this problem. The exponential involving y is equal to 1. At x = 1 km, σ_y = 157 m, σ_z = 110 m. (From problem 4).

$$\frac{Q}{2\pi\, \sigma_y\, \sigma_z\, u} = \frac{151}{2\pi\, 157\, (110)\, 4} = 3.5 \times 10^{-6} \text{ g m}^{-3}$$

Values for the estimation of $\chi(z)$ are given in Table 7-4.

PROBLEM 10: For the conditions given in problem 4, determine the distance at which the ground-level centerline concentration equals the centerline concentration at 150 meters above ground. Verify by computation of χ (x,0,0) and χ (x,0,150).

SOLUTION: The distance at which concentrations at the ground and at plume height are equal should occur where σ_z = 0.91 H (See Chapter 5). For B stability and H = 150 m, σ_z = 0.91 (150) = 136 m occurs at x = 1.2 km. At this distance σ_y = 181 m.

Table 7-4 DETERMINATION OF CONCENTRATIONS FOR VARIOUS HEIGHTS (PROBLEM 9)

a.	b.	c.	d.	e.	f.	g.
z, m	$\frac{z-H}{\sigma_z}$	$\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right]$	$\frac{z+H}{\sigma_z}$	$\exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]$	c + e.	$\chi(x,z)$, g m^{-3}
0	−1.36	0.397	1.36	0.397	0.794	2.78×10^{-4}
30	−1.09	0.552	1.64	0.261	0.813	2.85×10^{-4}
60	−0.82	0.714	1.91	0.161	0.875	3.06×10^{-4}
90	−0.55	0.860	2.18	0.0929	0.953	3.34×10^{-4}
120	−0.27	0.964	2.45	0.0497	1.014	3.55×10^{-4}
150	0.0	1.0	2.73	0.0241	1.024	3.58×10^{-4}
180	0.27	0.964	3.00	1.11×10^{-3}	0.975	3.41×10^{-4}
210	0.55	0.860	3.27	4.77×10^{-3}	0.865	3.03×10^{-4}
240	0.82	0.714	3.54	1.90×10^{-3}	0.716	2.51×10^{-4}
270	1.09	0.552	3.82	6.78×10^{-4}	0.553	1.94×10^{-4}
300	1.36	0.397	4.09	2.33×10^{-4}	0.397	1.39×10^{-4}
330	1.64	0.261	4.36	7.45×10^{-5}	0.261	9.14×10^{-5}
360	1.91	0.161	4.64	2.11×10^{-5}	0.161	5.64×10^{-5}
390	2.18	0.0929	4.91	5.82×10^{-6}	0.093	3.26×10^{-5}
420	2.45	0.0497	5.18	1.49×10^{-6}	0.050	1.75×10^{-5}
450	2.73	0.0241	5.45	3.55×10^{-7}	0.024	8.40×10^{-6}

These values are plotted in Figure 7-4.

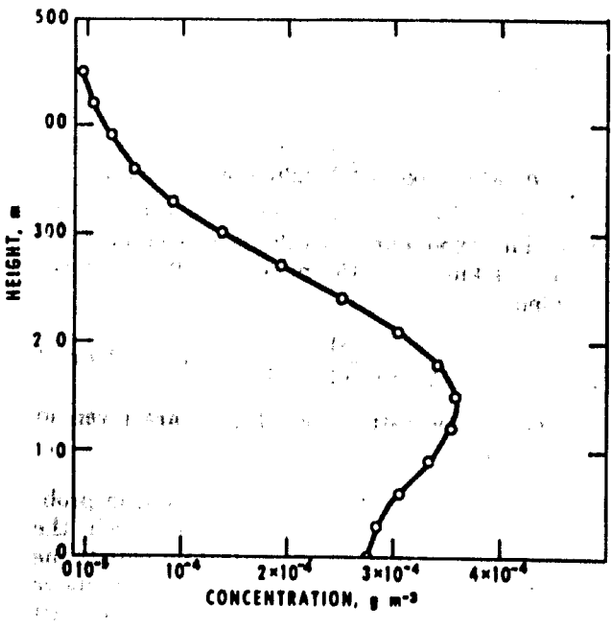

Figure 7-4. Concentration as a function of height (Problem 9).

Verifying:

$$\chi(x,0,0) = \frac{Q}{\pi \sigma_y \sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right]$$

$$= \frac{151}{\pi\, 181\,(136)\,4} \exp\left[-\frac{1}{2}\left(\frac{150}{136}\right)^2\right]$$

$$= 4.88 \times 10^{-4} \exp\left[-\tfrac{1}{2}(1.10)^2\right]$$

$$= 4.88 \times 10^{-4}\,(0.546)$$

$$= 2.7 \times 10^{-4} \text{ g m}^{-3}$$

$$\chi(x,0,150) = \frac{Q}{2\pi \sigma_y \sigma_z u}\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\}$$

$$= \frac{151}{2\pi\, 181\,(136)\,4}\left\{\exp\left[-\frac{1}{2}\left(\frac{0}{136}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{300}{136}\right)^2\right]\right\}$$

$$= 2.44 \times 10^{-4}\left\{1.0 + \exp\left[-\frac{1}{2}(2.21)^2\right]\right\}$$

$$= 2.44 \times 10^{-4}\,(1.0 + 8.70 \times 10^{-2})$$

$$= 2.44 \times 10^{-4}\,(1.087)$$

$$= 2.7 \times 10^{-4} \text{ g m}^{-3}$$

PROBLEM 11: For the power plant in problem 4, what will the maximum ground-level concentration be beneath the plume centerline and at what distance will it occur on a clear night with wind speed 4 m sec^{-1}?

SOLUTION: A clear night with wind speed 4 m sec^{-1} indicates E stability conditions. From Figure 3-9, the maximum concentration should occur at a distance of 13 km, and the maximum $\chi u/Q$ is 1.7×10^{-6}

$$\chi_{max} = \frac{\chi u}{Q} \times \frac{Q}{u} = \frac{1.7 \times 10^{-6} \times 151}{4}$$

$$= 6.4 \times 10^{-5} \text{ g m}^{-3} \text{ of } SO_2$$

PROBLEM 12: For the situation in problem 11, what would the fumigation concentration be the next morning at this point (x = 13 km) when superadiabatic lapse rates extend to include most of the plume and it is assumed that wind speed and direction remain unchanged?

SOLUTION: The concentration during fumigation conditions is given by Eq. (5.2) with the exponential involving y equal to 1. in this problem.

$$\chi_F(x,0,0;H) = \frac{Q}{\sqrt{2\pi}\, u\, \sigma_{yF}\, h_i}$$

For the stable conditions, which were assumed to be class E, at x = 13 km, σ_y = 520 m., and σ_z = 90 m. Using Eq. (5.3) to solve for h_i:
$h_i = H + 2\,\sigma_z = 150 + 2\,(90) = 330$ m.
From the horizontal spreading suggested by Eq. (5.4):

$$\sigma_{yF} = \sigma_y \text{ (stable)} + H/8 = 520 + 19 = 539$$

$$\chi_F = \frac{151}{\sqrt{2\pi}\, 4\ (539)\ 330}$$

$$= 8.5 \times 10^{-5} \text{ g m}^{-3} \text{ of } SO_2$$

Note that the fumigation concentrations under these conditions are about 1.3 times the maximum ground-level concentrations that occurred during the night (problem 11).

PROBLEM 13: An air sampling station is located at an azimuth of 203° from a cement plant at a distance of 1500 meters. The cement plant releases fine particulates (less than 15 microns diameter) at the rate of 750 pounds per hour from a 30-meter stack. What is the contribution from the cement plant to the total suspended particulate concentration at the sampling station when the wind is from 30° at 3 m sec^{-1} on a clear day in the late fall at 1600?

SOLUTION: For this season and time of day the C class stability should apply. Since the sampling station is off the plume axis, the x and y distances can be calculated:

$$x = 1500 \cos 7° = 1489$$

$$y = 1500 \sin 7° = 183$$

The source strength is:

$$Q = 750 \text{ lb hr}^{-1} \times 0.126 \frac{\text{g sec}^{-1}}{\text{lb hr}^{-1}} = 94.5 \text{ g sec}^{-1}$$

At this distance, 1489 m, for stability C, $\sigma_y = 150$ m, $\sigma_z = 87$. The contribution to the concentration can be calculated from Eq. (3.2):

$$\chi\ (x,y,0;H) = \frac{Q}{\pi\, \sigma_y\, \sigma_z\, u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right]$$

$$= \frac{94.5}{\pi\ 150\ (87)\ 3} \exp\left[-0.5\left(\frac{183}{150}\right)^2\right] \exp\left[-0.5\left(\frac{30}{87}\right)^2\right]$$

$$= \frac{94.5}{1.23 \times 10^5} \exp\left[-0.5\ (1.22)^2\right] \exp\left[-0.5\ (0.345)^2\right]$$

$$= 7.68 \times 10^{-4}\ (0.475)\ (0.943)$$

$$= 3.4 \times 10^{-4} \text{ g m}^{-3}$$

PROBLEM 14: A proposed source is to emit 72 g sec^{-1} of SO_2 from a stack 30 meters high with a diameter of 1.5 meters. The effluent gases are emitted at a temperature of 250°F (394°K) with an exit velocity of 13 m sec^{-1}. Plot on log-log paper a graph of maximum ground-level concentration as a function of wind speed for stability classes B and D. Determine the critical wind speed for these stabilities, i.e., the wind speed that results in the highest concentrations. Assume that the design atmospheric pressure is 970 mb and the design ambient air temperature is 20°C (293°K).

SOLUTION: Using Holland's effective stack height equation:

$$\Delta H = \frac{v_s\, d}{u}\left[1.5 + 2.68 \times 10^{-3}\, p\, \frac{T_s - T_a}{T_s}\, d\right]$$

$$= \frac{13\ (1.5)}{u}\left[1.5 + 2.68 \times 10^{-3}\ (970)\left(\frac{394 - 293}{394}\right)(1.5)\right]$$

$$= \frac{19.5}{u}\left[1.5 + 2.6\left(\frac{101}{394}\right) 1.5\right]$$

$$= \frac{19.5}{u}\ [1.5 + 2.6\ (0.256)\ 1.5]$$

$$= \frac{19.5}{u}\ [1.5 + 1.0]$$

$$= \frac{19.5\ (2.5)}{u}$$

$$= \frac{48.8}{u}$$

The effective stack heights for various wind speeds and stabilities are summarized in Table 7-5.

Table 7-5 EFFECTIVE STACK HEIGHTS (PROBLEM 14)

	Class D		Class B	
u, m sec^{-1}	ΔH, m	h + ΔH, m	1.15 ΔH, m	h + 1.15 ΔH, m
0.5	97.6	127.6	112.2	142.2
1.0	48.8	78.8	56.1	86.1
1.5	32.6	62.6	37.5	67.5
2	24.4	54.4	28.1	58.1
3	16.3	46.3	18.7	48.7
5	9.8	39.8	11.3	41.3
7	7.0	37.0	8.0	38.0
10	4.9	34.9		
20	2.4	32.4		

By use of the appropriate height, H, the maximum concentration for each wind speed and stability can be determined by obtaining the

maximum $\chi u/Q$ as a function of H and stability from Figure 3-9 and multiplying by the appropriate Q/u. The computations are summarized in Table 7-6, and plotted in Figure 7-5.

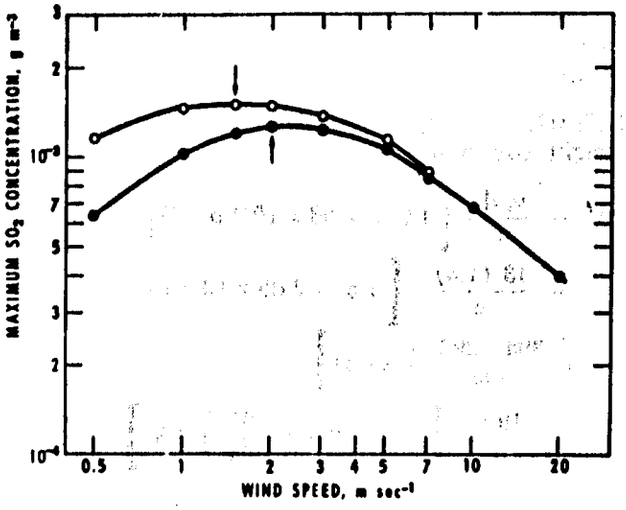

Figure 7-5. Maximum concentration as a function of wind speed (Problem 14).

Table 7-6 MAXIMUM CONCENTRATION AS A FUNCTION OF WIND SPEED (PROBLEM 14)

Stability Class	u, m sec^{-1}	H, m	$\chi u/Q_{max}$, m^{-2}	Q/u, g m^{-1}	χ_{max}, g m^{-3}
B	0.5	142.2	8.0×10^{-6}	144	1.15×10^{-3}
	1.0	86.1	2.0×10^{-5}	72	1.44×10^{-3}
	1.5	67.5	3.1×10^{-5}	48	1.49×10^{-3} ←
	2	58.1	4.1×10^{-5}	36	1.48×10^{-3}
	3	48.7	5.7×10^{-5}	24	1.37×10^{-3}
	5	41.3	7.8×10^{-5}	14.4	1.12×10^{-3}
	7	38.0	8.7×10^{-5}	10.3	8.96×10^{-4}
D	0.5	127.6	4.4×10^{-6}	144	6.34×10^{-4}
	1.0	73.8	1.42×10^{-5}	72	1.02×10^{-3}
	1.5	62.6	2.47×10^{-5}	48	1.19×10^{-3}
	2	54.4	3.5×10^{-5}	36	1.26×10^{-3} ←
	3	46.3	5.1×10^{-5}	24	1.22×10^{-3}
	5	39.8	7.3×10^{-5}	14.4	1.05×10^{-3}
	7	37.0	8.2×10^{-5}	10.3	8.45×10^{-4}
	10	34.9	9.4×10^{-5}	7.2	6.77×10^{-4}
	20	32.4	1.1×10^{-4}	3.6	3.96×10^{-4}

The wind speeds that give the highest maximum concentrations for each stability are, from Figure 7-5: B 1.5, D 2.0.

PROBLEM 15: A proposed pulp processing plant is expected to emit ½ ton per day of hydrogen sulfide from a single stack. The company property extends a minimum of 1500 meters from the proposed location. The nearest receptor is a small town of 500 inhabitants 1700 meters northeast of the plant. Plant managers have decided that it is desirable to maintain concentrations below 20 ppb (parts per billion by volume), or approximately 2.9×10^{-5} g m^{-3}, for any period greater than 30 minutes. Wind direction frequencies indicate that winds blow from the proposed location toward this town between 10 and 15 per cent of the time. What height stack should be erected? It is assumed that a design wind speed of 2 m sec^{-1} will be sufficient, since the effective stack rise will be quite great with winds less than 2 m sec^{-1}. Other than this stipulation, assume that the physical stack height and effective stack height are the same, to incorporate a slight safety factor.

SOLUTION: The source strength is:

$$Q = \frac{1000 \text{ lb day}^{-1} \times 453.6 \text{ g lb}^{-1}}{86{,}400 \text{ sec day}^{-1}} = 5.25 \text{ g sec}^{-1}$$

From Eq. (4.2):

$$\sigma_y \sigma_z = \frac{0.117\, Q}{\chi_d\, u} = \frac{0.117\,(5.25)}{(2.9 \times 10^{-5})\, 2}$$

$$= 1.06 \times 10^4 \text{ m}^2$$

At a design distance of 1500 meters (the limit of company property), $\sigma_y \sigma_z = 1.06 \times 10^4$ gives a point from Figure 4-1 about 0.2 from Class C to Class D along the line x = 1500 m. From Figure 3-3, $\sigma_z = 80$ for this stability.

$H = \sqrt{2}\, \sigma_z = 113$ meters

PROBLEM 16: In problem 15 assume that the stack diameter is to be 8 ft, the temperature of the effluent 250° F, and the stack gas velocity 45 ft sec^{-1}. From Holland's equation for effective stack height and the method used in problem 15, determine the physical stack height required to satisfy the conditions in problem 15. In estimating ΔH, use $T_a = 68°F$ and p = 920 mb.

SOLUTION: First determine the relation between ΔH and u from Holland's equation.

$v_s = 45$ ft sec^{-1} = 13.7 m sec^{-1}

d = 8 ft = 2.44 m

$T_s = 250°F = 121°C = 394°K$

$T_a = 68°F = 20°C = 293°K$

p = 920 mb

$$\Delta H = \frac{v_s\, d}{u}\left[1.5 + 2.68 \times 10^{-3}\, p\, \frac{T_s - T_a}{T_s}\, d\right]$$

$$= \frac{13.7\,(2.44)}{u}\left[1.5 + 2.68 \times 10^{-3}\,(920)\, \frac{394-293}{394}\,(2.44)\right]$$

$$= \frac{33.4}{u} [1.5 + (2.46)\ 0.256\ (2.44)]$$

$$= \frac{33.4}{u} (1.5 + 1.54)$$

$$\Delta H = \frac{102}{u}$$

The relation between $\sigma_y\ \sigma_z$ and u is:

$$\sigma_y\ \sigma_z = \frac{0.117\ Q}{\chi_d\ u} = \frac{0.117\ (5.25)}{2.9 \times 10^{-5}\ u} = \frac{2.12 \times 10^4}{u}$$

The required computations using Figure 4-1 are summarized in Table 7-7:

Table 7-7 REQUIRED PHYSICAL STACK HEIGHT AS A FUNCTION OF WIND SPEED (PROBLEM 16)

u, m sec^{-1}	ΔH, m	$\sigma_y\ \sigma_z$, m^2	Stability to Give $\sigma_y\ \sigma_z$ at 1500 m	σ_z, m	H′ = $\sqrt{2}\ \sigma_z$, m	h = H′-ΔH, m
0.5	204	4.24×10^4	0.9 from A to B	190	269	65
1.0	102	2.12×10^4	0.6 from B to C	120	170	68
1.5	68	1.41×10^4	0.9 from B to C	96	136	68
2.0	51	1.06×10^4	0.2 from C to D	76	108	57
2.5	41	8.48×10^3	0.4 from C to D	64	91	50
3.0	34	7.06×10^3	0.6 from C to D	56	79	45
5.0	20	4.24×10^3	D	42	60	40
7.0	15	3.03×10^3	0.5 from D to E	34	48	33
10.0	10	2.12×10^3	E	28	40	30
15.0	7	1.41×10^3	0.5 from E to F	23	33	26

The required physical height is 68 meters.

PROBLEM 17: A dispersion study is being made over relatively open terrain with fluorescent particles whose size yields 1.8×10^{10} particles per gram of tracer. Sampling is by membrane filters through which 9×10^{-3} m^3 of air is drawn each minute. A study involving a 1-hour release, which can be considered from ground-level, is to take place during conditions forecast to be slightly unstable with winds 5 m sec^{-1}. It is desirable to obtain a particle count of at least 20 particles upon membrane filters located at ground-level 2.0 km from the plume centerline on the sampling arc 8 km from the source. What should the total release be, in grams, for this run?

SOLUTION: The total dosage at the sampler is determined by the total sample in grams divided by the sampling rate:

$$D_T\ (\text{g sec m}^{-3}) = \frac{20 \text{ particles}}{1.8 \times 10^{10} \text{ particles g}^{-1}}$$

$$\frac{60 \text{ sec min}^{-1}}{9 \times 10^{-3} \text{ m}^3 \text{ min}^{-1}}$$

$$= \frac{1200}{16.2 \times 10^7}$$

$D_T = 7.41 \times 10^{-6}$ g sec m^{-3}

The total dosage is given in g sec m^{-3} from

$$D_T\ (x,y,0;0) = \frac{Q_T}{\pi\ u\ \sigma_y\ \sigma_z} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]$$

where Q_T is the total release in grams.

$$\text{Therefore } Q_T = \frac{\pi\ u\ \sigma_y\ \sigma_z\ D_T}{\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]}$$

For slightly unstable conditions (Class C) at x = 8 km, σ_y = 690 m, σ_z = 310 m; y = 2000 m, u = 5 m sec^{-1}

$$Q_T = \frac{\pi\ 5\ (690)\ 310\ (7.41 \times 10^{-6})}{\exp\left[-\frac{1}{2}\left(\frac{2000}{690}\right)^2\right]}$$

$$= \frac{24.9}{\exp\ [-0.5\ (2.90)^2]}$$

$$= \frac{24.9}{1.49 \times 10^{-2}}$$

$Q_T = 1670$ g

No correction has been made for the facts that the release is for 1 hour and the standard deviations represent time periods of 3 to 15 minutes.

PROBLEM 18: A release of 2 kg of fluorescent particles is made based on the results of the computation in problem 17. The conditions are class C stability and wind speed 5 m sec^{-1}. The crosswind-integrated ground-level dosage along the 8-km arc is determined from the samplers along this arc to be 8.2×10^{-1} g sec m^{-2}. What is the effective σ_z for this run?

SOLUTION: The crosswind-integrated dosage is given by:

$$D_{CWI} = \frac{2\ Q_T}{\sqrt{2\pi}\ \sigma_z\ u} \exp\left[-0.5\left(\frac{H}{\sigma_z}\right)^2\right]$$

Since the source is at ground-level, the exponential has a value of 1. Solving for σ_z:

$$\sigma_z = \frac{2\ Q_T}{\sqrt{2\pi}\ D_{CWI}\ u}$$

$$= \frac{2\ (2000)}{\sqrt{2\pi}\ (0.82)\ 5}$$

$$= \frac{4000}{10.28}$$

$\sigma_z = 389$ m

PROBLEM 19: At a point directly downwind from a ground-level source the 3- to 15-minute concentration is estimated to be 3.4×10^{-3} g m^{-3}. What would you estimate the 2-hour concentration to be at this point, assuming no change in stability or wind velocity?

SOLUTION: Using Eq. (5.12) and letting k = 3 min, s = 2 hours, and p = 0.2:

$$\chi_{2\ hour} = \left(\frac{3}{120}\right)^{0.2} 3.4 \times 10^{-3}$$

$$= \frac{1}{40^{0.2}} (3.4 \times 10^{-3})$$

$$= \frac{3.4 \times 10^{-3}}{2.09} = 1.6 \times 10^{-3} \text{ g m}^{-3}$$

Letting k = 15 min, s = 2 hours, and p = 0.17,

$$\chi_{2\ hour} = \left(\frac{15}{120}\right)^{0.17} 3.4 \times 10^{-3}$$

$$= \frac{1}{8^{0.17}} (3.4 \times 10^{-3})$$

$$= \frac{3.4 \times 10^{-3}}{1.42} = 2.4 \times 10^{-3} \text{ g m}^{-3}$$

The 2-hour concentration is estimated to be between 1.6×10^{-3} and 2.4×10^{-3} g m^{-3}.

PROBLEM 20: Two sources of SO_2 are shown as points A and B in Figure 7-6. On a sunny summer afternoon the surface wind is from 60° at 6 m sec^{-1}. Source A is a power plant emitting 1450 g sec^{-1} SO_2 from two stacks whose physical height is 120 meters and whose ΔH, from Holland's equation, is ΔH (m) = 538 (m sec^{-1})/u (m sec^{-1}). Source B is a refinery emitting 126 g sec^{-1} SO_2 from an effective height of 60 meters. The wind measured at 160 meters on a nearby TV tower is from 70° at 8.5 m sec^{-1}. Assuming that the mean direction of travel of both plumes is 245°, and there are no other sources of SO_2, what is the concentration of SO_2 at the receptor shown in the figure?

SOLUTION: Calculate the effective height of Source A using the observed wind speed at 160 meters.

$$\Delta H = \frac{538}{8.5} = 63.3$$

$$H_A = 120 + 63 = 183 \text{ m}$$

$$Q_A = 1450 \text{ g sec}^{-1}$$

$$H_B = 60 \text{ m}$$

$$Q_B = 126 \text{ g sec}^{-1}$$

For a sunny summer afternoon with wind speed 6 m sec^{-1}, the stability class to be expected is C. The equation to be used is Eq. (3.2):

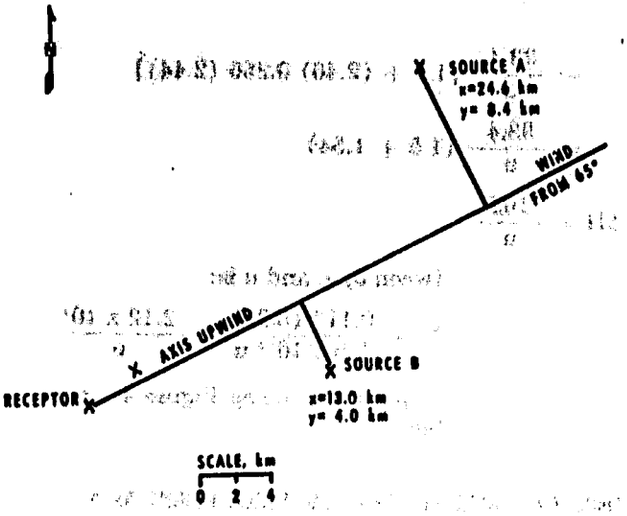

Figure 7-6. Locations of sources and receptor (Problem 20).

$$\chi(x,y,0;H) = \frac{Q}{\pi \sigma_y \sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right]$$

For Source A, x = 24.6 km, y = 8.4 km

σ_y = 1810 m, σ_z = 1120 m, u = 8.5 m sec^{-1}

$$\chi_A = \frac{1450}{\pi\ 1810\ (1120)\ 8.5} \exp\left[-0.5 \left(\frac{8400}{1810}\right)^2\right] \exp\left[-0.5 \left(\frac{183}{1120}\right)^2\right]$$

$$= \frac{1450}{5.42 \times 10^7} \exp[-0.5\ (4.64)^2] \exp[-0.5\ (0.164)^2]$$

$$= 2.67 \times 10^{-5})\ (2.11 \times 10^{-5})\ (0.987)$$

$$\chi_A = 5.6 \times 10^{-10} \text{ g m}^{-3}$$

For Source B, x = 13.0 km, y = 4.0 km.

σ_y = 1050 m, σ_z = 640 m, u = 7.0 m sec^{-1}

$$\chi_B = \frac{126}{\pi\ 1050\ (640)\ 7} \exp\left[-0.5 \left(\frac{4000}{1050}\right)^2\right] \exp\left[-0.5 \left(\frac{60}{640}\right)^2\right]$$

$$= \frac{126}{1.48 \times 10^7} \exp[-0.5\ (3.81)^2] \exp[-0.5\ (0.0938)^2]$$

$$= 8.5 \times 10^{-6}\ (7.04 \times 10^{-4})\ (0.996)$$

$$\chi_B = 6.0 \times 10^{-9} \text{ g m}^{-3}$$

$$\chi = \chi_A + \chi_B = 0.56 \times 10^{-9} + 6.0 \times 10^{-9}$$

$$= 6.6 \times 10^{-9} \text{ g m}^{-3}$$

PROBLEM 21: A stack 15 meters high emits 3 g sec^{-1} of a particular air pollutant. The surrounding terrain is relatively flat except for a rounded hill about 3 km to the northeast whose crest extends 15 meters above the stack top. What is the highest 3- to 15-minute concentration of this pollutant that can be expected on the facing slope of the hill on a clear night when the wind is blowing directly from the stack toward the hill at 4 m sec^{-1}? Assume that ΔH is less than 15 m. How much does the wind have to shift so that concentrations at this point drop below 10^{-7} g m^{-3}?

SOLUTION: A clear night with 4 m sec^{-1} indicates class E stability. Eq. (3.4) for ground-level concentrations from a ground-level source is most applicable (See Chapter 5). At 3 km for class E, $\sigma_y = 140$ m, $\sigma_z = 43$ m.

$$\chi = \frac{Q}{\pi \sigma_y \sigma_z u} = \frac{3}{\pi\, 140\ (43)\ 4}$$

$$\chi = 3.97 \times 10^{-5}\ g\ m^{-3}$$

To determine the crosswind distance from the plume centerline to produce a concentration of 10^{-7} g m^{-3} Eq. (3.8) is used:

$$y = \left[2 \ln \frac{\chi\ (x,0,0)}{\chi\ (x,y,0)} \right]^{1/2} \sigma_y$$

$$= \left[2 \ln \frac{3.97 \times 10^{-5}}{10^{-7}} \right]^{1/2} (140)$$

$$= (2 \ln 397)^{1/2}\ 140$$

$$= (2 \times 5.98)^{1/2}\ 140$$

$$= 3.46 \times 140$$

$$= 484 \text{ m.}$$

$$\tan \theta = \frac{484}{3000} = 0.1614$$

$$\theta = 9.2°$$

A wind shift of 9.2° is required to reduce the concentration to 10^{-7} g m^{-3}.

PROBLEM 22: An inventory of SO_2 emissions has been conducted in an urban area by square areas, 5000 ft (1524 meters) on a side. The emissions from one such area are estimated to be 6 g sec^{-1} for the entire area. This square is composed of residences and a few small commercial establishments. What is the concentration resulting from this area at the center of the adjacent square to the north when the wind is blowing from the south on a thinly overcast night with the wind at 2.5 m sec^{-1}? The average effective stack height of these sources is assumed to be 20 meters.

SOLUTION: A thinly overcast night with wind speed 2.5 m sec^{-1} indicates stability of class E. (It may actually be more unstable, since this is in a built-up area.) To allow for the area source, let $\sigma_{y0} = 1524/4.3 = 354$. For class E the virtual distance, $x_y = 8.5$ km. For $x = 1524$ m, $\sigma_z = 28.5$. For $x + x_y = 10{,}024$ m, $\sigma_y = 410$ m.

$$\chi = \frac{Q}{\pi \sigma_y \sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2 \right]$$

$$= \frac{6}{\pi 410\ (28.5)\ 2.5} \exp\left[-\frac{1}{2}\left(\frac{20}{28.5}\right)^2 \right]$$

$$= 6.54 \times 10^{-5}\ (0.783)$$

$$\chi = 5.1 \times 10^{-5}\ g\ m^{-3}$$

PROBLEM 23: An estimate is required of the total hydrocarbon concentration 300 meters downwind of an expressway at 1730 on an overcast day with wind speed 4 m sec^{-1}. The expressway runs north-south and the wind is from the west. The measured traffic flow is 8000 vehicles per hour during this rush hour, and the average speed of the vehicles is 40 miles per hour. At this speed the average vehicle is expected to emit 2×10^{-2} g sec^{-1} of total hydrocarbons.

SOLUTION: The expressway may be considered as a continuous infinite line source. To obtain a source strength q in grams sec^{-1} m^{-1}, the number of vehicles per meter of highway must be calculated and multiplied by the emission per vehicle.

$$\text{Vehicles/meter} = \frac{\text{Flow (vehicles hour}^{-1})}{\text{Average speed (miles hour}^{-1})\ 1600\ (\text{m mile}^{-1})}$$

$$= \frac{8000}{40 \times 1600} = 1.25 \times 10^{-1}\ (\text{vehicles m}^{-1})$$

$$q = 1.25 \times 10^{-1}\ (\text{vehicles m}^{-1}) \times 2 \times 10^{-2}\ (\text{g sec}^{-1}\ \text{vehicle}^{-1})$$

$$q = 2.5 \times 10^{-3} (\text{g sec}^{-1}\ \text{m}^{-1})$$

Under overcast conditions with wind speed 4 m sec^{-1} stability class D applies. Under D, at $x = 300$ meters, $\sigma_z = 12$ m. From Eq. (5.18):

$$\chi\ (300,0,0;0) = \frac{2q}{\sqrt{2\pi}\ \sigma_z u}$$

$$= \frac{2\ (2.5 \times 10^{-3})}{2.507\ (12)\ 4}$$

$$= 4.2 \times 10^{-6}\ g\ m^{-3} \text{ of total hydrocarbons.}$$

PROBLEM 24: A line of burning agricultural waste can be considered a finite line source 150 m long. It is estimated that the total emission of organics is at a rate of 90 g sec^{-1}. What is the 3- to 15-minute concentration of organics at a distance of 400 m directly downwind from the center of the line when the wind is blowing at 3 m sec^{-1} perpendicular to the line? Assume

that it is 1600 on a sunny fall afternoon. What is the concentration directly downwind from one end of the source?

SOLUTION: Late afternoon at this time of year implies slight insolation, which with 3 m sec^{-1} winds yields stability class C. For C stability at x = 400 m, σ_y = 45 m, σ_z = 26 m.

$$q = \frac{Q}{150} = \frac{90}{150} = 0.6 \text{ g sec}^{-1} \text{ m}^{-1}$$

Eq. (5.20) is appropriate.

$$\chi(x,0,0;0) = \frac{2q}{\sqrt{2\pi}\,\sigma_z u} \int_{p_1}^{p_2} \frac{1}{\sqrt{2\pi}} \exp(-0.5\,p^2)\,dp$$

$$p_1 = \frac{y}{\sigma_y} = \frac{-75}{45} = -1.67,\ p_2 = \frac{y}{\sigma_y} = \frac{75}{45} = +1.67$$

$$\chi(400,0,0;0) = \frac{2\,(0.6)}{\sqrt{2\pi}(26)3} \int_{-1.67}^{+1.67} \frac{1}{\sqrt{2\pi}} \exp(-0.5\,p^2)\,dp$$

$$= 6.14 \times 10^{-3}\,(0.91)$$

$$= 5.6 \times 10^{-3} \text{ g m}^{-3}$$

For a point downwind of one of the ends of the line:

$$p_1 = 0,\ p_2 = \frac{y}{\sigma_y} = \frac{150}{45} = +3.33$$

$$\chi(400,0,0;0) = 6.14 \times 10^{-3} \int_{0}^{+3.33} \frac{1}{\sqrt{2\pi}} \exp(-0.5\,p^2)\,dp$$

$$= 6.\ 4 \times 10^{-3}\,(0.4995)$$

$$= 3.\ \ \times 10^{-3} \text{ g m}^{-3}$$

PROBLEM 25: A core melt-down of a power reactor that has been operating for over a year occurs at 0200, releasing 1.5 x 10^6 curies of activity (1 second after the accident) into the atmosphere of the containment vessel. This total activity can be expected to decay according to $\left(\frac{t}{t_o}\right)^{-0.2}$. It is estimated that about 5.3 x 10^4 curies of this activity is due to iodine-131, which has a half-life of 8.04 days. The reactor building is hemispherically shaped with a radius of 20 meters. Assume the leak rate of the building is 0.1% day^{-1}.

The accident has occurred on a relatively clear night with wind speed 2.5 m sec^{-1}. What is the concentration in the air 3 kilometers directly downwind from the source at 0400 due to all radioactive material? due to iodine-131?

SOLUTION: Source strength = leak rate x activity (corrected for decay)

$$\text{Leak rate} = \frac{0.001 \text{ day}^{-1}}{86400 \text{ sec day}^{-1}}$$

$$= 1.157 \times 10^{-8} \text{ sec}^{-1}$$

Source strength of all products

$$Q_A \text{ (curies sec}^{-1}) = 1.157 \times 10^{-8}\,(1.5 \times 10^6) \left[\frac{t \text{ (sec)}}{t_o \text{ (sec)}}\right]^{-0.2}$$

$$= 1.74 \times 10^{-2} \left(\frac{t}{1}\right)^{-0.2}$$

To determine decay of materials with the half-life given, multiply by $\exp\left(\frac{-0.693\,t}{L}\right)$ where t is time and L is half-life.

Source strength of I^{131}.

$$Q_I \text{ (curies sec}^{-1}) = 1.157 \times 10^{-8}\,(5.3 \times 10^4) \exp\left(\frac{-0.693\,t}{L}\right)$$

For I_{131} L = 6.95 x 10^5 sec

$$Q_I = 6.13 \times 10^{-4} \exp\left(\frac{-0.693\,t}{6.95 \times 10^5}\right)$$

For a clear night with wind speed 2.5 m sec^{-1}, class F applies. Approximate the spreading at the reactor shell by 2.15 σ_{yO} = 2.15 σ_{zO} = the radius of the shell = 20 m $\sigma_{yO} = \sigma_{zO}$ = 9.3 m. The virtual distances to account for this are: x_y = 250 m, x_z = 560 m.

At x = 3000 m. $x + x_y$ = 3250 m, σ_y = 100 m.
$x + x_z$ = 3560 m, σ_z = 29 m.

$$\chi(x,0,0;0) = \frac{Q}{\pi\,\sigma_y\,\sigma_z\,u} = \frac{Q}{\pi\,100\,(29)\,2.5}$$

$$= 4.4 \times 10^{-5}\,Q$$

For concentration at 0400, 3000 m downwind due to all radioactivity, t = 7200 seconds.

$$\chi_A = 4.4 \times 10^{-5}\,(1.74 \times 10^{-2})\,(7200)^{-0.2}$$
$$= 7.66 \times 10^{-7}\,(0.17)$$

$$\chi_A = 1.3 \times 10^{-7} \text{ curies m}^{-3}$$

The concentration at 0400, 3000 m downwind due to I^{131} is:

$$\chi_I = 4.4 \times 10^{-5}\,(6.13 \times 10^4) \exp\left[-0.997 \times 10^{-6}\,(7200)\right]$$

2.7×10^{-8} (1.0) The decay of I^{131} is insignificant for 2 hours

$\chi_I = 2.7 \times 10^{-8}$ curies m^{-3}

PROBLEM 26: A spill estimated at 2.9×10^6 grams of unsymmetrical dimethyl hydrazine occurs at 0300 on a clear night while a rocket is being fueled. A circular area 60 meters in diameter built around the launch pad is revetted into squares 20 feet on a side to confine to as small an area as possible any spilled toxic liquids. In this spill only one such 20- by 20-foot area is involved. At the current wind speed of 2 m sec^{-1}, it is estimated that the evaporation rate will be 1100 g sec^{-1}. The wind direction is predicted to be from 310° ± 15° for the next hour. Table 7-8 gives the emergency tolerance limits for UDMH vapor.

Table 7-8 EMERGENCY TOLERANCE LIMITS FOR UDMH VAPOR VERSUS EXPOSURE TIME

Time, minutes	Emergency Tolerance Limits, g m^{-3}
5	1.2×10^{-1}
15	8.6×10^{-2}
30	4.9×10^{-2}
60	2.5×10^{-2}

What area should be evacuated?

SOLUTION: From Table 3-1, the stability class is determined to be Class F. This is not a point source but a small area source. Allowing 4.3 σ_{y0} to equal the width of the wetted area, 6.1 meters (20 feet), σ_{y0} = 1.4 meters. In attempting to determine the virtual distance, x_y, it is found to be less than 100 meters, and will be approximated by 40 meters. The release will take:

$$\frac{2.9 \times 10^6 \text{ g}}{1.1 \times 10^3 \text{ g sec}^{-1}} = 2.64 \times 10^3 \text{ sec} = 44 \text{ min.}$$

Therefore the concentration for an exposure time of 1 hour (2.5×10^{-2} g m^{-3}) is of main concern.

The equation for calculation of downwind concentrations is Eq. (3.4):

$$\chi(x,0,0;0) = \frac{Q}{\pi \sigma_y \sigma_z u}$$ where σ_y is a function of $x + x_y$.

Values of the parameters and of χ are given in Table 7-9.

Table 7-9 DETERMINATION OF CONCENTRATION AS A FUNCTION OF DISTANCE (PROBLEM 26)

x, km	σ_z, m	$x + x_y$, km	σ_y, m	χ, g m^{-3}
0.1	2.3	0.14	5.5	13.9
0.3	5.6	0.34	12.5	2.5
0.6	9.7	0.64	22	8.2×10^{-1}
1	14	1.04	35	3.6×10^{-1}
3	27	3.04	93	7.0×10^{-2}
6	37	6.04	175	2.7×10^{-2}
10	47	10.04	275	1.4×10^{-2}

These values of χ are graphed as a function of x in Figure 7-7. The downwind concentration drops below the critical value of 2.5×10^{-2} at a distance of 6.5 km.

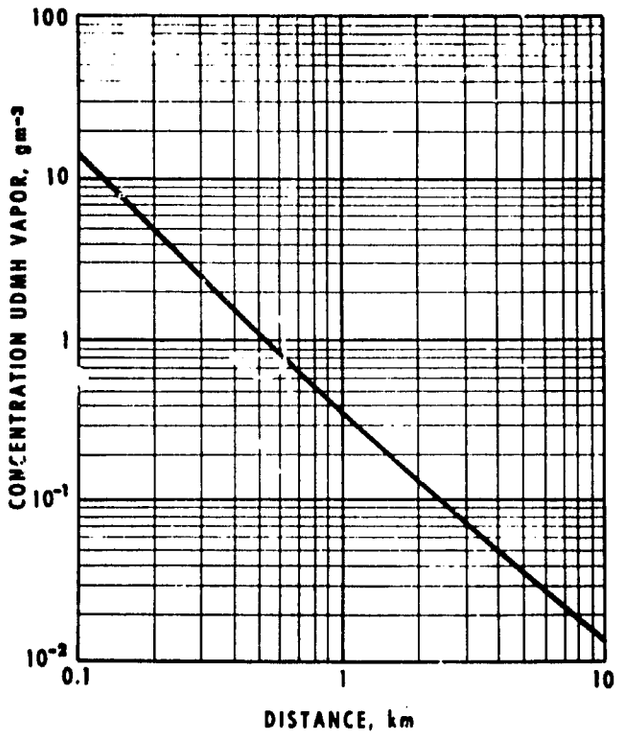

Figure 7-7. Concentration of UDMH as a function of downwind distance (Problem 26).

Calculated widths within a given isopleth are summarized in Table 7-10.

The maximum width of the area encompassed by an isopleth is about 140 meters from the downwind position. Since the wind direction is expected to be from 310° ± 15°, the sector at an azimuth of 115° to 145° plus a 140-meter rectangle on either side should be evacuated. See Figure 7-8.

Table 7-10. DETERMINATION OF WIDTHS WITHIN ISOPLETHS (PROBLEM 26)

x, km	$x + x_y$, km	σ_y, m	χ (centerline), g m^{-3}	χ (isopleth) / χ (centerline)	y / σ_y	y, m
0.1	0.14	5.5	13.9	1.8×10^{-3}	3.55	20
0.5	0.54	19	1.1	2.27×10^{-2}	2.75	52
1.0	1.04	35	3.6×10^{-1}	6.94×10^{-2}	2.31	80
2.0	2.04	66	1.3×10^{-1}	1.92×10^{-1}	1.82	120
3.0	3.04	93	7.0×10^{-2}	3.57×10^{-1}	1.44	134
4.0	4.04	120	4.8×10^{-2}	5.20×10^{-1}	1.14	137
5.0	5.04	149	3.5×10^{-2}	7.14×10^{-1}	0.82	122
6.0	6.04	175	2.7×10^{-2}	9.26×10^{-1}	0.39	68

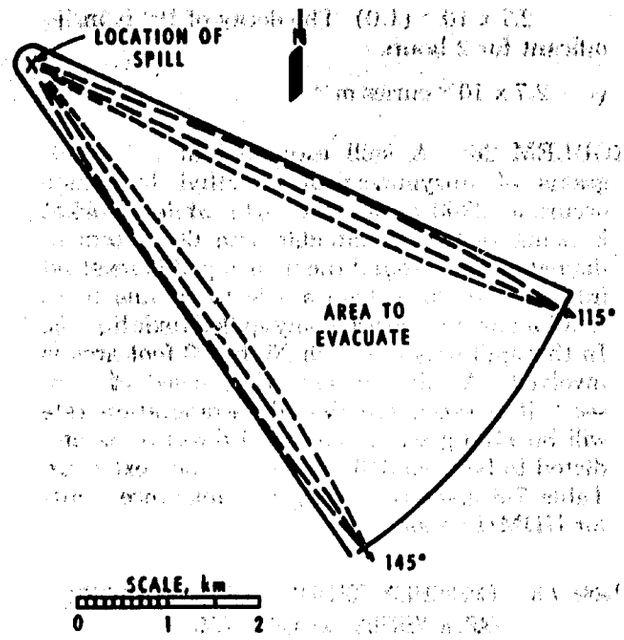

Figure 7-8. Possible positions of the 2.5×10^{-2} g m^{-3} isopleth and the evacuation area (Problem 26).

APPENDICES

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Appendix 1: ABBREVIATIONS AND SYMBOLS

Abbreviations

cal calorie
g gram
°K degrees Kelvin
m meter
mb millibar
sec second

Symbols

a ratio of horizontal eddy velocity to vertical eddy velocity
c_p specific heat at constant pressure
C_y Sutton horizontal dispersion parameter
C_z Sutton vertical dispersion parameter
d inside stack diameter at stack top
D_T (x,y,0;H) Total dosage
e 2.7183, the base of natural logarithms
f (O,S,N) frequency of wind direction for a given stability and wind speed class
h physical stack height
h_i height of the base of an inversion
H effective height of emission
H_u effective height of emission for a particular wind speed
k von Karman's constant, approximately equal to 0.4
K eddy diffusivity
L two uses: 1. the height of an air layer that is relatively stable compared to the layer beneath it; a lid
2. the half-life of a radioactive material
n Sutton's exponent
N an index for wind speed class
p three uses: 1. Bosanquet's horizontal dispersion parameter
2. atmospheric pressure
3. a dummy variable in the equation for a Gaussian distribution.
q two uses: 1. Bosanquet's vertical dispersion parameter
2. emission rate per length of a line source
Q emission rate of a source
Q_T total emission during an entire release
R net rate of sensible heating of an air column by solar radiation
s the length of the edge of a square area source
S an index for stability
t_k a short time period
t_m time required for the mixing layer to develop from the top of the stack to the top of the plume
t_n a time period
T_a ambient air temperature
T_s stack gas temperature at stack top
u wind speed
u_N a mean wind speed for the wind speed class N.
v′ horizontal eddy velocity
v_s stack gas velocity at the stack top
v_x a velocity used by Calder
w′ vertical eddy velocity
x distance downwind in the direction of the mean wind
x_d design distance, a particular downwind distance used for design purposes
x_L the distance at which $\sigma_z = 0.47L$
x_x a virtual distance so that σ_x (x_x) equals the initial standard deviation, σ_{xo}
x_y a virtual distance so that σ_y (x_y) equals the initial standard deviation, σ_{yo}
x_z a virtual distance so that σ_z (x_z) equals the initial standard deviation, σ_{zo}
y crosswind distance
z height above ground level
z_o roughness parameter
$\frac{\delta\Theta}{\delta z}$ the rate of change of potential temperature with height
ΔH the rise of the plume centerline above the stack top
Θ two uses: 1. wind direction azimuth or sector
2. potential temperature
π 3.1416
ρ_A ambient air density
σ_A the standard deviation of azimuth (wind direction) as determined from a wind vane or bi-directional vane
σ_E the standard deviation of wind elevation angle as determined from a bi-directional vane
σ_x the standard deviation in the downwind direction of a puff concentration distribution
σ_{xo} an initial downwind standard deviation
σ_y the standard deviation in the crosswind direction of the plume concentration distribution
σ_{yo} an initial crosswind standard deviation
σ_z the standard deviation in the vertical of the plume concentration distribution
σ_{zL} an effective σ_z equal to 0.8 L
σ_{zo} an initial vertical standard deviation
σ_{zS} the vertical standard deviation of the plume concentration at a particular downwind distance for the stability, S.

the angle between the wind direction and a line source

concentration

χ_y crosswind-integrated concentration

a ground-level concentration for design purposes

inversion break-up fumigation concentration

concentration measured over a sampling time, t_s

χ_x maximum ground-level centerline concentration with respect to downwind distance

χ_s concentration measured over a sampling time, t_s

$\frac{\chi}{Q}$ relative concentration

$\frac{\chi u}{Q}$ relative concentration normalized for wind speed

$\chi(x,y,z;H)$ concentration at the point (x, y, z) from an elevated source with effective height, H.

$\chi(x,\theta)$ the long-term average concentration at distance x, for a direction θ from a source.

Appendix 2: CHARACTERISTICS OF THE GAUSSIAN DISTRIBUTION

The Gaussian or normal distribution can be depicted by the bellshaped curve shown in Figure A-1. The equation for the ordinate value of this curve is:

$$y = \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{1}{2}\left(\frac{x-\bar{x}}{\sigma}\right)^2\right] \quad (A.1)$$

Figure A-2 gives the ordinate value at any distance from the center of the distribution (which occurs at x). This information is also given in Table A-1. Figure A-3 gives the area under the Gaussian curve from $-\infty$ to a particular value of p where $p = \frac{x-\bar{x}}{\sigma}$.

This area is found from Eq. (A.2):

$$\text{Area } (-\infty \text{ to } p) = \int_{-\infty}^{p} \frac{1}{\sqrt{2\pi}} \exp(-0.5\,p^2)\,dp \quad (A.2)$$

Figure A-4 gives the area under the Gaussian curve from $-p$ to $+p$. This can be found from Eq. (A.3):

$$\text{Area } (-p \text{ to } +p) = \int_{-p}^{+p} \frac{1}{\sqrt{2\pi}} \exp(-0.5\,p^2)\,dp \quad (A.3)$$

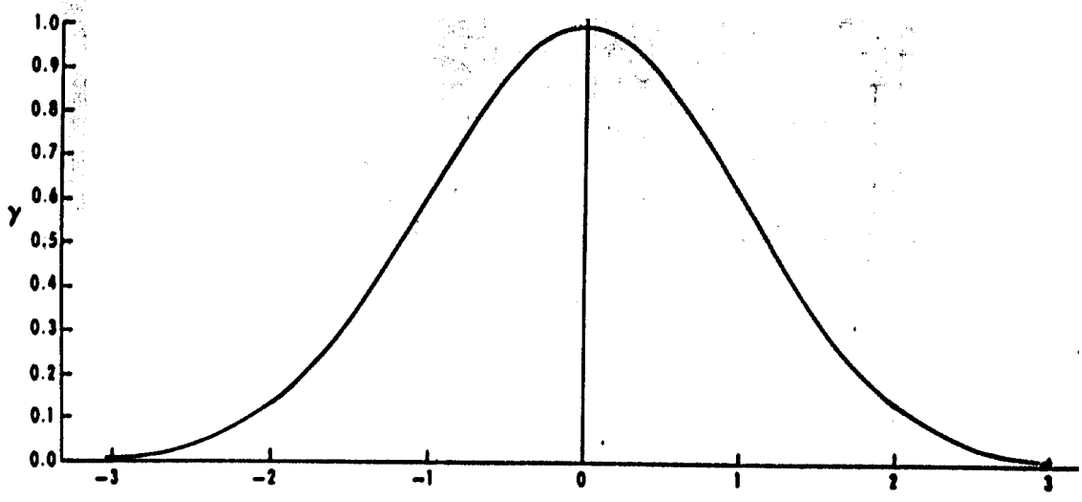

Figure A-1. The Gaussian distribution curve.

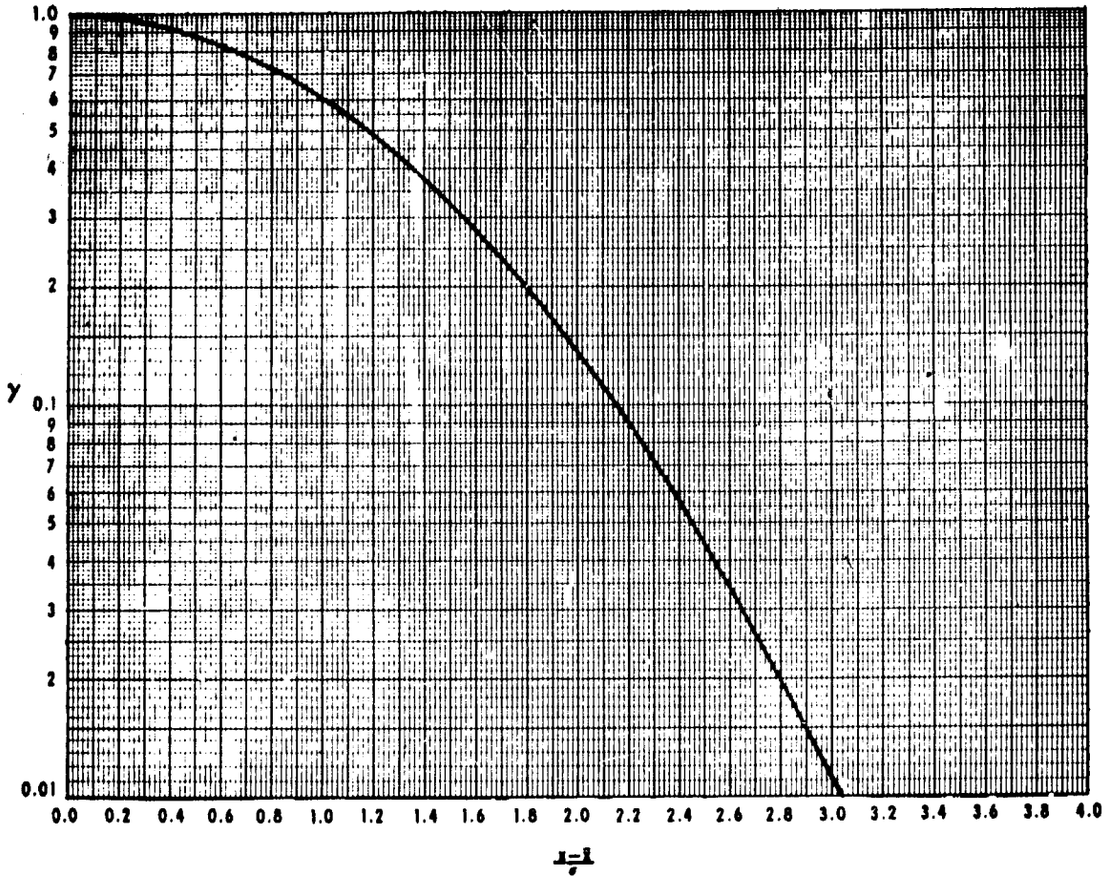

Figure A-2. Ordinate values of the Gaussian distribution.

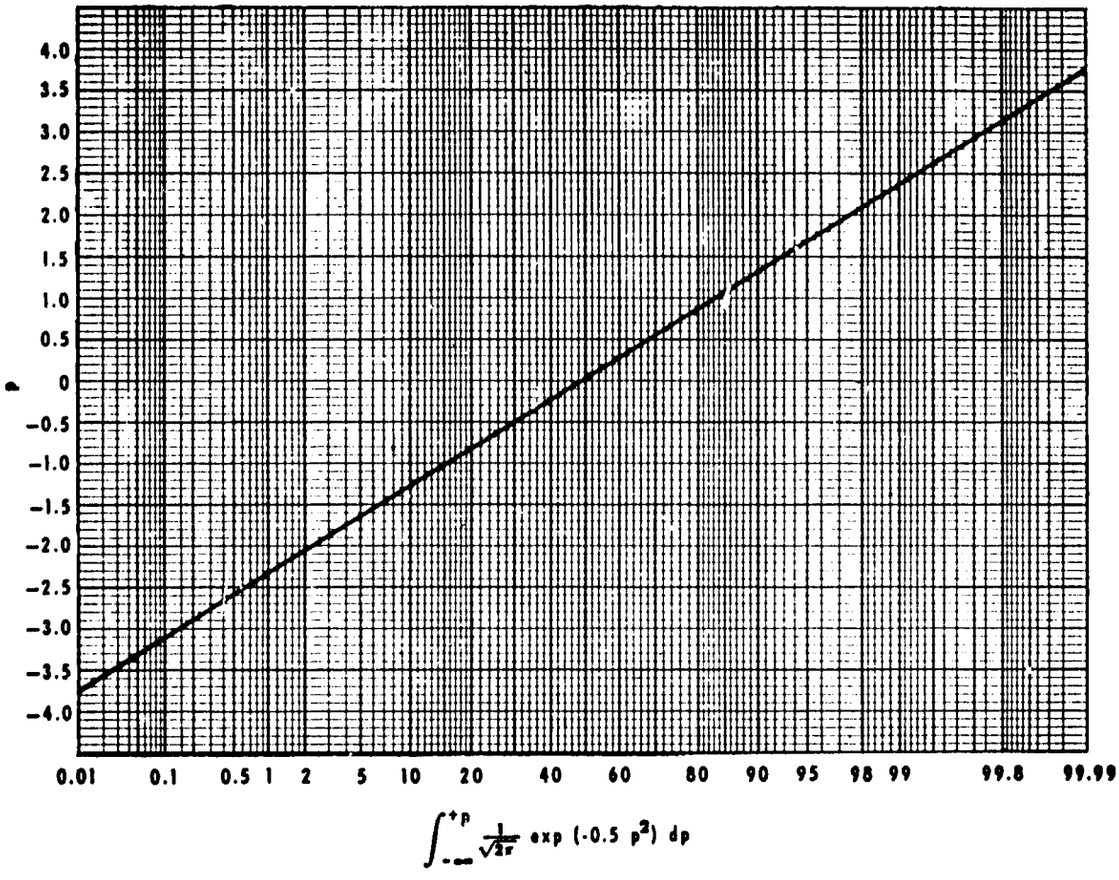

Figure A-3. Area under the Gaussian distribution curve from $-\infty$ to p.

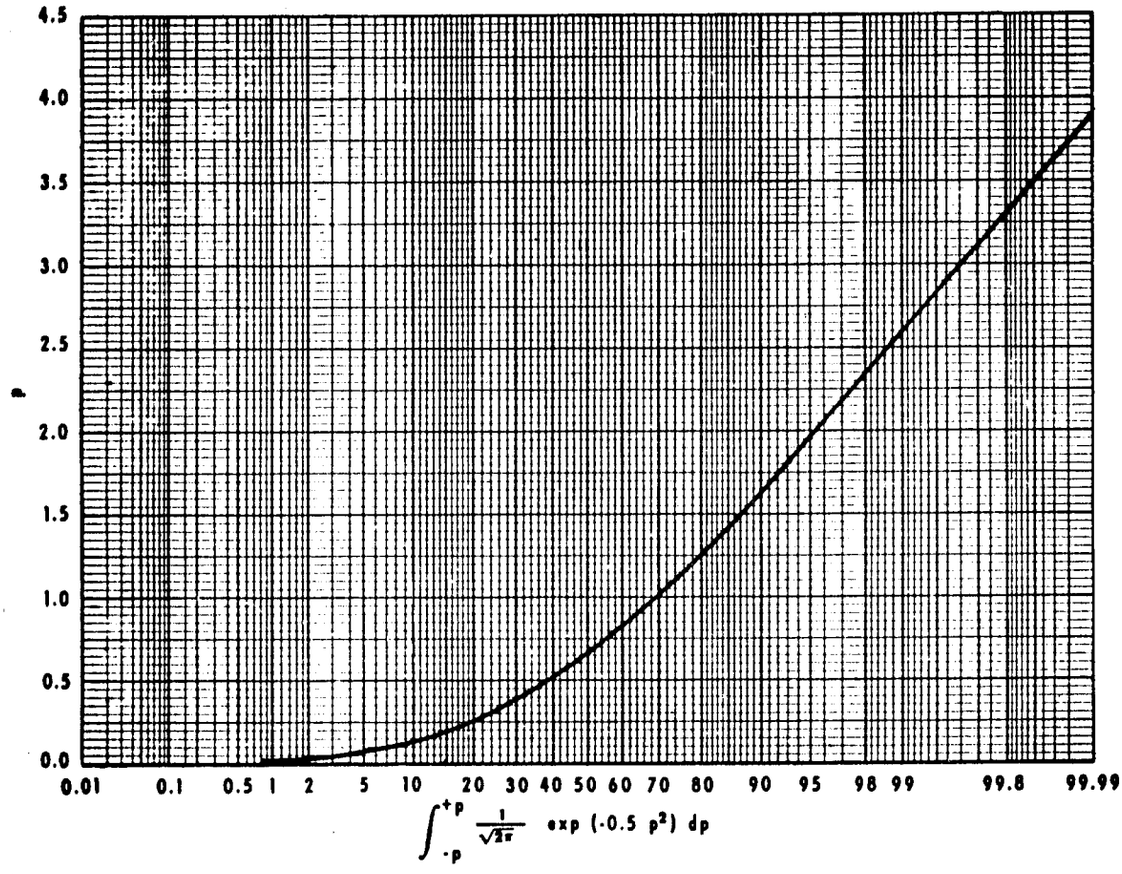

Figure A-4. Area under the Gaussian distribution curve between —p and +p.

Appendix 3: SOLUTIONS TO EXPONENTIALS

Expressions of the form exp $[-0.5\ A^2]$ where A is H/σ_z or y/σ_y frequently must be evaluated. Table A-1 gives B as a function of A where B = exp $[-0.5\ A^2]$. The sign and digits to the right of the E are to be considered as an exponent of 10. For example, if A is 3.51, B is given as 2.11E — 03 which means 2.11×10^{-3}

Table A-1 SOLUTIONS TO EXPONENTIALS B = exp [—0.5A²]
The notation 2.16 E-1 means 2.16 x 10^{-1}

A	0.00 B	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.00	1.00E 0	1.00E 0	10.00E -1	10.00E -1	9.99E -1	9.99E -1	9.98E -1	9.98E -1	[illegible]	9.96E -1
0.10	9.95E -1	9.94E -1	9.93E -1	9.92E -1	9.90E -1	9.89E -1	9.87E -1	9.86E -1	9.84E -1	9.82E -1
0.20	9.80E -1	9.78E -1	9.76E -1	9.74E -1	9.72E -1	9.69E -1	9.67E -1	9.64E -1	9.62E -1	9.59E -1
0.30	9.56E -1	9.53E -1	9.50E -1	9.47E -1	9.44E -1	9.41E -1	9.37E -1	9.34E -1	9.30E -1	9.27E -1
0.40	9.23E -1	9.19E -1	9.16E -1	9.12E -1	9.08E -1	9.04E -1	9.00E -1	8.95E -1	8.91E -1	8.87E -1
0.50	8.83E -1	8.78E -1	8.74E -1	8.69E -1	8.64E -1	8.60E -1	8.55E -1	8.50E -1	8.45E -1	8.40E -1
0.60	8.35E -1	8.30E -1	8.25E -1	8.20E -1	8.15E -1	8.10E -1	8.04E -1	7.99E -1	7.94E -1	7.88E -1
0.70	7.83E -1	7.77E -1	7.72E -1	7.66E -1	7.61E -1	7.55E -1	7.49E -1	7.44E -1	7.38E -1	7.32E -1
0.80	7.26E -1	7.20E -1	7.15E -1	7.09E -1	7.03E -1	6.97E -1	6.91E -1	6.85E -1	6.79E -1	6.73E -1
0.90	6.67E -1	6.61E -1	6.55E -1	6.49E -1	6.43E -1	6.37E -1	6.31E -1	6.25E -1	6.19E -1	6.13E -1
1.00	6.07E -1	6.01E -1	5.94E -1	5.88E -1	5.82E -1	5.76E -1	5.70E -1	5.64E -1	5.58E -1	5.52E -1
1.10	5.46E -1	5.40E -1	5.34E -1	5.28E -1	5.22E -1	5.16E -1	5.10E -1	5.04E -1	4.99E -1	4.93E -1
1.20	4.87E -1	4.81E -1	4.75E -1	4.69E -1	4.64E -1	4.58E -1	4.52E -1	4.46E -1	4.41E -1	4.35E -1
1.30	4.30E -1	4.24E -1	4.18E -1	4.13E -1	4.08E -1	4.02E -1	3.97E -1	3.91E -1	3.86E -1	3.81E -1
1.40	3.75E -1	3.70E -1	3.65E -1	3.60E -1	3.55E -1	3.50E -1	3.45E -1	3.39E -1	3.35E -1	3.30E -1
1.50	3.25E -1	3.20E -1	3.15E -1	3.10E -1	3.06E -1	3.01E -1	2.96E -1	2.92E -1	2.87E -1	2.83E -1
1.60	2.78E -1	2.74E -1	2.69E -1	2.65E -1	2.61E -1	2.56E -1	2.52E -1	2.48E -1	2.44E -1	2.40E -1
1.70	2.36E -1	2.32E -1	2.28E -1	2.24E -1	2.20E -1	2.16E -1	2.13E -1	2.09E -1	2.05E -1	2.02E -1
1.80	1.98E -1	1.94E -1	1.91E -1	1.87E -1	1.84E -1	1.81E -1	1.77E -1	1.74E -1	1.71E -1	1.68E -1
1.90	1.65E -1	1.61E -1	1.58E -1	1.55E -1	1.52E -1	1.49E -1	1.47E -1	1.44E -1	1.41E -1	1.38E -1
2.00	1.35E -1	1.33E -1	1.30E -1	1.27E -1	1.25E -1	1.22E -1	1.20E -1	1.17E -1	1.15E -1	1.13E -1
2.10	1.10E -1	1.08E -1	1.06E -1	1.04E -1	1.01E -1	9.91E -2	9.70E -2	9.50E -2	9.29E -2	9.09E -2
2.20	8.89E -2	8.70E -2	8.51E -2	8.32E -2	8.14E -2	7.96E -2	7.78E -2	7.60E -2	7.43E -2	7.27E -2
2.30	7.10E -2	6.94E -2	6.78E -2	6.62E -2	6.47E -2	6.32E -2	6.17E -2	6.03E -2	5.89E -2	5.75E -2
2.40	5.61E -2	5.48E -2	5.35E -2	5.22E -2	5.10E -2	4.97E -2	4.85E -2	4.73E -2	4.62E -2	4.51E -2
2.50	4.39E -2	4.29E -2	4.18E -2	4.07E -2	3.97E -2	3.87E -2	3.78E -2	3.68E -2	3.59E -2	3.49E -2
2.60	3.41E -2	3.32E -2	3.23E -2	3.15E -2	3.07E -2	2.99E -2	2.91E -2	2.83E -2	2.76E -2	2.68E -2
2.70	2.61E -2	2.54E -2	2.47E -2	2.41E -2	2.34E -2	2.28E -2	2.22E -2	2.16E -2	2.10E -2	2.04E -2
2.80	1.98E -2	1.93E -2	1.88E -2	1.82E -2	1.77E -2	1.72E -2	1.67E -2	1.63E -2	1.58E -2	1.54E -2
2.90	1.49E -2	1.45E -2	1.41E -2	1.37E -2	1.33E -2	1.29E -2	1.25E -2	1.22E -2	1.18E -2	1.15E -2
3.00	1.11E -2	1.08E -2	1.05E -2	1.02E -2	9.85E -3	9.55E -3	9.26E -3	8.98E -3	8.71E -3	8.45E -3
3.10	8.19E -3	7.94E -3	7.70E -3	7.46E -3	7.23E -3	7.00E -3	6.79E -3	6.58E -3	6.37E -3	6.17E -3
3.20	5.98E -3	5.79E -3	5.60E -3	5.43E -3	5.25E -3	5.09E -3	4.92E -3	4.77E -3	4.61E -3	4.46E -3
3.30	4.32E -3	4.18E -3	4.04E -3	3.91E -3	3.78E -3	3.66E -3	3.54E -3	3.42E -3	3.31E -3	3.20E -3
3.40	3.09E -3	2.99E -3	2.89E -3	2.79E -3	2.69E -3	2.60E -3	2.51E -3	2.43E -3	2.35E -3	2.27E -3
3.50	2.19E -3	2.11E -3	2.04E -3	1.97E -3	1.90E -3	1.83E -3	1.77E -3	1.71E -3	1.65E -3	1.59E -3
3.60	1.53E -3	1.48E -3	1.43E -3	1.38E -3	1.33E -3	1.28E -3	1.23E -3	1.19E -3	1.15E -3	1.11E -3
3.70	1.07E -3	1.03E -3	9.89E -4	9.53E -4	9.18E -4	8.84E -4	8.51E -4	8.20E -4	7.89E -4	7.60E -4
3.80	7.32E -4	7.05E -4	6.79E -4	6.53E -4	6.28E -4	6.04E -4	5.82E -4	5.60E -4	5.38E -4	5.18E -4
3.90	4.98E -4	4.79E -4	4.61E -4	4.43E -4	4.26E -4	4.09E -4	3.93E -4	3.78E -4	3.63E -4	3.49E -4
4.00	3.34E -4	3.22E -4	3.10E -4	2.97E -4	2.86E -4	2.74E -4	2.63E -4	2.53E -4	2.43E -4	2.33E -4
4.10	2.24E -4	2.15E -4	2.06E -4	1.98E -4	1.90E -4	1.82E -4	1.75E -4	1.68E -4	1.61E -4	1.54E -4
4.20	1.48E -4	1.42E -4	1.36E -4	1.30E -4	1.25E -4	1.20E -4	1.15E -4	1.10E -4	1.05E -4	1.01E -4
4.30	9.66E -5	9.25E -5	8.86E -5	8.49E -5	8.13E -5	7.78E -5	7.45E -5	7.13E -5	6.83E -5	6.53E -5
4.40	6.25E -5	5.98E -5	5.72E -5	5.48E -5	5.24E -5	5.01E -5	4.79E -5	4.58E -5	4.38E -5	4.19E -5
4.50	4.01E -5	3.83E -5	3.66E -5	3.50E -5	3.34E -5	3.20E -5	3.05E -5	2.92E -5	2.79E -5	2.66E -5
4.60	2.54E -5	2.43E -5	2.32E -5	2.21E -5	2.11E -5	2.02E -5	1.93E -5	1.84E -5	1.75E -5	1.67E -5
4.70	1.60E -5	1.52E -5	1.45E -5	1.39E -5	1.32E -5	1.26E -5	1.20E -5	1.15E -5	1.09E -5	1.04E -5
4.80	9.93E -6	9.46E -6	9.02E -6	8.59E -6	8.19E -6	7.80E -6	7.43E -6	7.08E -6	6.74E -6	6.42E -6
4.90	6.11E -6	5.82E -6	5.54E -6	5.28E -6	5.02E -6	4.78E -6	4.55E -6	4.33E -6	4.12E -6	3.92E -6

Table A-1 (continued) SOLUTIONS TO EXPONENTIALS

A —	0.00 B	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
5.00	3.73E -6	3.55E -6	3.37E -6	3.21E -6	3.05E -6	2.90E -6	2.76E -6	2.62E -6	2.49E -6	2.37E -6
5.10	2.25E -6	2.14E -6	2.03E -6	1.93E -6	1.83E -6	1.74E -6	1.65E -6	1.57E -6	1.49E -6	1.42E -6
5.20	1.34E -6	1.28E -6	1.21E -6	1.15E -6	1.09E -6	1.04E -6	9.82E -7	9.32E -7	8.84E -7	8.38E -7
5.30	7.95E -7	7.54E -7	7.15E -7	6.78E -7	6.43E -7	6.09E -7	5.77E -7	5.47E -7	5.19E -7	4.91E -7
5.40	4.64E -7	4.41E -7	4.18E -7	3.96E -7	3.75E -7	3.55E -7	3.36E -7	3.18E -7	3.01E -7	2.85E -7
5.50	2.70E -7	2.56E -7	2.42E -7	2.29E -7	2.17E -7	2.05E -7	1.94E -7	1.83E -7	1.73E -7	1.64E -7
5.60	1.55E -7	1.47E -7	1.39E -7	1.31E -7	1.24E -7	1.17E -7	1.11E -7	1.05E -7	9.87E -8	9.32E -8
5.70	8.81E -8	8.32E -8	7.86E -8	7.42E -8	7.01E -8	6.62E -8	6.25E -8	5.90E -8	5.57E -8	5.25E -8
5.80	4.96E -8	4.68E -8	4.41E -8	4.16E -8	3.93E -8	3.70E -8	3.49E -8	3.29E -8	3.11E -8	2.93E -8
5.90	2.76E -8	2.60E -8	2.45E -8	2.31E -8	2.18E -8	2.05E -8	1.94E -8	1.82E -8	1.72E -8	1.62E -8
6.00	1.52E -8	1.43E -8	1.35E -8	1.27E -8	1.20E -8	1.13E -8	1.06E -8	9.98E -9	9.39E -9	8.84E -9
6.10	8.32E -9	7.82E -9	7.36E -9	6.92E -9	6.51E -9	6.12E -9	5.76E -9	5.41E -9	5.09E -9	4.79E -9
6.20	4.50E -9	4.23E -9	3.97E -9	3.73E -9	3.51E -9	3.29E -9	3.09E -9	2.91E -9	2.73E -9	2.56E -9
6.30	2.41E -9	2.26E -9	2.12E -9	1.99E -9	1.87E -9	1.75E -9	1.65E -9	1.55E -9	1.45E -9	1.36E -9
6.40	1.28E -9	1.20E -9	1.12E -9	1.05E -9	9.87E-10	9.25E-10	8.67E-10	8.13E-10	7.62E-10	7.14E-10
6.50	6.69E-10	6.27E-10	5.88E-10	5.50E-10	5.16E-10	4.83E-10	4.52E-10	4.24E-10	3.97E-10	3.71E-10
6.60	3.48E-10	3.25E-10	3.05E-10	2.85E-10	2.67E-10	2.50E-10	2.34E-10	2.19E-10	2.04E-10	1.91E-10
6.70	1.79E-10	1.67E-10	1.56E-10	1.46E-10	1.37E-10	1.28E-10	1.19E-10	1.12E-10	1.04E-10	9.74E-11
6.80	9.10E-11	8.50E-11	7.94E-11	7.42E-11	6.93E-11	6.47E-11	6.04E-11	5.64E-11	5.27E-11	4.92E-11
6.90	4.59E-11	4.28E-11	4.00E-11	3.73E-11	3.48E-11	3.25E-11	3.03E-11	2.82E-11	2.63E-11	2.46E-11
7.00	2.29E-11	2.14E-11	1.99E-11	1.86E-11	1.73E-11	1.61E-11	1.50E-11	1.40E-11	1.30E-11	1.22E-11
7.10	1.13E-11	1.05E-11	9.81E-12	9.14E-12	8.51E-12	7.92E-12	7.38E-12	6.87E-12	6.39E-12	5.95E-12
7.20	5.54E-12	5.15E-12	4.79E-12	4.46E-12	4.15E-12	3.86E-12	3.59E-12	3.34E-12	3.10E-12	2.88E-12
7.30	2.68E-12	2.49E-12	2.32E-12	2.15E-12	2.00E-12	1.86E-12	1.73E-12	1.60E-12	1.49E-12	1.38E-12
7.40	1.29E-12	1.19E-12	1.11E-12	1.03E-12	9.55E-13	8.87E-13	8.23E-13	7.64E-13	7.09E-13	6.58E-13
7.50	6.10E-13	5.66E-13	5.25E-13	4.87E-13	4.52E-13	4.19E-13	3.88E-13	3.60E-13	3.34E-13	3.09E-13
7.60	2.87E-13	2.66E-13	2.46E-13	2.28E-13	2.11E-13	1.96E-13	1.81E-13	1.68E-13	1.56E-13	1.44E-13
7.70	1.34E-13	1.24E-13	1.14E-13	1.06E-13	9.80E-14	9.07E-14	8.39E-14	7.77E-14	7.19E-14	6.65E-14
7.80	6.15E-14	5.69E-14	5.26E-14	4.86E-14	4.50E-14	4.16E-14	3.84E-14	3.55E-14	3.28E-14	3.04E-14
7.90	2.80E-14	2.59E-14	2.39E-14	2.21E-14	2.04E-14	1.89E-14	1.74E-14	1.61E-14	1.49E-14	1.37E-14
8.00	1.27E-14	1.17E-14	1.08E-14	9.96E-15	9.19E-15	8.48E-15	7.82E-15	7.22E-15	6.66E-15	6.14E-15
8.10	5.66E-15	5.22E-15	4.81E-15	4.44E-15	4.09E-15	3.77E-15	3.48E-15	3.20E-15	2.95E-15	2.72E-15
8.20	2.51E-15	2.31E-15	2.13E-15	1.96E-15	1.80E-15	1.66E-15	1.53E-15	1.41E-15	1.30E-15	1.19E-15
8.30	1.10E-15	1.01E-15	9.30E-16	8.56E-16	7.87E-16	7.24E-16	6.66E-16	6.13E-16	5.64E-16	5.18E-16
8.40	4.77E-16	4.38E-16	4.03E-16	3.70E-16	3.40E-16	3.13E-16	2.87E-16	2.64E-16	2.43E-16	2.23E-16
8.50	2.05E-16	1.88E-16	1.73E-16	1.59E-16	1.46E-16	1.34E-16	1.23E-16	1.13E-16	1.03E-16	9.49E-17
8.60	8.71E-17	7.99E-17	7.33E-17	6.72E-17	6.17E-17	5.66E-17	5.19E-17	4.76E-17	4.36E-17	4.00E-17
8.70	3.67E-17	3.36E-17	3.08E-17	2.82E-17	2.59E-17	2.37E-17	2.17E-17	1.99E-17	1.82E-17	1.67E-17
8.80	1.53E-17	1.40E-17	1.28E-17	1.17E-17	1.07E-17	9.83E-18	9.00E-18	8.23E-18	7.53E-18	6.89E-18
8.90	6.31E-18	5.77E-18	5.28E-18	4.83E-18	4.41E-18	4.04E-18	3.69E-18	3.37E-18	3.08E-18	2.82E-18
9.00	2.58E-18	2.36E-18	2.15E-18	1.97E-18	1.80E-18	1.64E-18	1.50E-18	1.37E-18	1.25E-18	1.14E-18
9.10	1.04E-18	9.52E-19	8.69E-19	7.93E-19	7.24E-19	6.61E-19	6.03E-19	5.50E-19	5.02E-19	4.58E-19
9.20	4.18E-19	3.81E-19	3.47E-19	3.17E-19	2.89E-19	2.63E-19	2.40E-19	2.19E-19	1.99E-19	1.82E-19
9.30	1.66E-19	1.51E-19	1.37E-19	1.25E-19	1.14E-19	1.04E-19	9.46E-20	8.61E-20	7.84E-20	7.14E-20
9.40	6.50E-20	5.92E-20	5.38E-20	4.90E-20	4.46E-20	4.06E-20	3.69E-20	3.36E-20	3.05E-20	2.78E-20
9.50	2.53E-20	2.30E-20	2.09E-20	1.90E-20	1.73E-20	1.57E-20	1.43E-20	1.30E-20	1.18E-20	1.07E-20
9.60	9.72E-21	8.83E-21	8.02E-21	7.29E-21	6.62E-21	6.01E-21	5.46E-21	4.95E-21	4.50E-21	4.08E-21
9.70	3.70E-21	3.36E-21	3.05E-21	2.77E-21	2.51E-21	2.28E-21	2.07E-21	1.87E-21	1.70E-21	1.54E-21
9.80	1.40E-21	1.27E-21	1.15E-21	1.04E-21	9.43E-22	8.55E-22	7.75E-22	7.02E-22	6.36E-22	5.76E-22
9.90	5.22E-22	4.73E-22	4.28E-22	3.88E-22	3.51E-22	3.18E-22	2.88E-22	2.60E-22	2.36E-22	2.13E-22

Appendix 4: CONSTANTS, CONVERSION EQUATIONS, CONVERSION TABLES

Constants

$$e = 2.7183 \quad \frac{1}{e} = 0.3679$$

$$\pi = 3.1416 \quad \frac{1}{\pi} = 0.3183$$

$$2\pi = 6.2832 \quad \frac{1}{2\pi} = 0.1592$$

$$\sqrt{2\pi} = 2.5066 \quad \frac{1}{\sqrt{2\pi}} = 0.3989$$

$$\frac{2}{\sqrt{2\pi}} = 0.7979$$

$$(2\pi)^{3/2} = 15.75$$

Conversion Equations and Tables

$$T(°C) = 5/9\ (T(°F) - 32)$$

$$T(°K) = T(°C) + 273.16$$

$$T(°F) = (9/5\ T(°C)\ ) + 32$$

CONVERSION FACTORS - VELOCITY

GIVEN UNITS \ DESIRED UNITS	METERS PER SEC	FT PER SEC	FT PER MIN	KM PER HR	MI(STAT) PER HR	KNOTS	MI(STAT) PER DAY
METERS PER SEC	1.0000 E 00	3.2808 E 00	1.9685 E 02	3.6000 E 00	2.2369 E 00	1.9425 E 00	5.3686 E 01
FT PER SEC	3.0480 E-01	1.0000 E 00	6.0000 E 01	1.0973 E 00	6.8182 E-01	5.9209 E-01	1.6364 E 01
FT PER MIN	5.0800 E-03	1.6667 E-02	1.0000 E 00	1.8288 E-02	1.1364 E-02	9.8681 E-03	2.7273 E-01
KM PER HR	2.7778 E-01	9.1134 E-01	5.4681 E 01	1.0000 E 00	6.2137 E-01	5.3959 E-01	1.4913 E 01
MI(STAT) PER HR	4.4704 E-01	1.4667 E 00	8.8000 E 01	1.6093 E 00	1.0000 E 00	8.6839 E-01	2.4000 E 01
KNOTS	5.1479 E-01	1.6889 E 00	1.0134 E 02	1.8532 E 00	1.1516 E 00	1.0000 E 00	2.7637 E 01
MI(STAT) PER DAY	1.8627 E-02	6.1111 E-02	3.6667 E 00	6.7056 E-02	4.1667 E-02	3.6183 E-02	1.0000 E 00

TO CONVERT A VALUE FROM A GIVEN UNIT TO A DESIRED UNIT, MULTIPLY THE GIVEN VALUE BY THE FACTOR OPPOSITE THE GIVEN UNITS AND BENEATH THE DESIRED UNIT. NOTE THAT E-XX MEANS 10 TO THE -XX POWER.

CONVERSION FACTORS - EMISSION RATES

GIVEN UNITS \ DESIRED UNITS	GRAMS PER SEC	GRAMS PER MIN	KG PER HOUR	KG PER DAY	LBS PER MIN	LBS PER HOUR	LBS PER DAY	TONS PER HOUR	TONS PER DAY
GRAMS PER SEC	1.0000 E 00	6.0000 E 01	3.6000 E 00	8.6400 E 01	1.3228 E-01	7.9366 E 00	1.9048 E 02	3.9683 E-03	9.5240 E-02
GRAMS PER MIN	1.6667 E-02	1.0000 E 00	6.0000 E-02	1.4400 E 00	2.2046 E-03	1.3228 E-01	3.1747 E 00	6.6139 E-05	1.5873 E-03
KG PER HOUR	2.7778 E-01	1.6667 E 01	1.0000 E 00	2.4000 E 01	3.6744 E-02	2.2046 E 00	5.2911 E 01	1.1023 E-03	2.6459 E-02
KG PER DAY	1.1574 E-02	6.9444 E-01	4.1667 E-02	1.0000 E 00	1.5310 E-03	9.1859 E-02	2.2046 E 00	4.5930 E-05	1.1023 E-03
LBS PER MIN	7.5599 E 00	4.5359 E 02	2.7216 E 01	6.5317 E 02	1.0000 E 00	6.0000 E 01	1.4400 E 03	3.0000 E-02	7.2000 E-01
LBS PER HOUR	1.2600 E-01	7.5599 E 00	4.5359 E-01	1.0886 E 01	1.6667 E-02	1.0000 E 00	2.4000 E 01	5.0000 E-04	1.2000 E-02
LBS PER DAY	5.2499 E-03	3.1499 E-01	1.8900 E-02	4.5359 E-01	6.9444 E-04	4.1667 E-02	1.0000 E 00	2.0833 E-05	5.0000 E-04
TONS PER HOUR	2.5200 E 02	1.5120 E 04	9.0718 E 02	2.1772 E 04	3.3333 E 01	2.0000 E 03	4.8000 E 04	1.0000 E 00	2.4000 E 01
TONS PER DAY	1.0500 E 01	6.2999 E 02	3.7799 E 01	9.0718 E 02	1.3889 E 00	8.3333 E 01	2.0000 E 03	4.1667 E-02	1.0000 E 00

TO CONVERT A VALUE FROM A GIVEN UNIT TO A DESIRED UNIT, MULTIPLY THE GIVEN VALUE BY THE FACTOR OPPOSITE THE GIVEN UNITS AND BENEATH THE DESIRED UNIT. NOTE THAT E-XX MEANS 10 TO THE -XX POWER.

CONVERSION FACTORS - LENGTH

GIVEN UNITS \ DESIRED UNITS	METER	CM	MICRON	KILOMETER	INCH	FOOT	YARD	MILE(STAT)	MILE(NAUT)
METER	1.0000 E 00	1.0000 E 02	1.0000 E 06	1.0000 E-03	3.9370 E 01	3.2808 E 00	1.0936 E 00	6.2137 E-4	5.3959 E-04
CM	1.0000 E-02	1.0000 E 00	1.0000 E 04	1.0000 E-05	3.9370 E-01	3.2808 E-02	1.0936 E-02	6.2137 E-06	5.3959 E-06
MICRON	1.0000 E-06	1.0000 E-04	1.0000 E 00	1.0000 E-09	3.9370 E-05	3.2808 E-06	1.0936 E-06	6.2137 E-10	5.3959 E-10
KILOMETER	1.0000 E 03	1.0000 E 05	1.0000 E 09	1.0000 E 00	3.9370 E 04	3.2808 E 03	1.0936 E 03	6.2137 E-01	5.3959 E-01
INCH	2.5400 E-02	2.5400 E 00	2.5400 E 04	2.5400 E-05	1.0000 E 00	8.3333 E-02	2.7778 E-02	1.5783 E-05	1.3706 E-05
FOOT	3.0480 E-01	3.0480 E 01	3.0480 E 05	3.0480 E-04	1.2000 E 01	1.0000 E 00	3.3333 E-01	1.8939 E-04	1.6447 E-04
YARD	9.1440 E-01	9.1440 E 01	9.1440 E 05	9.1440 E-04	3.6000 E 01	3.0000 E 00	1.0000 E 00	5.6818 E-04	4.9340 E-04
MILE(STAT)	1.6093 E 03	1.6093 E 05	1.6093 E 09	1.6093 E 00	6.3360 E 04	5.2800 E 03	1.7600 E 03	1.0000 E 00	8.6839 E-01
MILE(NAUT)	1.8532 E 03	1.8532 E 05	1.8532 E 09	1.8532 E 00	7.2962 E 04	6.0802 E 03	2.0267 E 03	1.1516 E 00	1.0000 E 00

TO CONVERT A VALUE FROM A GIVEN UNIT TO A DESIRED UNIT, MULTIPLY THE GIVEN VALUE BY THE FACTOR OPPOSITE THE GIVEN UNITS AND BENEATH THE DESIRED UNIT. NOTE THAT E-XX MEANS 10 TO THE -XX POWER.

CONVERSION FACTORS - AREA

GIVEN UNITS \ DESIRED UNITS	SQ METER	SQ KM	SQ CM	SQ INCH	SQ FOOT	SQ YARD	ACRE	SQ STAT MILE	SQ NAUT MILE
SQ METER	1.0000 E 00	1.0000 E-06	1.0000 E 04	1.5500 E 03	1.0764 E 01	1.1960 E 00	2.4710 E-04	3.8610 E-07	2.9116 E-07
SQ KM	1.0000 E 06	1.0000 E 00	1.0000 E 10	1.5500 E 09	1.0764 E 07	1.1960 E 06	2.4710 E 02	3.8610 E-01	2.9116 E-01
SQ CM	1.0000 E-04	1.0000 E-10	1.0000 E 00	1.5500 E-01	1.0764 E-03	1.1960 E-04	2.4710 E-08	3.8610 E-11	2.9116 E-11
SQ INCH	6.4516 E-04	6.4516 E-10	6.4516 E 00	1.0000 E 00	6.9444 E-03	7.7160 E-04	1.5942 E-07	2.4910 E-10	1.8785 E-10
SQ FOOT	9.2903 E-02	9.2903 E-08	9.2903 E 02	1.4400 E 02	1.0000 E 00	1.1111 E-01	2.2957 E-05	3.5870 E-08	2.7050 E-08
SQ YARD	8.3613 E-01	8.3613 E-07	8.3613 E 03	1.2960 E 03	9.0000 E 00	1.0000 E 00	2.0661 E-04	3.2283 E-07	2.4345 E-07
ACRE	4.0469 E 03	4.0469 E-03	4.0469 E 07	6.2726 E 06	4.3560 E 04	4.8400 E 03	1.0000 E 00	1.5625 E-03	1.1783 E-03
SQ STAT MILE	2.5900 E 06	2.5900 E 00	2.5900 E 10	4.0145 E 09	2.7878 E 07	3.0976 E 06	6.4000 E 02	1.0000 E 00	7.5411 E-01
SQ NAUT MILE	3.4345 E 06	3.4345 E 00	3.4345 E 10	5.3235 E 09	3.6969 E 07	4.1076 E 06	8.4869 E 02	1.3261 E 00	1.0000 E 00

TO CONVERT A VALUE FROM A GIVEN UNIT TO A DESIRED UNIT, MULTIPLY THE GIVEN VALUE BY THE FACTOR OPPOSITE THE GIVEN UNITS AND BENEATH THE DESIRED UNIT. NOTE THAT E-XX MEANS 10 TO THE -XX POWER.

CONVERSION FACTORS - VOLUME

GIVEN UNITS \ DESIRED UNITS	CU METER	LITER	CU INCH	CU FOOT	CU STAT MILE	CU NAUT MILE	U S FLUID OUNCE	U S QUART	U S GALLON
CU METER	1.0000 E 00	9.9997 E 02	6.1023 E 04	3.5314 E 01	2.3991 E-10	1.5711 E-10	3.3814 E 04	1.0567 E-03	2.6417 E 02
LITER	1.0000 E-03	1.0000 E 00	6.1025 E 01	3.5315 E-02	2.3992 E-13	1.5711 E-13	3.3815 E 01	1.0567 E-06	2.6418 E-01
CU INCH	1.6387 E-05	1.6387 E-02	1.0000 E 00	5.7870 E-04	3.9315 E-15	2.5746 E-15	5.5412 E-01	1.7316 E-08	4.3290 E-03
CU FOOT	2.8317 E-02	2.8316 E 01	1.7280 E 03	1.0000 E 00	6.7936 E-12	4.4488 E-12	9.5751 E 02	2.9922 E-05	7.4805 E 00
CU STAT MILE	4.1682 E 09	4.1681 E 12	2.5436 E 14	1.4720 E 11	1.0000 E 00	6.5486 E-01	1.4094 E 14	4.4045 E 06	1.1011 E 12
CU NAUT MILE	6.3650 E 09	6.3649 E 12	3.8842 E 14	2.2478 E 11	1.5270 E 00	1.0000 E 00	2.1523 E 14	6.7259 E 06	1.6815 E 12
U S FLUID OUNCE	2.9574 E-05	2.9573 E-02	1.8047 E 00	1.0444 E-03	7.0950 E-15	4.6462 E-15	1.0000 E 00	3.1250 E-08	7.8125 E-03
U S QUART	9.4635 E 02	9.4633 E 05	5.7750 E 07	3.3420 E 04	2.2704 E-07	1.4868 E-07	3.2000 E 07	1.0000 E 00	2.5000 E 05
U S GALLON	3.7854 E-03	3.7853 E 00	2.3100 E 02	1.3368 E-01	9.0817 E-13	5.9472 E-13	1.2800 E 02	4.0000 E-06	1.0000 E 00

TO CONVERT A VALUE FROM A GIVEN UNIT TO A DESIRED UNIT, MULTIPLY THE GIVEN VALUE BY THE FACTOR OPPOSITE THE GIVEN UNITS AND BENEATH THE DESIRED UNIT. NOTE THAT E-XX MEANS 10 TO THE -XX POWER.

CONVERSION FACTORS - MASS

GIVEN UNITS \ DESIRED UNITS	GRAM	MICROGRAM	KILOGRAM	METRIC TON	SHORT TON	LONG TON	GRAIN	OUNCE	LB (AVDP)
GRAM	1.0000 E 00	1.0000 E 06	1.0000 E-03	1.0000 E-06	1.1023 E-06	9.8421 E-07	1.5432 E 01	3.5274 E-02	2.2046 E-03
MICROGRAM	1.0000 E-06	1.0000 E 00	1.0000 E-09	1.0000 E-12	1.1023 E-12	9.8421 E-13	1.5432 E-05	3.5274 E-08	2.2046 E-09
KILOGRAM	1.0000 E 03	1.0000 E 09	1.0000 E 00	1.0000 E-03	1.1023 E-03	9.8421 E-04	1.5432 E 04	3.5274 E 01	2.2046 E 00
METRIC TON	1.0000 E 06	1.0000 E 12	1.0000 E 03	1.0000 E 00	1.1023 E 00	9.8421 E-01	1.5432 E 07	3.5274 E 04	2.2046 E 03
SHORT TON	9.0718 E 05	9.0718 E 11	9.0718 E 02	9.0718 E-01	1.0000 E 00	8.9286 E-01	1.4000 E 07	3.2000 E 04	2.0000 E 03
LONG TON	1.0160 E 06	1.0160 E 12	1.0160 E 03	1.0160 E 00	1.1200 E 00	1.0000 E 00	1.5680 E 07	3.5840 E 04	2.2400 E 03
GRAIN	6.4799 E-02	6.4799 E 04	6.4799 E-05	6.4799 E-08	7.1428 E-08	6.3775 E-08	1.0000 E 00	2.2857 E-03	1.4286 E-04
OUNCE (AVDP)	2.8349 E 01	2.8349 E 07	2.8349 E-02	2.8349 E-05	3.1250 E-05	2.7902 E-05	4.3750 E 02	1.0000 E 00	6.4500 E-02
LB (AVDP)	4.5359 E 02	4.5359 E 08	4.5359 E-01	4.5359 E-04	5.0000 E-04	4.4643 E-04	7.0000 E 03	1.6000 E 01	1.0000 E 00

TO CONVERT A VALUE FROM A GIVEN UNIT TO A DESIRED UNIT, MULTIPLY THE GIVEN VALUE BY THE FACTOR OPPOSITE THE GIVEN UNITS AND BENEATH THE DESIRED UNIT. NOTE THAT E-XX MEANS 10 TO THE -XX POWER.

CONVERSION FACTORS - FLOW

GIVEN UNITS \ DESIRED UNITS	CU METER PER SEC	CU METER PER HR	LITER PER SEC	LITER PER MIN	LITER PER HR	CU FT PER SEC	CU FT PER MIN	CU FT PER HR	CU CM PER
CU METER PER SEC	1.0000 E 00	3.6000 E 03	9.9997 E 02	5.9998 E 04	3.5999 E 06	3.5314 E 01	2.1189 E 03	1.2713 E 05	1.0000 E 06
CU METER PER HR	2.7778 E-04	1.0000 E 00	2.7777 E-01	1.6666 E 01	9.9997 E 02	9.8096 E-03	5.8857 E-01	3.5314 E 01	2.7778 E 02
LITER PER SEC	1.0000 E-03	3.6001 E 00	1.0000 E 00	6.0000 E 01	3.6000 E 03	3.5315 E-02	2.1189 E 00	1.2714 E 02	1.0000 E 03
LITER PER MIN	1.6667 E-05	6.0002 E-02	1.6667 E-02	1.0000 E 00	6.0000 E 01	5.8859 E-04	3.5315 E-02	2.1189 E 00	1.6667 E 01
LITER PER HR	2.7779 E-07	1.0000 E-03	2.7778 E-04	1.6667 E-02	1.0000 E 00	9.8098 E-06	5.8859 E-04	3.5315 E-02	2.7779 E-01
CU FT PER SEC	2.8317 E-02	1.0194 E 02	2.8316 E 01	1.6990 E 03	1.0194 E 05	1.0000 E 00	6.0000 E 01	3.6000 E 03	2.8317 E 04
CU FT PER MIN	4.7195 E-04	1.6990 E 00	4.7194 E-01	2.8316 E 01	1.6990 E 03	1.6667 E-02	1.0000 E 00	6.0000 E 01	4.7195 E 02
CU FT PER HR	7.8658 E-06	2.8317 E-02	7.8656 E-03	4.7194 E-01	2.8316 E 01	2.7778 E-04	1.6667 E-02	1.0000 E 00	7.8658 E 00
CU CM PER SEC	1.0000 E-06	3.6000 E-03	9.9997 E-04	5.9998 E-02	3.5999 E 00	3.5314 E-05	2.1189 E-03	1.2713 E-01	1.0000 E 00

TO CONVERT A VALUE FROM A GIVEN UNIT TO A DESIRED UNIT, MULTIPLY THE GIVEN VALUE BY THE FACTOR OPPOSITE THE GIVEN AND BENEATH THE DESIRED UNIT. NOTE THAT E-XX MEANS 10 TO THE -XX POWER.

CONVERSION FACTORS - CONCENTRATION, DENSITY

GIVEN UNITS \ DESIRED UNITS	GRAM PER CU METER	MG PER CU METER	MICROGRAM PER CU M	MICROGRAM PER LITER	GRAIN PER CU FT	OUNCE PER CU FT	LB PER CU FT	GRAM PER CU FT	LB PER CU METER
GRAM PER CU METER	1.0000 E 00	1.0000 E 03	1.0000 E 06	1.0000 E 03	4.3700 E-01	9.9885 E-04	6.2428 E-05	2.8317 E-02	2.2046 E-03
MG PER CU METER	1.0000 E-03	1.0000 E 00	1.0000 E 03	1.0000 E 00	4.3700 E-04	9.9885 E-07	6.2428 E-08	2.8317 E-05	2.2046 E-06
MICROGRAM PER CU M	1.0000 E-06	1.0000 E-03	1.0000 E 00	1.0000 E-03	4.3700 E-07	9.9885 E-10	6.2428 E-11	2.8317 E-08	2.2046 E-09
MICROGRAM PER LITER	9.9997 E-04	9.9997 E-01	9.9997 E 02	1.0000 E 00	4.3699 E-04	9.9883 E-07	6.2427 E-08	2.8316 E-05	2.2046 E-06
GRAIN PER CU FT	2.2883 E 00	2.2883 E 03	2.2883 E 06	2.2884 E 03	1.0000 E 00	2.2857 E-03	1.4286 E-04	6.4799 E-02	5.0449 E-03
OUNCE PER CU FT	1.0011 E 03	1.0011 E 06	1.0011 E 09	1.0012 E 06	4.3750 E 02	1.0000 E 00	6.2500 E-02	2.8349 E 01	2.2072 E 00
LB PER CU FT	1.6018 E 04	1.6018 E 07	1.6018 E 10	1.6019 E 07	7.0000 E 03	1.6000 E 01	1.0000 E 00	4.5359 E 02	3.5314 E 01
GRAM PER CU FT	3.5314 E 01	3.5314 E 04	3.5314 E 07	3.5315 E 04	1.5432 E 01	3.5274 E-02	2.2046 E-03	1.0000 E 00	7.7855 E-02
LB PER CU METER	4.5359 E 02	4.5359 E 05	4.5359 E 08	4.5360 E 05	1.9822 E 02	4.5307 E-01	2.8317 E-02	1.2844 E 01	1.0000 E 00

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CONVERSION FACTORS - DEPOSITION RATE (SHORT TON .STAT. MILE)

GIVEN UNITS \ DESIRED UNITS	GM PER SQ M PER MO	KG PER SQ KM PER MO	MG PER SQ CM PER MO	TON PER SQ MI PER MO	OZ PER SQ FT PER MO	LB PER ACRE PERMO	GM PER SQ FT PER MO	MG PER SQ IN PER MO
GM PER SQ M PER MO	1.0000 E 00	1.0000 E 03	1.0000 E-01	2.8550 E 00	3.2771 E-03	8.9218 E 00	9.2903 E-02	6.4516 E-01
KG PER SQ KM PER MO	1.0000 E-03	1.0000 E 00	1.0000 E-04	2.8550 E-03	3.2771 E-06	8.9218 E-03	9.2903 E-05	6.4516 E-04
MG PER SQ CM PER MO	1.0000 E 01	1.0000 E 04	1.0000 E 00	2.8550 E 01	3.2771 E-02	8.9218 E 01	9.2903 E-01	6.4516 E 00
TON PER SQ MI PER MO	3.5026 E-01	3.5026 E 02	3.5026 E-02	1.0000 E 00	1.1478 E-03	3.1250 E 00	3.2541 E-02	2.2598 E-01
OZ PER SQ FT PER MO	3.0515 E 02	3.0515 E 05	3.0515 E 01	8.7120 E 02	1.0000 E 00	2.7225 E 03	2.8349 E 01	1.9687 E 02
LB PER ACRE PERMO	1.1208 E-01	1.1208 E 02	1.1208 E-02	3.2000 E-01	3.6731 E-04	1.0000 E 00	1.0413 E-02	7.2313 E-02
GM PER SQ FT PER MO	1.0764 E 01	1.0764 E 04	1.0764 E 00	3.0731 E 01	3.5274 E-02	9.6033 E 01	1.0000 E 00	6.9444 E 00
MG PER SQ IN PER MO	1.5500 E 00	1.5500 E 03	1.5500 E-01	4.4252 E 00	5.0795 E-03	1.3829 E 01	1.4400 E-01	1.0000 E 00

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CONVERSION FACTORS - PRESSURE

GIVEN UNITS \ DESIRED UNITS	MILLIBAR	BAR	ATMOSPHERE	DYNES PER SQ CM	KG PER SQ CM	LBS PER SQ IN	MM MERCURY	IN MERCURY
MILLIBAR	1.0000 E 00	1.0000 E-03	9.8692 E-04	1.0000 E 03	1.0197 E-03	1.4504 E-02	7.5006 E-01	2.9530 E-02
BAR	1.0000 E 03	1.0000 E 00	9.8692 E-01	1.0000 E 06	1.0197 E 00	1.4504 E 01	7.5006 E 02	2.9530 E 01
ATMOSPHERE	1.0133 E 03	1.0133 E 00	1.0000 E 00	1.0133 E 06	1.0332 E 00	1.4696 E 01	7.6000 E 02	2.9921 E 01
DYNES PER SQ CM	1.0000 E-03	1.0000 E-06	9.8692 E-07	1.0000 E 00	1.0197 E-06	1.4504 E-05	7.5006 E-04	2.9530 E-05
KG PER SQ CM	9.8066 E 02	9.8066 E-01	9.6784 E-01	9.8066 E 05	1.0000 E 00	1.4223 E 01	7.3556 E 02	2.8959 E 01
LBS PER SQ IN	6.8947 E 01	6.8947 E-02	6.8046 E-02	6.8947 E 04	7.0307 E-02	1.0000 E 00	5.1715 E 01	2.0360 E 00
MM MERCURY	1.3332 E 00	1.3332 E-03	1.3158 E-03	1.3332 E 03	1.3595 E-03	1.9337 E-02	1.0000 E 00	3.9370 E-02
IN MERCURY	3.3864 E 01	3.3864 E-02	3.3421 E-02	3.3864 E 04	3.4532 E-02	4.9115 E-01	2.5400 E 01	1.0000 E 00

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CONVERSION FACTORS - TIME

GIVEN UNITS \ DESIRED UNITS	SECOND	MINUTE	HOUR	WEEK	MONTH (28)	MONTH (30)	MONTH (31)	YEAR (365)	YEAR (366)
SECOND	1.0000 E 00	6.0000 E 01	3.6000 E 03	6.0480 E 05	2.4192 E 06	2.5920 E 06	2.6784 E 06	3.1536 E 07	3.1622 E 07
MINUTE	1.6667 E-02	1.0000 E 00	6.0000 E 01	1.0080 E 04	4.0320 E 04	4.3200 E 04	4.4640 E 04	5.2560 E 05	5.2704 E 05
HOUR	2.7778 E-04	1.6667 E-02	1.0000 E 00	1.6800 E 02	6.7200 E 02	7.2000 E 02	7.4400 E 02	8.7600 E 03	8.7840 E 03
WEEK	1.6534 E-06	9.9206 E-05	5.9524 E-03	1.0000 E 00	4.0000 E 00	4.2857 E 00	4.4286 E 00	5.2143 E 01	5.2286 E 01
MONTH (28)	4.1336 E-07	2.4802 E-05	1.4881 E-03	2.5000 E-01	1.0000 E 00	1.0714 E 00	1.1071 E 00	1.3036 E 01	1.3071 E 01
MONTH (30)	3.8580 E-07	2.3148 E-05	1.3889 E-03	2.3333 E-01	9.3333 E-01	1.0000 E 00	1.0333 E 00	1.2167 E 01	1.2200 E 01
MONTH (31)	3.7336 E-07	2.2401 E-05	1.3441 E-03	2.2581 E-01	9.0323 E-01	9.6774 E-01	1.0000 E 00	1.1774 E 01	1.1806 E 01
YEAR (365)	3.1710 E-08	1.9026 E-06	1.1416 E-04	1.9178 E-02	7.6712 E-02	8.2192 E-02	8.4932 E-02	1.0000 E 00	1.0027 E 00
YEAR (366)	3.1623 E-08	1.8974 E-06	1.1384 E-04	1.9126 E-02	7.6503 E-02	8.1967 E-02	8.4699 E-02	9.9727 E-01	1.0000 E 00

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CONVERSION FACTORS - POWER

GIVEN UNITS \ DESIRED UNITS	WATT (INT)	KILOWATT (INT)	MEGAWATT (INT)	CAL (INT) PER SEC	BTU PER MIN	BTU PER HR	JOULES ABS PER SEC	WATT (ABS)	ELECT. HORSEPOWER
WATT (INT)	1.0000 E 00	1.0000 E-03	1.0000 E-06	2.3880 E-01	5.6857 E-02	3.4114 E 00	1.0002 E 00	1.0002 E 00	1.3407 E-03
KILOWATT (INT)	1.0000 E 03	1.0000 E 00	1.0000 E-03	2.3880 E 02	5.6857 E 01	3.4114 E 03	1.0002 E 03	1.0002 E 03	1.3407 E 00
MEGAWATT (INT)	1.0000 E 06	1.0000 E 03	1.0000 E 00	2.3880 E 05	5.6857 E 04	3.4114 E 06	1.0002 E 06	1.0002 E 06	1.3407 E 03
CAL (INT) PER SEC	4.1876 E 00	4.1876 E-03	4.1876 E-06	1.0000 E 00	2.3810 E-01	1.4286 E 01	4.1884 E 00	4.1884 E 00	5.6145 E-03
BTU PER MIN	1.7588 E 01	1.7588 E-02	1.7588 E-05	4.2000 E 00	1.0000 E 00	6.0000 E 01	1.7591 E 01	1.7591 E 01	2.3581 E-02
BTU PER HR	2.9313 E-01	2.9313 E-04	2.9313 E-07	7.0000 E-02	1.6667 E-02	1.0000 E 00	2.9319 E-01	2.9319 E-01	3.9301 E-04
JOULES ABS PER SEC	9.9981 E-01	9.9981 E-04	9.9981 E-07	2.3875 E-01	5.6846 E-02	3.4108 E 00	1.0000 E 00	1.0000 E 00	1.3405 E-03
WATT (ABS)	9.9981 E-01	9.9981 E-04	9.9981 E-07	2.3875 E-01	5.6846 E-02	3.4108 E 00	1.0000 E 00	1.0000 E 00	1.3405 E-03
ELECT. HORSEPOWER	7.4586 E 02	7.4586 E-01	7.4586 E-04	1.7811 E 02	4.2407 E 01	2.5444 E 03	7.4600 E 02	7.4600 E 02	1.0000 E 00

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CONVERSION FACTORS - ENERGY, WORK

GIVEN UNITS \ DESIRED UNITS	ERG	DYNE-CM	ABS JOULE	CAL (INT)	CAL (15)	INT KW-HR	ABS KW-HR	BTU
ERG	1.0000 E 00	1.0000 E 00	1.0000 E-07	2.3884 E-08	2.3892 E-08	2.7773 E-14	2.7778 E-14	9.4781 E-11
DYNE-CM	1.0000 E 00	1.0000 E 00	1.0000 E-07	2.3884 E-08	2.3892 E-08	2.7773 E-14	2.7778 E-14	9.4781 E-11
ABS JOULE	1.0000 E 07	1.0000 E 07	1.0000 E 00	2.3884 E-01	2.3892 E-01	2.7773 E-07	2.7778 E-07	9.4781 E-04
CAL (INT)	4.1868 E 07	4.1868 E 07	4.1868 E 00	1.0000 E 00	1.0003 E 00	1.1628 E-06	1.1630 E-06	3.9683 E-03
CAL (15)	4.1855 E 07	4.1855 E 07	4.1855 E 00	9.9968 E-01	1.0000 E 00	1.1624 E-06	1.1626 E-06	3.9671 E-03
INT KW-HR	3.6007 E 13	3.6007 E 13	3.6007 E 06	8.6000 E 05	8.6027 E 05	1.0000 E 00	1.0002 E 00	3.4128 E 03
ABS KW-HR	3.6000 E 13	3.6000 E 13	3.6000 E 06	8.5984 E 05	8.6011 E 05	9.9981 E-01	1.0000 E 00	3.4121 E 03
BTU	1.0551 E 10	1.0551 E 10	1.0551 E 03	2.5200 E 02	2.5208 E 02	2.9302 E-04	2.9307 E-04	1.0000 E 00

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CONVERSION FACTORS - ENERGY PER UNIT AREA

GIVEN UNITS \ DESIRED UNITS	LANGLEY	CAL (15) PER SQ CM	BTU PER SQ FT	INT KW-HR PER SQ M	ABS JOULES PER SQ CM
LANGLEY	1.0000 E 00	1.0000 E 00	3.6855 E 00	1.1624 E-02	4.1855 E 00
CAL (15) PER SQ CM	1.0000 E 00	1.0000 E 00	3.6855 E 00	1.1624 E-02	4.1855 E 00
BTU PER SQ FT	2.7133 E-01	2.7133 E-01	1.0000 E 00	3.1540 E-03	1.1357 E 00
INT KW-HR PER SQ M	8.6029 E 01	8.6029 E 01	3.1706 E 02	1.0000 E 00	3.6007 E 02
ABS JOULES PER SQ CM	2.3892 E-01	2.3892 E-01	8.8054 E-01	2.7772 E-03	1.0000 E 00

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CONVERSION FACTORS - POWER PER UNIT AREA (CAL ARE 15 DEG)

GIVEN UNITS \ DESIRED UNITS	CAL PER SQ M PER SEC	CAL PER SQ CM PER MIN	LANGLEY PER MIN	CAL PER SQ CM PER DAY	BTU PER SQ FT PER MIN	BTU PER SQ FT PER DAY	ABS WATT PER SQ CM
CAL PER SQ M PER SEC	1.0000 E 00	6.0000 E-03	6.0000 E-03	8.6400 E 00	2.2113 E-02	3.1843 E 01	4.1855 E-04
CAL PER SQ CM PER MIN	1.6667 E 02	1.0000 E 00	1.0000 E 00	1.4400 E 03	3.6855 E 00	5.3071 E 03	6.9758 E-02
LANGLEY PER MIN	1.6667 E 02	1.0000 E 00	1.0000 E 00	1.4400 E 03	3.6855 E 00	5.3071 E 03	6.9758 E-02
CAL PER SQ CM PER DAY	1.1574 E-01	6.9444 E-04	6.9444 E-04	1.0000 E 00	2.5594 E-03	3.6855 E 00	4.8443 E-05
BTU PER SQ FT PER MIN	4.5222 E 01	2.7133 E-01	2.7133 E-01	3.9072 E 02	1.0000 E 00	1.4400 E 03	1.8928 E-02
BTU PER SQ FT PER DAY	3.1404 E-02	1.8843 E-04	1.8843 E-04	2.7133 E-01	6.9445 E-04	1.0000 E 00	1.3144 E-05
ABS WATT PER SQ CM	2.3892 E 03	1.4335 E 01	1.4335 E 01	2.0643 E 04	5.2833 E 01	7.6079 E 04	1.0000 E 00

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*U.S. GOVERNMENT PRINTING OFFICE: 1973-746-779/4404