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# METEOROLOGY
## AND
## ATOMIC
## ENERGY

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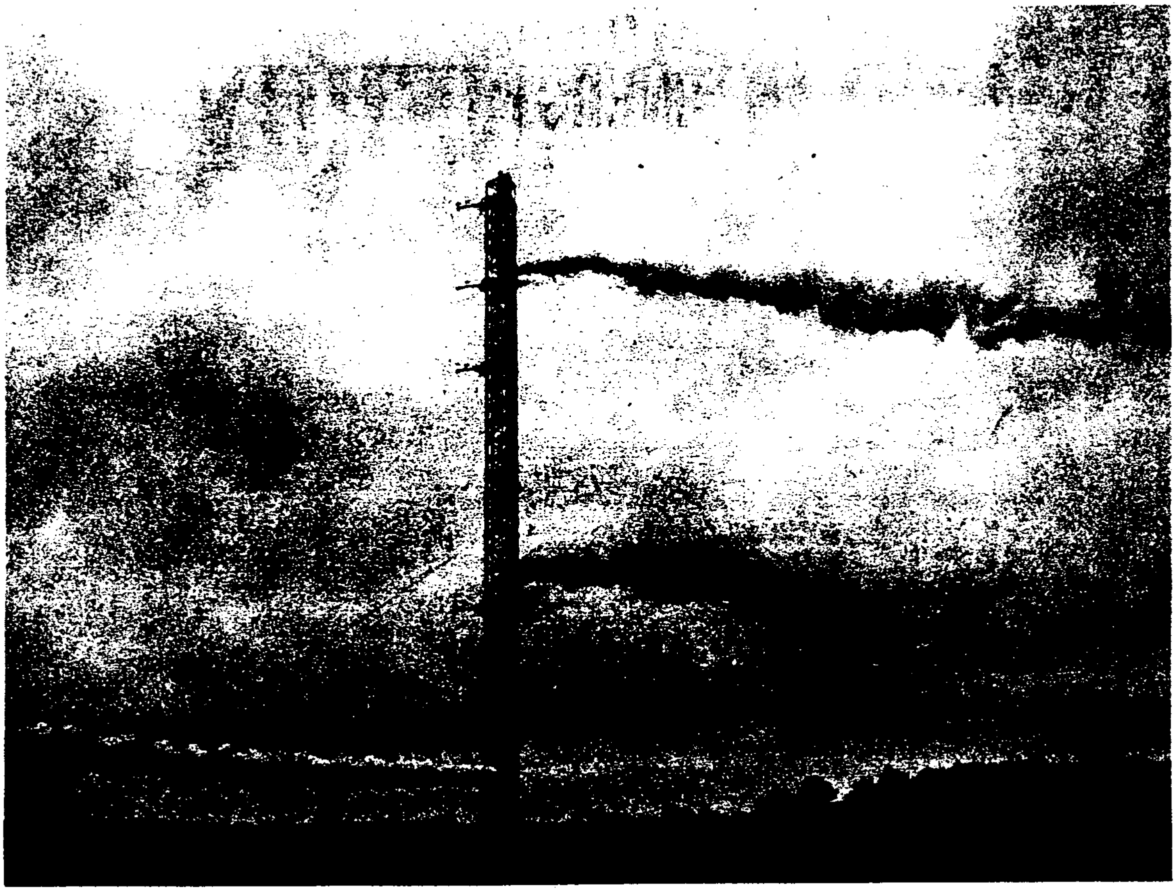

The meteorological tower at the Brookhaven National Laboratory, showing an occasion when experimental smoke went three different directions.

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# METEOROLOGY
# AND
# ATOMIC ENERGY

*Prepared by*

UNITED STATES DEPARTMENT OF COMMERCE
WEATHER BUREAU *for*

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# AEC Preface

The emergence of a new technology reflects the integrated efforts of many men and women of science. This is certainly true for advancements in the atomic energy industry. The earliest phases of the development of nuclear energy were mostly in the fields of physics and chemistry, but as the program expanded it recruited knowledge from a wider spectrum of scientists.

Meteorology, a member of the earth sciences, was asked to provide information that would be of assistance in the choice of favorable plant locations and in the evaluation of significant relations between meteorology and the design, construction, and operation of plant and facilities, especially those from which radioactive or toxic products could be released to the atmosphere. Under a continuing contract with the Atomic Energy Commission during the past six years, the Weather Bureau has carried out this study with great proficiency.

The assembly of the information in the manual *Meteorology and Atomic Energy* is one of the many fruits of this effort. It is an outstanding contribution by the staff of the Weather Bureau to the atomic energy industry. Furthermore, it is a product of cooperation between two governmental agencies of which each can be proud.

The data in this manual are of wide application and will have great benefit to the atomic energy industry as it goes forward.

W. Kenneth Davis, Director
Reactor Development Division
U. S. Atomic Energy Commission

# DISCLAIMER

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# Foreword

The science of meteorology has many assignments in a modern technical age, ranging from the measurement of winds miles above the surface of the earth to the prediction of rainfall days in advance of its occurrence. Of the numerous applications of meteorology, none is more interesting and potentially more vital than the forecasting of the action of the atmosphere in diluting and dispersing foreign materials released into it. If there were no means of removing contaminants from the surface layer of air around a building or a plant, the atmosphere in that area would soon become intolerable for plant and animal life. Fortunately, gases and small particles released into the atmosphere are subjected to all the complex whirls and eddies that characterize the movement of air near the ground and are thus diluted and removed.

The cleansing efficiency of the atmosphere, however, will vary from day to day or even from hour to hour. If remedial action is not taken under conditions of light wind and little vertical air movement, the concentration of foreign material may rise to undesirable levels. Since it is not practical to artifically clean the air after material has entered it, steps must be taken to minimize the release of unwanted gases or particles during periods when the dilution efficiency of the air is low.

The meteorologist can assist in minimizing possible concentrations by his quantitative measurements of the diffusing properties of the atmosphere under various conditions of geography and climate. With these data at hand, production can be planned to reduce emissions. Tall stacks can be designed, or other means can be developed to maintain the purity of the atmosphere.

Already the information gained through the intensive meteorological programs for the Atomic Energy Commission has been applied in many localities to predict or to reduce the concentration of materials as varied as dust, condensation nuclei, and sulfur dioxide. It is to be expected that additional information obtained from future programs will be equally valuable not only to the atomic energy industry but also for wide application throughout our industrial areas.

F. W. Reichelderfer
Chief, Weather Bureau

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# Preface

Early in the development of atomic energy, it was realized that the required processing and production of radioactive and toxic materials could result in release to the atmosphere of significant quantities of these materials. Furthermore, it was seen that not only would the operation of nuclear reactors require the concentration of energy in a limited volume, a situation always hazardous, but also that these machines could produce materials more dangerous than their original constituents. It was therefore desirable to determine what would happen to materials that purposely, or accidentally, became airborne. The meteorologist was asked to determine the distribution, in three dimensions, of effluents that could be released to the atmosphere. To do this it was necessary to consider air motions ranging from near the molecular scale to planetary magnitude. In addition, the release of material may vary through ranges at least as great from test-tube experiments to the detonation of thermonuclear devices.

In common with many aspects of the atomic energy field, the air-pollution problem is not simple. Nor can it be said that exact solutions to the travel, dilution, and deposition of atmospheric contaminants have yet been reached. However a number of useful mathematical treatments exist, and a considerable background of experience in the application of the more promising approaches has been obtained.

It is the purpose of this publication to provide a summary of some of the meteorological techniques that are available and to describe their applications to the possible atmospheric pollution deriving from the use of atomic energy.

Harry Wexler

Chief, Scientific Services Division
U. S. Weather Bureau

Member, Advisory Committee
on Reactor Safeguards, U.S.A.E.C.

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Although many persons of the Scientific Services Division of the Weather Bureau assisted in the collection of data and the preparation of this publication, mention is made of the following: Frank Gifford, Jr., J. Z. Holland, P. A. Humphrey, R. J. List, L. Machta, K. M. Nagler, R. A. McCormick, R. F. Myers, D. H. Pack, F. Pooler, Jr., F. D. White, and E. M. Wilkins. The entire project was under the direction and guidance of Dr. Harry Wexler, Chief, Scientific Services Division, Weather Bureau.

Many of the illustrations included in this publication are reproduced with the kind permission of the Atomic Energy Commission and the many workers in this field.

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# Introduction

The use of weather information to promote health and safety must be nearly as old as man himself. The action of the prehistoric hunter watching the sway of grass and leaves in order to circle downwind from a mammoth had exactly the same purpose as the procedure followed by the architectural engineer when he reviews a meteorological summary before locating an exhaust stack downwind from a production complex. The methods differ but the object is the same, accomplishment of a mission with the least hindrance and greatest safety possible. Common to both, and man's distinctive talent, is the ability to use intelligently the forces of nature.

The use of weather information and meteorological advice by industry for construction, transportation, marketing, and a host of other purposes is well established and constantly increasing. Although, from this standpoint, meteorology is very useful to the atomic energy industry, it is the potential hazard from airborne radioactive materials and the use of meteorology to help minimize this hazard that has assumed the most importance. For this reason, and because the conventional uses of meteorology are rather well known, this publication will deal primarily with the uses of meteorology in the air-pollution aspects of the atomic industry.

The capacity of the atmosphere to dilute the various gases, aerosols, and particles that may be released varies with season, time of day, and geographical location. The winter fogs of London, the early morning smoke palls over most cities, and the Los Angeles smogs all occur when the structure and motions of the atmosphere do not permit rapid diffusion of contaminants.

However, we know that London does not have "pea soup" fogs every winter, that some mornings are crystal clear even in the most industrialized cities, and that the Los Angeles smog does disappear.

We have considerable qualitative evidence that the dilution efficiency of the atmosphere varies over a wide interval. Since radioactive wastes may be several orders of magnitude more toxic than the usual industrial effluents, it is necessary and desirable to know quantitatively what changes in air and ground concentrations result from the variation in atmospheric dilution capacity.

This requirement for quantitative diffusion estimates enormously complicates the problem. The dilution efficiency of the atmosphere

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depends essentially on the wind and temperature gradients. These gradients may vary vertically, horizontally, and with time. They may also change their relation to each other through the same three dimensions. Major climatic regimes (e.g., the persistent West Coast inversion "lid") may be the primary dilution control, or a small scale topographical feature (e.g., wind channeling by mountains) may predominate. However, meteorological techniques for the evaluation and prediction of atmospheric diffusion exist, and these have been applied with considerable success.

In the ideal situation meteorology is one of the items first considered when a new facility is contemplated. If a site can be chosen at random, the meteorologist may be able to select a favorable climate for construction, living conditions, and atmospheric diffusion. If, as is more likely, the geographical location of the facility is fixed within narrow limits, the meteorological characteristics of the site can be examined and the facility designed to exploit favorable conditions and minimize those which might hinder operations. In either event it will usually be necessary to obtain meteorological data for the proposed location.

The design and scope of a meteorological survey for the atomic energy industry will vary widely. The requirement for precise and detailed meteorological information is directly proportional to the estimated magnitude of the pollution possibility, the size of the site, and the topography of the site location. A laboratory which occasionally handles small amounts of low-level radioactive material would probably not require any meteorological information, whereas a plant engaged in the production of large amounts of very "hot" materials would need an elaborate and permanent network of stations constantly furnishing data. A large site, or one with complex topography, is likely to need more data than an operation in a single building on a level plain.

The first step in a survey is to define the macrometeorological or gross weather conditions resulting from the geographical location. These features (average temperature, rainfall, etc.) can usually be approximated from the large body of existing climatological records. The second step is to obtain a knowledge of the fine-scale space-time variation of wind and temperature required for the qualitative and quantitative estimates of atmospheric diffusion. Data on these elements, to the proper scale, are not ordinarily available, nor, at present, can the few existing records be translated to other locations with the preciseness and detail required. It is usually necessary therefore to design a measuring program to provide this information. The third step is to analyze these data into categories typical of various pollution conditions and then, by considering actual operating factors, predict pollution concentrations.

The following material discusses the application of meteorology to the air-pollution problem of the atomic industry and offers methods and suggestions for the collection, analysis, and use of meteorological data.

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# Air Pollution Aspects of the Atomic Energy Industry

Meteorology is important to the atomic energy industry for engineering and operational applications common to industry generally, but, in particular, it is important because of its usefulness when dealing with radioactivity in the atmosphere. Meterology must be used in estimating environmental exposure risks if radioactivity is released through tall stacks and laboratory type vents as part of a routine waste disposal procedure or when it is necessary to consider accidental releases under a variety of circumstances. An outstanding use of meteorology is in the estimation of the spread of contaminants from a reactor disaster.

## 1. THE NATURE OF RADIOACTIVE MATERIALS

Some of the radioactive materials to be found in nuclear reactors are the most potent poisons known. They are three million to two billion times as toxic as chlorine, the most potent poison commonly used by industry, and two million times as deadly as the cancer formers, benzidene and naphthylamine.

Radioactivity cannot be detected by the human senses or by ordinary analytical techniques applied to other industrial wastes; however, with proper instrumentation it can be readily measured at significant levels. Also, it is virtually impossible to treat any given amount of an element so that its radioactivity is reduced. Time is the only significant factor which will reduce radioactivity. Half of some particular radioisotopes are altered in less than 1 sec, but other isotopes may have half lives of centuries. Rarely do wastes from other industries continue to maintain their original characteristics over an extended period of time. Usually any hazard which might result from their release would produce its effects shortly thereafter. The effect of radioactive damage to living organisms may be cumulative and insidious. In the case of toxic material, such as lead and other metals, or biologic infestations, the effects may be also slow; but usually detectable symptoms develop to reveal their presence in time to permit remedial measures to be taken. If the victim recovers, the recovery is substantially complete; whereas, in the case of a serious exposure to radioactivity, the damage is considered to be permanent, and there is the possibility of genetic changes whose full effects may not be apparent for several generations.

Neither the meteorologist nor the atomic scientist works alone on problems dealing with the atmospheric dispersion of radioactivity. Information on the nature of the source must be furnished by nuclear physicists, chemists, or engineers. Criteria for the permissible concentrations in air, or dosages, are usually determined by health physicists. Meteorology determines the conditions under which a given source can lead to concentrations or dosages exceeding the permissible limits.

A tremendous effort is being exerted to obtain a better understanding of the biological effects of radiation. Permissible amounts of radioactivity in the atmosphere will vary according to circumstances and to the interpretation of individual health physicists, and they may change as further knowledge is acquired through research.

Even a general knowledge of radioactivity and its extremely toxic effects reveals why the atomic energy industry must make intensive use of meteorology. Nevertheless, it is worth while for the meteorologist to seek for himself the numerous publications and other educational media available in order to acquire knowledge of the terms, tolerances, and techniques used in working with nuclear energy. At the same time it is obviously important that the nuclear scientists and engineers who will be responsible for structures, installations, and experiments should gain a working familiarity with the fundamentals of air pollution meteorology.

## 2. SOURCES OF AIRBORNE CONTAMINATION

Recognizing the level of toxicity, or radioactivity, encountered and the amounts of harmful material which could possibly be airborne, each type of facility will be described briefly with special attention being given to the gaseous waste disposal systems. Facilities may be divided into those which handle only low-level radioactive materials and those which handle high-level materials. The first group is primarily concerned with processing fissionable metallic elements, such as uranium, whereas the second is concerned with the products of fission or of nuclear bombardment. Reactors and chemical processing plants for reactor fuel may be classified as outstanding potential sources of large amounts of high-level radioactive materials. Therefore more information is presented here for these types of facilities.

Although the following discussion separates the various processes and/or devices that could release radioactivity to the atmosphere, it is more usual to have several sources of potential contamination at a single facility site. Such a situation will result in complex and interacting dispersion patterns and often dictates an urgent requirement for meteorological advice.

2.1 *Mining and Ore Handling Facilities.* In mining, transporting, and storing raw uranium ores, workers are protected from exposure to the dusts and from prolonged contact with the ore. Although the level of radioactivity is low, large concentrations of materials may give off sufficient rays to damage human tissue if intimate exposure to them is prolonged. Radon, a decay product from the radium present, may also be hazardous, especially when inhaled. Radioactive dusts result during drying, crushing, grinding, sieving, and packaging operations.

Airborne materials are kept to a safe level by good industrial housekeeping and ventilating facilities and by the use of air cleaning equipment, such as cyclones, electrostatic precipitators, bag and diaphragm filters, and scrubbers. Meteorological measurements for a facility of this type should seldom be necessary.

2.2 *Feed Plants.* The chemical processing of the prepared uranium ore for the production of its brown oxide ($UO_2$) presents the ordinary problems of chemical industries which use toxic solvents and extracting solutions and complicated equipment. Processes involve solution of uranium compounds in many different ways with the precipitation, extraction, and filtration of the collected salts. Dusts, mists, and fumes are satisfactorily controlled with industrial air cleaning equipment. Because of the high monetary value of the materials being processed, waste disposal systems are usually closed, and salvage procedures are in effect.

In the preparation of the uranium hexafluoride material for gaseous diffusion plants, fluorine and hydrogen fluoride must be used in large amounts. If the concentrated acid is spilled accidentally, sufficient heat is produced by hydration or reaction to vaporize quantities of the liquid hydrogen fluoride. The uranium hexafluoride can cause lethal chemical burns and is extremely irritating, even in minute concentrations.

An elaborate meteorological program will usually not be required for a feed plant; however, records of wind velocity and possibly temperature gradient may be desirable.

2.3 *Gaseous Diffusion Plants.* Gaseous diffusion plants for separating fissionable $U^{235}$ from natural uranium are not considered to have an effluent during normal operations.

The hazard of a gaseous diffusion plant as a source of air pollution lies in the potential leakage of uranium hexafluoride in large amounts. The gas is very corrosive when traces of moisture are present and will eat through most substances, including glass. A leak could result in fine particles being formed in the air which would produce hydrofluoric acid in contact with moisture, as in the respiratory tract. With respect to toxicity, the radioactivity of the uranium isotope is of less significance than the extremely irritative chemical effects due to the element fluorine.

Elaborate precautions are taken in the piping and equipment to prevent accumulation of sufficient $U^{235}$ in a geometrical configuration which could become critical and start an uncontrolled chain reaction.

Since these plants are usually very large, a meteorological program to provide information for construction may be feasible. Such a program would be designed to provide basic data on wind movement to aid in assessing the

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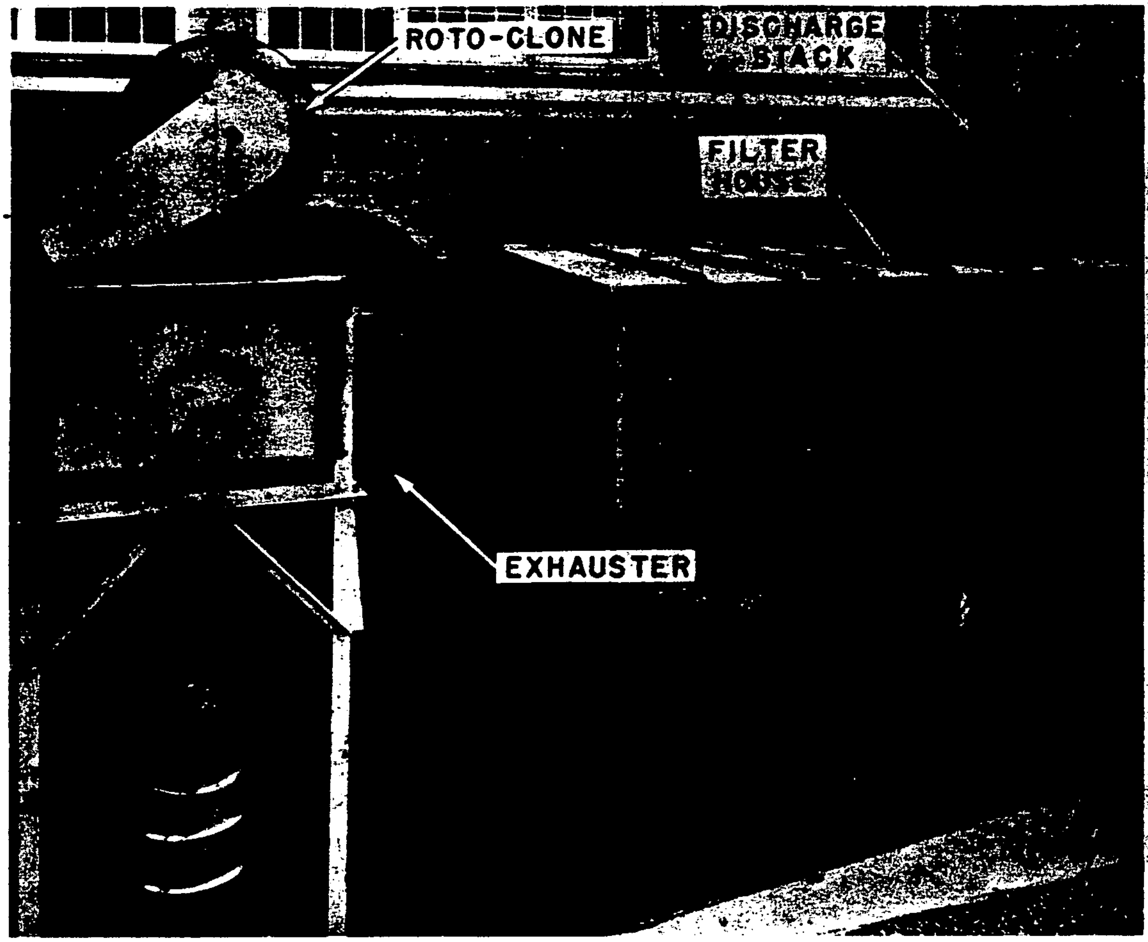

Fig. 1.1—Air cleaning equipment for a beryllium machining facility installed at the base of a 50-ft stack (Oak Ridge).

movement of effluent generated during unusual conditions.

2.4 *Machine Shops.* When shaping and forming metals which are alpha emitters, such as uranium, or which are quite toxic, such as beryllium, dusts and fumes may be produced. Dry and wet machinery operations are handled by separate exhaust systems, with the working area of each machine enclosed in a plastic high velocity hood. Chips and large-diameter particles are removed by inertial or centrifugal devices; then smaller particles may be removed by self-cleaning oil filters and filter paper. An air cleaning installation for a machine shop is shown in Fig. 1.1. These devices will usually control any contaminant so that meteorological tracing is unnecessary.

Metallic uranium dust or small chips exposed to the air have been known to ignite spontaneously and burn with the formation of oxide fumes. A fire might require the evacuation of a building and perhaps the immediate area downwind. The use of respirators probably would be required.

Monitoring devices utilizing filters are used within the shops, and at times outside, to ensure that tolerable levels of contamination are not exceeded.

2.5 *Laboratories.* Atomic laboratories differ from the usual industrial and collegiate research laboratories mainly in the special facilities required to protect workers from radiation and to prevent radioactive contamination from being released to the air or water in sufficient concentrations to be at all harmful to the surrounding area.

Bulk shielding, ranging from rubber gloves for alpha emitters to many feet of lead or concrete for gamma and neutron sources, may be required for direct radiation protection. In ad-

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dition, the exhaust system for an atomic laboratory contains filters to prevent the release of fine particulates to the air. A common arrangement utilizes a filter, or filters, in the line from each hood or other working enclosure to its vent pipe in the roof. If the laboratory area is large, a regular forest of low vents may result, each with its own filter system (Fig. 1.2).

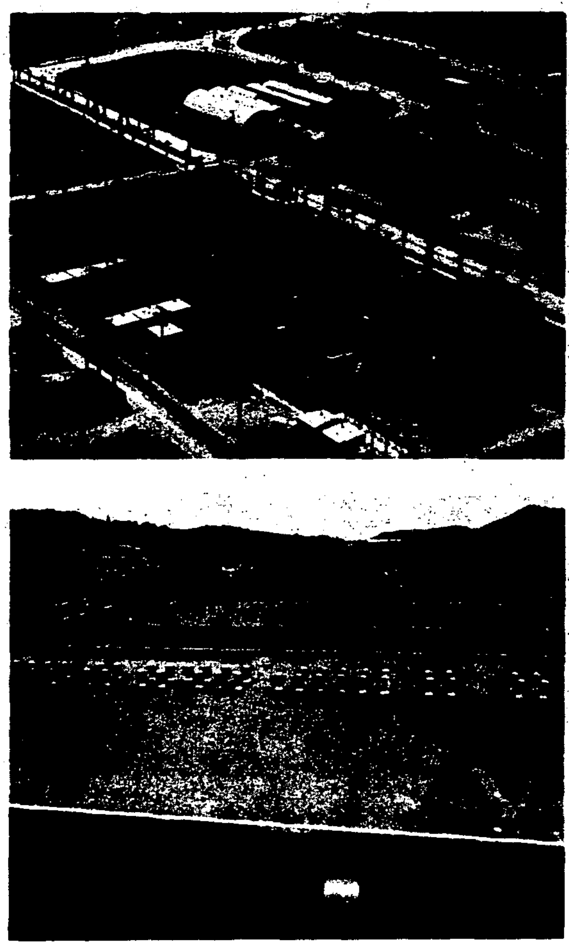

Fig. 1.2—Typical hood vents on laboratory buildings (Oak Ridge).

An alternate installation of an exhaust system utilizes a roughing filter of glass fibers or similar material on each laboratory hood with a common stack preceded by a fine particulate filter. Such a system is difficult to balance so that all hoods have the proper ventilation.

Usually unfilterable radioactivity from hoods is mixed with enough clean air before reaching roof vents that the permissible activity level specified by the industrial hygienist or health physicists will not be exceeded. However, if any uncertainty exists as to the amount of radioactivity being released, in addition to other precautions, certain laboratory operations producing airborne materials are sometimes scheduled to take advantage of favorable meteorological conditions. The requirement for a meteorological program for a laboratory alone will depend on the size of the laboratory and on the levels of the "hot" materials handled. A minimum precaution for locations handling moderate and high activity materials would seem to be continuous recording of wind direction and speed.

2.6 *Particle Accelerators.* The highest energy radiation generated anywhere in the atomic energy program is produced in the particle accelerators, such as the cyclotrons, synchrocyclotrons, and linear accelerators. These machines produce intense beams of high energy particles which can give rise to airborne contamination, although the amount is relatively small and usually insufficient to require consideration of exterior weather conditions.

As an example, momentary failure of target cooling apparatus or difficulties with the focusing beam can cause vaporization of the target surface, grossly contaminating the inner surfaces of the machine. When the target tank is opened, this material can escape and become airborne. Plastic bags (Fig. 1.3) have been used to help control this hazard, as have ventilation methods common to chemical laboratories handling radioactive materials.

2.7 *Nuclear Reactors.* The term "reactor" is here interpreted broadly to mean any assembly of fissionable material which can go critical, excluding weapons. Another definition is that a reactor is a device which is capable of producing a controlled self-sustaining nuclear chain reaction and which consists essentially of fissionable fuel, moderator (if a thermal reactor), controls, and the supporting structures. Cohen[28] has stated:

> Reactors can be made out of a bewildering variety of materials. A reactor can use natural uranium, pure $U^{235}$, plutonium, $U^{233}$, *which is made from thorium*, or any mixture of these elements as fuel. The fuel may be a metal, oxide, salt, or alloy; may be fabricated in the form of pills, plates, powders, prisms, rods, or threads; or may be liquid. The reactor may contain graphite, or water, or heavy water, or beryllium, or a number of other compounds as moderators to slow down the neutrons, or it can be built without moderators at all. It will, in addition, contain jackets and structures made of any isotope of nearly 100 ele-

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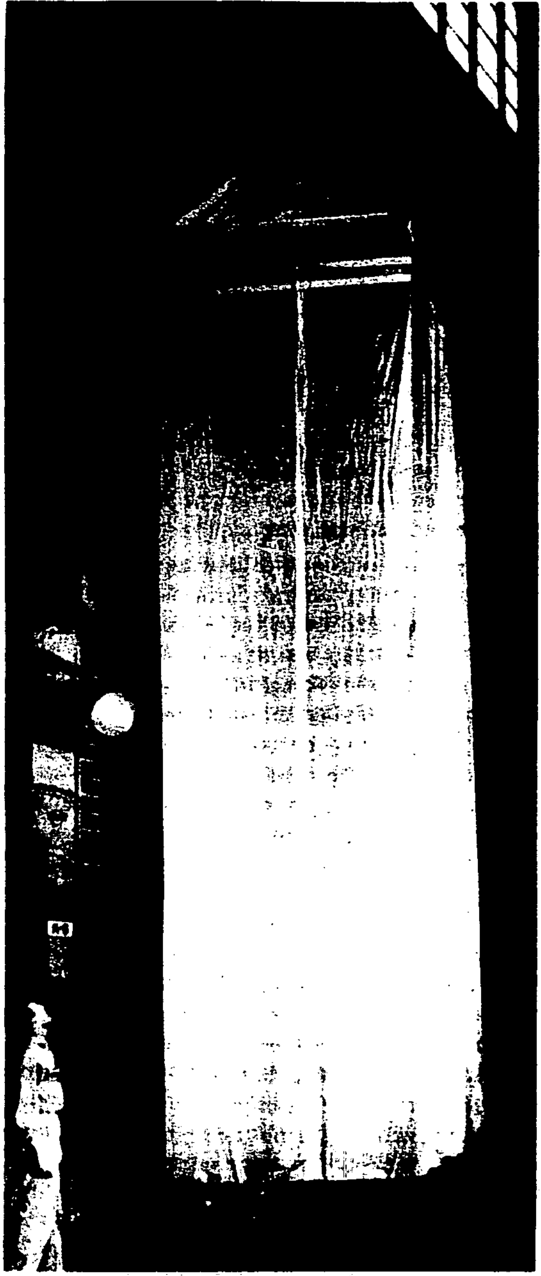

Fig. 1.3—Plastic bag used to prevent the spread of airborne contamination when moving parts of a cyclotron for maintenance (Oak Ridge).

ments. The heat can be removed with air, water, oil, liquid metals, or anything else imaginable. The core can be homogeneous or heterogeneous; it can be surrounded by a reflector, by a breeding blanket, by both or by neither; the variety of each of these adjuncts is as great as that of the core. The reactor core can be spherical, cylindrical, flat, divided, or shaped like a pair of waterwings; and it can be as small as a football or as large as a six-room house. A reactor can be built like a fine watch and shielded with rare metals or it can have no structure at all and be shielded with water or tamped earth. In addition, it may operate hot or cold, and at low or high pressures.

There are two main hazard problems of reactors. The first problem is the possibility that the nuclear reaction will get out of control, the power will rise to a very high level in an exceedingly short time, and parts of the reactor will melt or vaporize. The second problem is the fact that reactors store up fission products, and fission products are exceedingly poisonous substances. If these extremely toxic materials are permitted to get out of the reactor enclosure, even in minute amounts, persons and other forms of life may be seriously damaged.

Thermal reactors (atomic piles) appear to have a very low probability of getting out of control and causing blast damage. Fast reactors (such as the Experimental Breeder Reactor) are perhaps more hazardous in this respect, but even in this case it would appear that the damage due to blast would be limited to the reactor and associated equipment. However, it is conceivable that parts of certain reactors can vaporize. The real hazard resides in the possible poisoning effect of the fission products, plutonium, and uranium either by external body irradiation or by ingestion.

The possibility of dispersing these poisons over large areas, over large numbers of people, and at distances tens and even hundreds of miles from the reactor is the problem that is of concern.

There are certain secondary effects also of importance from a hazard point of view. If we have a highly radioactive liquid under high pressure, such as in homogeneous power reactors, then there is an additional problem. The use of sodium as a primary reactor coolant introduces an additional radioactive hazard plus a chemical one. If graphite is used as a moderator, there is the possible danger that unexpected energy release could cause a serious graphite fire. Beryllium is highly toxic, and its dispersion would be an additional toxic hazard. Finally it is known that aluminum, zirconium, uranium, and thorium can react violently with water under certain conditions, but whether it is reasonable to assume conditions for explosive reaction is a question under study at the present time.

It is convenient to distinguish between solid fuel reactors and liquid fuel reactors when

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specific hazards are discussed. Good examples of reactors with solid fuel are the original Oak Ridge reactor, the Brookhaven reactor, the gigantic Hanford reactors, the "swimming pool" reactors, and the submarine reactors. In fact, all the large reactors which now exist have solid fuel. Examples of liquid fuel reactors are the Homogeneous Reactor Experiment at Oak Ridge and the Raleigh Research Reactor at North Carolina State University.

Fig. 1.4—Jacketed or "canned" fuel slugs being inserted in the Oak Ridge graphite reactor.

A significant difference between the two types, as far as air pollution is concerned, is that in a liquid fuel reactor, combining fuel and moderator in one solution, the gaseous fission products are liberated from the fuel directly and must be diluted or allowed to decay before release to the atmosphere. The Raleigh Research Reactor provides for holding up the gaseous fission products until they have decayed to permissible levels.

If a solid fuel is used, the metal must be protected from oxidation and corrosion by a jacket that is a good heat conductor, has low neutron absorption, and has high corrosion resistance, such as aluminum. Jacketed fuel slugs are shown in Fig. 1.4 being inserted in the Oak Ridge graphite reactor.

Since the radioisotopes are formed within the canned metal by fission of the uranium atom, no large amount of fission product activity can be released without the melting, burning, or vaporization of the fuel.

There are three sources of airborne contamination connected with the operation of solid fuel reactors, excluding uncontrolled nuclear reactions. The first source is an imperfection or failure of the jacket which protects metal fuel elements. Even a pinhole leak in a jacket will admit oxygen to the surface of the uranium. The uranium will readily oxidize at high temperature, and particles of uranium oxide which contain an amount of fission products proportional to the neutron flux and the irradiation time will be carried out by the coolant. The Oak Ridge graphite-uranium reactor has an elaborate filter installation to prevent particles of larger than submicron size from escaping in case of an accidental slug rupture.

The second source of airborne contamination in normal reactor operation is induced activity by neutron irradiation of the coolant. The coolant may be used in a single-pass system, such as the air for the Oak Ridge graphite reactor or the water passing through the Hanford reactors, or it may be circulated in a closed loop, as has been postulated in designs for proposed power reactors. The Materials Testing Reactor at the National Reactor Testing Station in Idaho with its tall stack for exhausting cooling air is shown in Fig. 1.5. Air is a secondary coolant for this reactor. The amount of activity formed in the coolant may be determined for each element. It depends on the average neutron flux, the absorption cross section for the element (thermal or total, depending on energy spectrum of the neutrons), the number of atoms of the element irradiated (which is determined by the time for a parcel of coolant to pass through the reactor core), the concentration of the element in the coolant, and the half life of the isotope formed. The relatively large cross section and short half life of $A^{41}$ means that for short irradiation time almost all the activity in air will come from the $A^{40}$ which normally comprises about 0.93 wt.% of the air. Permissible concentrations of radioactivity may be achieved by diluting the coolant and by placing the point of discharge in a favorable location. At the reactor of the Brookhaven National Laboratory, Long Island, the stack of the air cooled reactor is over 300 ft above the surface. The volume of air flow for cooling the reactor is about 300,000 cu ft/min.

If the intake air is not filtered or if in flow through ducts to the reactor the air picks up

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dusts of various kinds, the dusts become irradiated in the reactor and contaminate the cooling air stream with radioactive particulates. For this reason the sizes and locations of air intakes are carefully selected. Usually the incoming air is filtered, and provision is made to prevent dust in air passageways or ducts.

If water is the coolant, the dissolved impurities are often a source of great activity, but in normal reactor operation the cooling water is not a source of airborne activity.

The third source of possible airborne activity from the operation of a reactor is the rupture of a capsule or container of material inserted into the reactor for irradiation. Gases, volatile material, or a chemically active material, such as sodium, could leak out if a container failed or could rupture the container if coolant failure allowed the temperature to rise considerably in the sample.

If the fuel is liquid, in addition to rapid vaporization, leaks and auxiliary equipment failure may result in liberation of airborne contamination.

Operating accidents could occur if additional fuel were suddenly dropped into the operating reactor, if safety interlocks on the controls were to fail or were intentionally overridden, or if large amounts of a neutron absorbing material were suddenly withdrawn from the operating reactor. In some cases injudicious alterations in the geometrical arrangement of materials, in the amount of moderating or shielding substances, or in the temperature could result in uncontrolled power excursions.

If the reactor coolant fails or is not adequate, controls are provided to shut down or "scram" the reactor as rapidly as possible; however, if the reactor is not "scrammed," hot spots will form in the fuel elements and chemical reactions may be possible between the fuel and the coolant or moderator as a result of high temperatures.

Fig. 1.5—Materials Testing Reactor at the NRTS with a tall stack for discharging cooling air.

The attractiveness of liquid metals, such as sodium, potassium, and their alloys, as high temperature heat transfer media has given rise to considerable experimental work in this field. It has been found that it is possible to work safely with such metals up to quite high temperatures; however, imperfections in pipes, valves, pumps, welds, or fittings can cause a fire that is difficult to control and which generates toxic fumes of oxides and hydroxides. If the liquid metal has been irradiated, the fumes will also be radioactive and may become an airborne contamination hazard. As a safety measure, the practice of enclosing all pipes and fittings in a helium blanket has been adopted by some workers.

Earthquakes, flash floods, and tornadoes are natural phenomena which could conceivably damage a reactor, causing an uncontrolled release of radioactive matter into the atmosphere. However, reactors which otherwise might pos-

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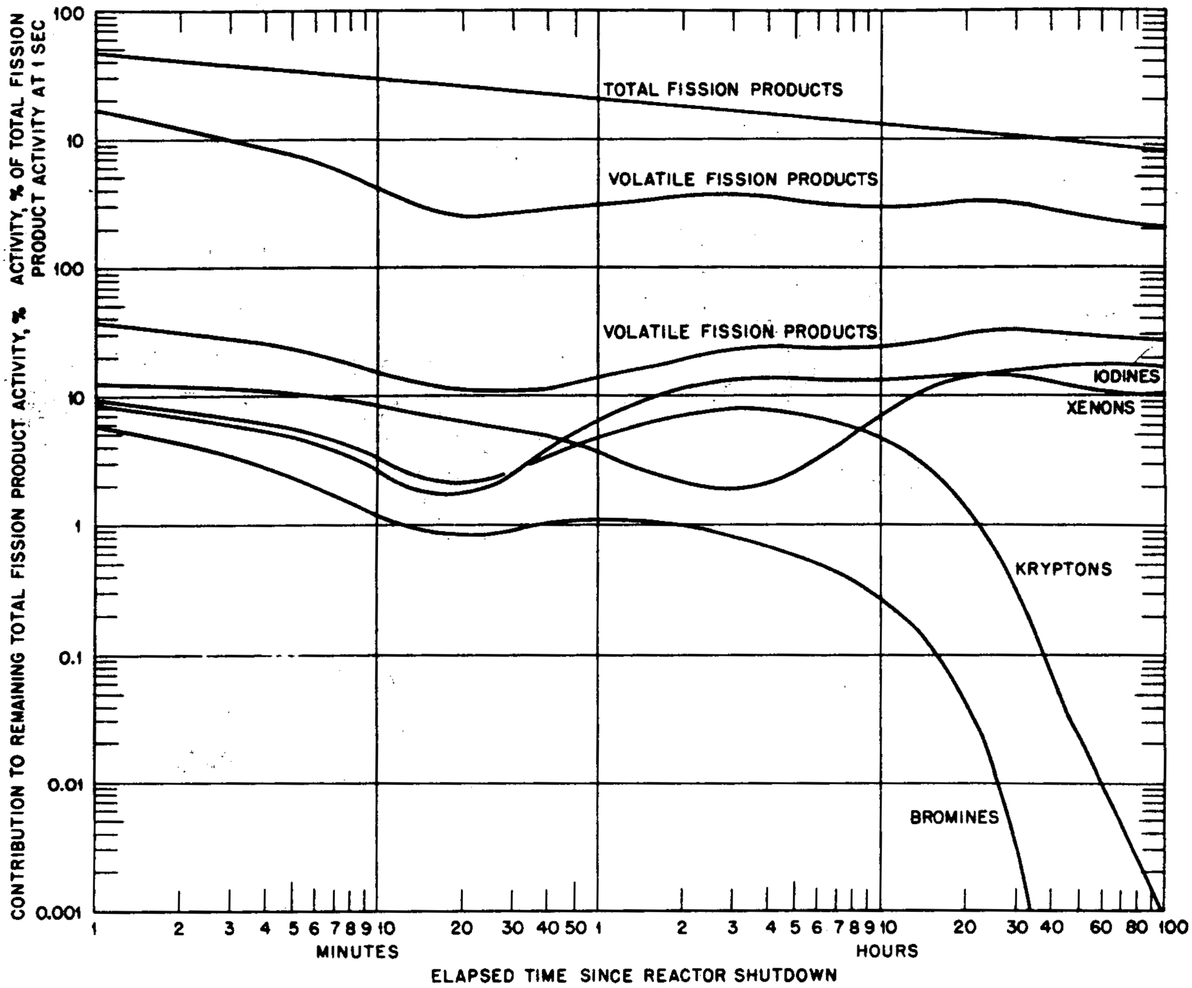

Fig. 1.6—Fission product activity after immediate reactor shutdown or total disaster (Hunter and Ballou).

sibly run away are designed with safeguards so that they are shut down automatically if jarred, or if there is an electrical failure.

In the event of a reactor disaster, an estimate of the magnitude of the contamination that may be released is required.

The total activity which is contained as fission products in a reactor has been given as a function of the reactor power by Mills.[111] The assumption has been made that the reactor has operated for a period sufficiently long that the fission products are formed as rapidly as they decay. If the further assumption is made that each decay event has an energy of 1.0 Mev, the contained activity at a time t seconds after shutdown will be given by

$$A = \frac{10P}{(t)^{0.2}}$$

where A = activity in curies
P = power in watts
t = time in seconds

Hence a 1-megawatt reactor at 1000 sec after shutdown would contain

$$A = \frac{10 \times 10^6}{(1000)^{0.2}} = \frac{10^7}{3.98} = 2.5 \times 10^6 \text{ curies}$$

If a reactor runaway occurs during a "clean" start-up or from a very low power, the fission products present will be generated during the power excursion. In this case a decay factor of $t^{-1.2}$ applies, and the relative amounts of volatile and total fission product activity may be estimated from the work of Hunter and Ballou.[85]

Figure 1.6 shows the contribution of the individual elements in percentage of gross activity of the remaining fission products at various times after slow neutron fission of $U^{235}$. The upper two curves give the activity of the total and volatile fission products in terms of the percentage of the total fission product at 1 sec after immediate reactor shutdown (or total disaster). Two "thumb rule" approximations may be stated for estimating the possible total amount of activity released.

The first one is that 1 watt of reactor power produces 10 curies of activity at 1 sec or 1 curie of activity after one day.

The second is that for decay times of importance meteorologically, 1 watt of reactor power produces 0.2 curies of volatile fission products.

In the event of a reactor disaster, it seems unrealistic to expect all the contained activity to become airborne. Various estimates have been made of the percentage which would be condensed on the structural material and which would remain as solid pieces too large to become airborne, but these are very speculative. It is usually assumed for the sake of conservatism in reactor environmental planning that 50% of the total contained activity will become airborne.

From the preceding discussion it can be seen that airborne radioactivity could originate from a reactor in routine operations through cooling processes, from relatively minor malfunctions, such as slug ruptures or pipe leaks, or from complete reactor failure and dissolution.

A meteorological program designed to measure atmospheric diffusion parameters and formulate estimates of the travel, concentration, and deposition of airborne materials will provide essential information for all these possibilities. Actual experience with routine emissions and accidental releases has shown that adequate meteorological information is vital from both health and economic standpoints. Postulated reactor failures usually base the area of radioactive hazard on meteorological data and estimations. Later in this report methods for estimating airborne radiation hazards from the meteorological standpoint will be discussed.

2.8 *Chemical Processing Plants.* The chemical plants which handle irradiated reactor fuel are potentially very hazardous sources of air contamination. The fission of the uranium produces a multitude of highly radioactive isotopes. At Hanford, according to the "Eighth Semiannual Report of the Atomic Energy Commission," radioactive materials are handled in tons, not merely in milligram or gram amounts. The irradiated slugs contain the unaffected part of the original uranium, the plutonium, and the fission products whose composition and activity depend on the neutron density and irradiation time.

In the Hanford chemical plant, the slugs are dissolved and processed to separate the plutonium from the uranium and the fission products. The activity, handled by remote control, may contain tens of thousands of curies of radiation and also give off radioactive gases. Other fuel processing plants which do not handle as large total amounts of activity as the Hanford plants may still have a high rate of emission of radioactive gases if the dissolvings are carried out as a batch process.

The gaseous radioactivity liberated when spent metallic fuel is dissolved consists principally of the noble gases $Xe^{133}$ and $Kr^{85}$ and the halogens $I^{131}$ and $Br^{82}$. Of these elements, the one of primary concern is $I^{131}$ because of the greater relative abundance and the biological significance since the element concentrates in the thyroid gland.

The radioactivity in the off-gases depends upon the age of the irradiated reactor fuel, counted from the time the fuel was removed from the reactor. It is common practice to allow a reasonable "cooling" period for radioactive decay before dissolving and thereby reduce the activity in the off-gas by a factor of 10,000 or more. Aging is used in particular to reduce the iodine hazard. Of course, if it is required to recover short-lived products, such aging is ruled out. Other methods include the use of wet scrubbers with silver nitrate, special filtering systems, and meteorological control.

Some work has been done on the use of activated charcoal to absorb the noble gases. This technique has not been widely adopted for continuous use because of the requirement for considerable low temperature cooling when the lighter gases, such as krypton, must be absorbed from a large volume of effluent.

Without previous experience, it is difficult for nuclear physicists and chemists to predict the activity of the off-gas for a particular dissolving, even if the amounts of radioactive isotopes in the fuel can be theoretically estimated. Some of the noble gases may escape from the fuel prior to the dissolving, and more than insignificant quantities of the potentially gaseous effluent may remain liquid.

The output of stack effluent from a chemical plant is not likely to be continuous and uniform.

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Fig. 1.7—Precipitron, filter house, and duct work for the hot stack of a chemical processing plant (ORNL).

With a single dissolving, the activity will rise rapidly to a peak and then subside. Following the dissolving, there may be a lingering activity from the dissolving vessel and from the internal contamination of the off-gas system.

In hot chemical plants the actual processing must be carried on in sealed compartments, or "cells," by remote control and behind much shielding to reduce the intensity of the radiation from the process. Most equipment is installed in duplicate to prevent clogged or leaking pipelines or valves from hindering the operation. It is considered good practice to provide a process off-gas system which will handle the gases and mists evolved in any of the process vessels. Studies made on the stack effluent of such systems have shown that almost all the effluent was either gaseous or of a particulate nature less than 1 $\mu$ in diameter. Figure 1.7 shows the complex installation of air cleaning equipment typical of a hot stack. Particulates may also be removed by deep bed sand filters somewhat similar to those used in water filtration plants.

Supplementing the system for off-gases, a separate system for the ventilation air of the cells is usually installed. This air is also scrubbed and filtered before it goes up the stack in the event that a leak or failure releases activity into the cell.

Chemical plants may be required to separate special isotopes of high activity in conjunction with the processing of reactor fuel. As a result, off-gases may contain many times the activity that would occur during normal processing. Such separation operations may produce added hazards should there be operational error, equipment failure, fire, or some other catastrophe.

In addition to the radioactive material in the off-gases from chemical plants, there may be varying amounts of solvent vapors, ammonia, nitrous oxides, mercury vapor, fluorine, hydrogen fluoride, chlorine, and other toxic chemicals. These may be present in negligible amounts or, owing to equipment failure or accidental release, may become primary air contaminants.

Here, too, meteorological advice has been of assistance. A different treatment is required for this type of operation, and Chap. 5 deals specifically with emissions from stacks and other elevated "point" sources. Even if the individual emissions are of low-level radioactivity, any release of long lived material generates interest in the average (and atypical) wind and stability patterns for concentration build-up estimates.

2.9 *Waste Disposal Facilities.* Radioactive wastes which are essentially liquid or solid may require separate disposal facilities in addition to those already mentioned. These facilities include treatment plants for chemical residues, incinerators, sewage plants which handle radioactive wastes, and burial and storage areas for solid wastes.

The disposal of radioactive or toxic wastes presents problems not yet completely solved. There are two philosophies which are applied. These are "concentrate and contain" and "dilute and disperse."

As examples of the first policy, we see the evaporation or segregation of liquid wastes followed by piping into tanks or underground cribs and the burial of contaminated solids or drums of liquid. Certain high-level wastes may be contained by concrete before or after burial. Adequate coverage is provided to shield against radiation at the surface, and burial grounds are selected with the advice of ground-water geologists.

Some residues from chemical processing of irradiated fuels have considerable value. They contain certain unspent fuel which is reclaimable as well as fissionable material which also has potential value. These residues are highly radioactive and hazardous. From an environmental standpoint such wastes are particularly important because certain isotopes in the waste residue will be highly radioactive for decades. It is customary to store high-level and valuable radioactive waste residues in underground tanks, pending development of feasible and economical treatments and possible recovery methods.

The tanks used for storing liquid wastes have been known to cause airborne contamination, particularly when steam jets were used to transfer material to the tanks or from one tank to another. Spray and mist formed during the jetting can be emitted directly from the air vents of the tank or can dry to form extremely small airborne solid particles which find their way into the air. Seepage from a leaking tank can contaminate the ground, and later harmful dusts can be relocated by surface winds to become a problem in air pollution.

At particular sites near the Atlantic and Pacific coasts, radioactive wastes are disposed of at sea by dumping in designated areas in water off the continental shelf. It is the general practice to encase these wastes in a mixture of concrete, usually within steel drums.

As an example of the second policy, we see the closely regulated discharge of liquid waste to rivers or streams. At Hanford and Oak Ridge large retention basins are used to permit radioactive decay before liquids are finally released. Of course, the discharge of gaseous wastes through stacks and vents is another example of the "dilute and disperse" principle.

A type of waste disposal which is really a combination of these two principles is the incineration of contaminated, combustible, solid material. The intent is to reduce the bulk to be stored as much as possible and to dilute the effluent given off in combustion to safe concentrations. The use of an oxygen atmosphere is sometimes resorted to in order to reduce the ash as far as possible.

Incineration may offer two possible sources of airborne contamination. Toxic or radioactive gases may be given off through the stack, or airborne contamination from incinerators may occur during the removal and ultimate disposal of the ashes. If scrubbers are used in the clean-up of the gases of combustion, care must be taken that radioactive liquid wastes difficult to dispose of do not result and create a new problem. Since a good incinerator system for radioactive wastes is expensive, some sites rely entirely on burial or storage.

In salvaging normal uranium from wastes (such as contaminated work gloves and garments and absorbent paper sheets), the wastes are burned in special furnaces, leaving a residue from which it is possible to salvage the small amount of contained uranium. Since the operation must be as inexpensive as possible to pay its way economically, expensive and elaborate air cleaning devices are not usually a part of the installation. Such an operation may be a source of airborne contamination if considerable amounts of material are handled and if small active particulates or gases are formed in the combustion process.

Although the use of the atmosphere as a dilutent is certainly not new, the toxicity of the effluent from the various atomic energy installations, the uncertainty of the cumulative biological effects, and the experimental nature of the machines producing the fission products is such as to impose rigid standards on the amount of material that may be released. It seems certain that as additional knowledge and experience is obtained the possibility of environmental hazard created by installations handling fissionable materials will decrease.

# 2

# Meteorology in Site Operations

During the site selection and design phases of a plant, meteorological assistance must be based on past records, usually accumulated at stations not actually on the site. These preliminary advices will be averages and extremes that might be expected.

After a location has been chosen and work has begun, current and forecast weather conditions become of immediate concern. On-site meteorological observations and forecasts have many applications to the operating program of an atomic energy site. Requirements may range from observations of the daily minimum temperatures to forecasts of radiation dosages from airborne clouds.

## 1. SITE CONSTRUCTION

The conventional uses of meteorology will be most important during the construction period at a site. Where the construction program is large enough and of sufficient duration, a meteorological program may be justified for this reason alone. Such programs proved of value in the construction phases of the Savannah River and Portsmouth Area installations.

On such large projects it may be necessary to furnish climatological data for prospective bidders, seasonal work scheduling, evaluation of time extension requests, or management analyses of work progress. Climatic data for construction programs may require information not commonly available, such as freeze-thaw cycle frequency and annual wet-bulb temperature frequencies and ranges. Such data can be quickly and easily obtained from a site meteorologist.

Experience has shown that on-site adaptation and emphasis of the standard forecasts of temperature, precipitation, and wind will enable a saving of time and material through appropriate work scheduling. The site meteorologist, in contact with the various project engineers, can follow work progress and emphasize the elements most likely to affect operations (temperature and rain for concrete work; wind and freezing rain for steel erection, etc.).

After an atomic energy site begins operations involving radioactive materials, meteorological services may be required under the following conditions:

1. If there is a continuous or intermittent source of radioactive effluent present on the area or if there is a source potentially present to the extent that an atmospheric monitoring program is required.

2. If there is a daily or occasional requirement for weather forecasts. The forecast requirement may be divided into two categories: forecasts of diffusion conditions required for the control of stack effluent or in the event of a sudden release of radioactivity and forecasts for engineering and construction operations. Detailed forecasts, particularly of diffusion, require on-site weather observations for forecast preparation.

3. If there are recurring requirements for climatic data from the area itself for locating, designing, and orienting facilities. Meteorological programs which could be justified for this reason would be at the larger AEC areas, where facilities are added from time to time.

4. If there is a need for meteorological observations for documentation and historical purposes. These records may be used in conjunction with testing and experimentation, in the preparation of administrative reports, or in the event of legal action arising from alleged radiation exposure.

5. If it is desired to conduct micrometeorological research in diffusion, as at the Brookhaven National Laboratory.

## 2. SITE OPERATIONS

Disregarding meteorological control, which is discussed in Sec. 3, there are numerous ways that the work of the meteorologists may assist other groups at an atomic energy site. Some of the ways which are particularly significant to the atomic energy industry are listed below.

*Health Physicists.* 1. Obtain meteorological observational data for making correlations with background radiation or for determining or confirming causes of unusual readings on monitoring instruments. Meteorological records and instruments provide additional clues when tracing sources of radioactivity detected in radiological surveys.

2. Receive estimates of ground concentrations of stack effluents and estimated locations of concentration maxima. These are computed from diffusion formulae, using actual meteorological observations at the site.

3. Receive advice for locating monitoring instruments. Permanent locations are often decided on the basis of wind direction frequencies and on estimates of the distances from a stack where maximum ground concentrations are likely to occur. Mobile monitoring may require forecast information. If biological samples are collected, past weather records may be helpful. Sometimes it is desirable to establish a monitoring station or to collect samples for control purposes. There meteorological information is used to ensure little or no site influence.

4. Receive assistance with regard to radioactive debris from bomb tests. A meteorologist is often helpful in anticipating the arrival of such debris so that anomalous readings on sensitive monitoring instruments do not cause alarm. Meteorological observations also explain some of the variations in concentration of radioactivity which occur from bomb clouds, e.g., variation due to "rain-out."

*Safety Engineers.* The safety engineers use meteorological data in a manner similar to health physicists when studying problems of airborne harmful materials that are nonradioactive, beryllium dust, for instance.

*Reactor Engineers.* 1. Receive meteorological observations for incorporation into histories of reactor start-ups and tests. For example, air temperature and wet-bulb temperature may be important factors when determining the behavior of a particular kind of reactor during a certain period.

2. Receive assistance in the preparation of technical reports, such as the reactor hazards analyses.

3. Receive information on natural dustiness useful for designing air cleaning equipment.

4. Receive meteorological data concurrent with malfunctions, such as leaks and power excursions.

*Sanitary Engineers.* 1. Use temperature records when studying the efficiency of sewage disposal plants.

2. Use diffusion data if stream, well, or reservoir pollution from airborne material is possible.

3. Use rainfall records where dilution by natural stream flow is used.

*Legal Officers.* Legal officers use meterological records if there are claims of personal or property damage from exposure to airborne materials. Other uses of meteorological forecasts or data will occur to the reader.

## 3. METEOROLOGICAL CONTROL

A meteorological program may be required if some operation requires forecasts for meteorological control of stack effluent. Nearly always, and especially where air pollution is of concern, the words "meteorological control" mean stopping or slowing down plant operations during meteorological conditions which are estimated to produce above-tolerance ground concentrations.

Two atomic energy sites where experience has been obtained in routine forecasting for the control of radioactive effluents are Brookhaven[10,99] and Hanford.[26] The scheme for estimating probable ground concentrations at Brookhaven was based on O. G. Sutton's diffusion theories and on empirical relations and certain micrometeorological variables (primarily the gustiness and the wind speed) at the 355-ft level.[95,96,122] A series of templates was prepared for a wide range of weather conditions, which give the mean value of the dose rate averaged for 1 hr over an area 1 kilometer by 10 deg, extending from the chimney base outward for a distance of 15 kilometers.

Since the radiation dosage tolerance for both on- and off-site locations was on a seven-day basis, the stack output for the previous six days was converted by means of the appropriate templates into radiation dosage values. A diffusion forecast was then made for the final day of the period and was converted into radiation values, and the forecaster could determine whether continuation of reactor operations would result in dosages higher than the specified maximum.

As the experience at Brookhaven grew, as information and data relative to the dispersal of the stack activity was accumulated, and as the biological effects of the effluent were further evaluated, it became evident that the curtailment of reactor operations due to meteorological conditions was sufficiently infrequent to warrant discontinuation of the regular forecast service. Accordingly, routine 24-hr forecasts of radiation dosages were discontinued on Nov. 30, 1952. Since then the six-day dosages have been computed from the past meteorological and stack output records, but a forecast is prepared only when there is a chance of exceeding the permissible radiation limits.

At Hanford a somewhat different forecasting procedure has been used. Teletype reports, instrument records from the 410-ft tower, and pilot-balloon observations four times daily have been used to arrive at the "least dilution" factor[23] which is likely to occur during a particular plant operation.

In planning for any new atomic energy area or in reconsidering the requirements of an established area, the decision on the scope of the required meteorological program is fundamental to economical operations and safety. This is especially true where meteorological control of operation is being considered. In most instances the use of reliable air cleaning devices, sufficiently high stacks, or isolated sites will be more economical and much more satisfactory than operating a program only during favorable meteorological conditions.

Atomic energy plants should consider meteorological control only as a last resort since:

1. It is usually not economical.
2. Considerable difficulty may be encountered in stopping or restarting some atomic processes.
3. Success depends upon plant location, and for a given location favorable meteorological conditions might not be sufficiently frequent.
4. Changes in the physical environment, such as the development of a nearby plant facility or community, may create unforeseen problems.
5. Dispersion forecasts may be in error, perhaps as much as 10 to 20% of the time, for some operations.

Nevertheless, in a few instances certain kinds of meteorological control may be advantageous and the most economical solution, particularly where a meteorological program is already in operation. The types of control that may be desirable are as follows:

1. Scheduling of an auxiliary operation which can be conveniently conducted during favorable weather.
2. The operation of special air cleaning equipment or a stack heater (for increasing effective stack height) only during poor atmospheric diffusion conditions in order to save on operating costs, or the shutting down of such equipment for repairs during periods of good conditions.
3. The conducting of experiments of brief duration that are particularly hazardous and which involve a risk of releasing harmful airborne wastes.
4. Situations where the control of the long period cumulative risk is desired.

Ordinarily a routine program for predicting ground concentrations is relatively expensive. The services of a professional meteorologist, as well as one or more observers for chart preparation, is likely to be required. Although the cost of employing these persons may be feasible for one shift, as a rule plant operations are continuous, and consideration must be given to providing meteorological personnel to cover nights, weekends, holiday periods, etc. Thus the cost of a program for meteorological control may be found to be prohibitive for many plants.

When considering meteorological control, it should not be overlooked that climatic data can be used for routine scheduling of plant operations. At some sites it may be found that poorest diffusion conditions nearly always occur during a particular part of the day, and it may be possible to regularly avoid any releases during hours that are likely to be unfavorable. (A dissolving run at a chemical plant is one type of operation which could be scheduled only for certain hours.)

Another possibility for inexpensive meteorological control is the formulation, through meteorological consultation, of operating criteria based on direct readings of wind and/or temperature gradient instruments. This information could be fed into recorders on a control panel and made immediately available to the operators, who could then regulate the processes to avoid undesirable atmospheric concentrations.

The uses of meteorology in the operation of an atomic energy site, as listed here, are based on actual applications at the several national laboratories, production areas, and the reactor testing site. However, the few items mentioned by no means exhaust the current uses or the possible applications of meteorology. At each location the mutual exchange of ideas and the accumulation of experience continually results in the discovery of new ways of using meteorological information.

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# 3

# Meteorological Fundamentals for Air Pollution Studies

Each science eventually develops nomenclatures and methods of procedure applicable to its particular problems but not necessarily familiar, at first glance, to persons trained in other disciplines.

This section introduces and describes some of the more important meteorological factors directly related to air pollution.

Other portions of this report give quantitative methods for evaluating the behavior of contaminants introduced into the atmosphere. These methods require that certain properties of the atmosphere be measured. Given the numerical values to substitute into the equations, solution of the equations can provide diffusion estimates.

Recognition of certain meteorological fundamentals will assist in determining the requirements for the various measurements, the validity of the measurements, and the limitations of current diffusion theory.

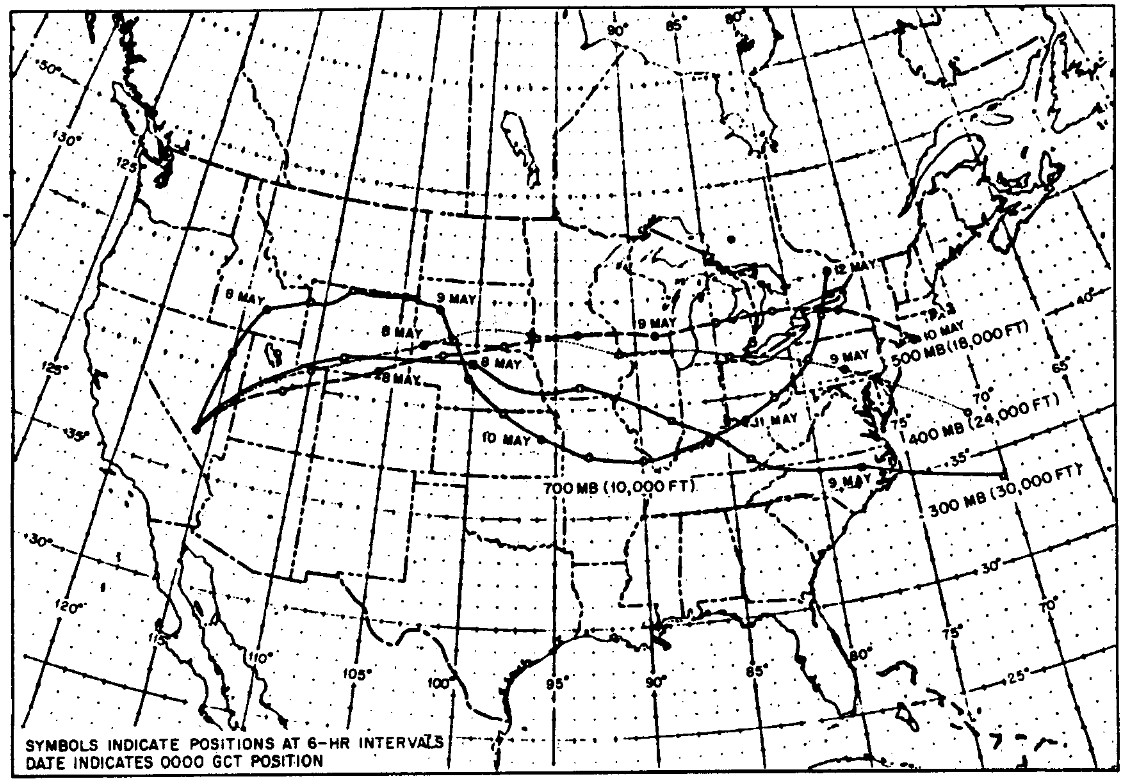
In practice, the following questions may arise:

1. What types of observations are required? What meteorological elements must be considered? What features of these elements are significant? What types of instruments are necessary?
2. How many locations must be used as observation points? Can observations made at a single point provide the information? Is it necessary to consider the atmosphere in three dimensions?
3. What should be the duration of the period for which observations are considered? Should observations be limited to a particular time of day, season, or meteorological condition?
4. How representative of a site are observations made at some other location? What are the effects of distance, altitude, and terrain features?
5. How are observations affected by abnormal climatic conditions? When may observations be assumed to be average or typical?
6. What are the effects of man-made objects on observations?

Much meteorological experience is usually necessary to answer such questions, and some of them are so complex that meteorologists themselves can answer only in general terms. It is impractical to present in condensed form all the meteorological fundamentals which are required to cope with the various problems which will be encountered. Rather it is hoped that this material will introduce the basic concepts and make it easier to recognize the more important aspects of air pollution problems.

## 1. TRANSPORT

There are many similarities between the behavior of a mass of air and that of water. Knowledge of the principles of hydrodynamics is as important to the meteorologist as to the hydraulic engineer. Suppose that in a volume of clean air some polluting source has placed an amount of foreign material. In the atomic energy industry the material may be highly radioactive and poisonous far beyond substances usually encountered in industry, and the source could be a stack, a leaking container, or a runaway reactor. For the time being, let us consider that the foreign material occurs as a puff. Of course, if the material is heavier than air it will settle, but suppose that it consists of a gas that has the same density as air or that it consists of particles with negligible settling ve-



SYMBOLS INDICATE POSITIONS AT 6-HR INTERVALS
DATE INDICATES 0000 GCT POSITION

Fig. 3.1—Trajectory analysis for an atomic bomb cloud from a test at the Nevada Proving Grounds (List[114]).

locities. Under these conditions that material will move as the volume moves. Its speed and direction will be the same as that of the volume, and its position at some later time will be determined by the location of the volume.

Primarily in air pollution problems we must determine the horizontal transport of contaminants. Our tools are wind vanes and anemometers, or perhaps balloons, which probe the atmosphere to determine the direction of movement and the speed of air passing by. Usually it is assumed that measurements at one point in the volume are sufficient to determine the movement of any material being transported by it.

## 2. TRAJECTORIES

It is usually assumed that the trajectory of material is determined by the motion of the volume of air in which it is contained. A trajectory analysis may be shown as arrival times at consecutive points on a map. An example of a trajectory analysis for an atomic bomb cloud from a test at the Nevada Proving Grounds is shown in Fig. 3.1. For an industrial problem a trajectory analysis would probably include only the region that would be affected by pollution from the plant.

## 3. EFFECTS OF OBSTRUCTIONS AND CHANNELING

In many applications of meteorology there is little interest in air after it passes beyond wind instruments or in trajectories. In the construction of an airport runway, it is hardly necessary to consider that an air volume is being sampled by the instruments; however, this is not true in air pollution work. On a level plain with no obstructions, wind instruments at a single point will usually be sufficient for the estimation of trajectories. Wind data from a station where wind flow is obstructed in one way or another must be carefully interpreted.

Obstructions are usually solid objects, such as hills or mountains, but may also be denser, colder, masses of air. Polluting material may be lifted as the air mass in which it is contained encounters and passes over a wedge of denser air, or the colder air may run under the volume and lift it. Also, in some cases where the air is flowing downhill, it may move out over colder air as shown in Fig. 3.2.

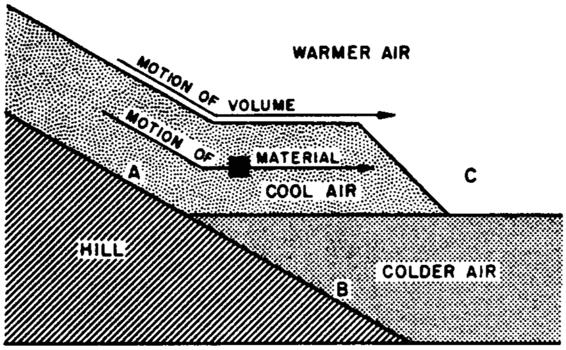


Fig. 3.2—Cool air moving down a slope can move out over cold, more dense air so that the trajectory of material in the cool air is affected.

The effect of obstructing masses of cold air is actually important in practice, e.g., a plant or laboratory may be on a hillside with a city below, or a plant may be in a valley below a mountain slope and be subjected to wedges of cold air originating as the mountain slope cools at night. Note in Fig. 3.2 that a single wind vane at A might lead us to expect the polluting material to arrive at B, when actually it will probably arrive at C. Wind vanes alone are inadequate to determine trajectories in cases such as this. We need to know the depth of the cold air. In complicated instances trajectories may have to be estimated from the behavior of airborne tracers, such as fluorescent particles.[119]

Channeling may occur when the general wind pattern is across a valley but not at a right angle to it. The surface wind direction may turn parallel to the valley as shown in Fig. 3.3.

## 4. DEFORMATIONS

As the air mass is transported, it will be subject to changes in shape as it encounters physical objects. In passing through a gorge or over a mountain range, it may be stretched, and as a result the wind speeds will be greater. On the other hand, if the volume expands vertically or horizontally at the expense of its longitudinal dimensions, wind speeds within it will be less, as, for example, in crossing a valley (see Fig. 3.4).

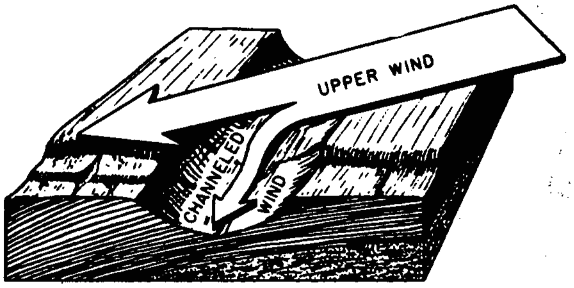


Fig. 3.3—Channeling of wind by a valley.

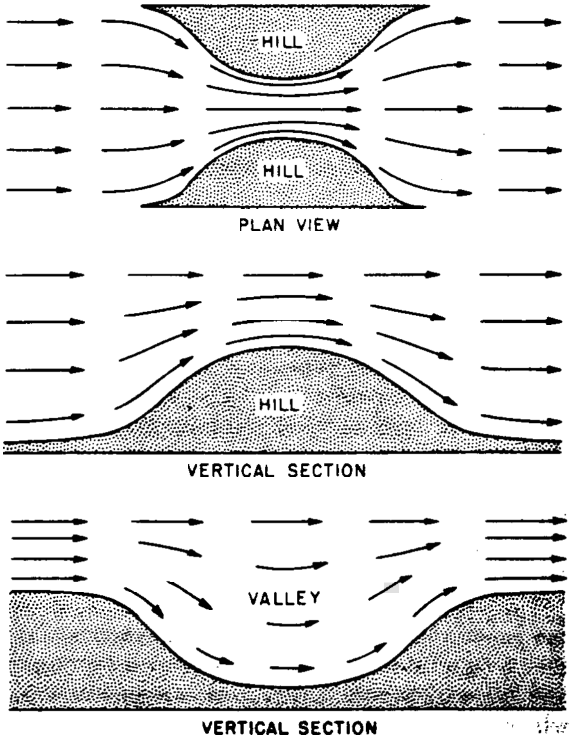


Fig. 3.4—Schematic diagram showing effects of terrain on wind flow. Arrows are proportional to wind speed.

Note in Fig. 3.5 how a mass of cold air can pour through a mountain pass to cause strong winds. The "Santa Ana" wind of Southern California and the Columbia Gorge winds are outstanding examples of this phenomenon in the United States.

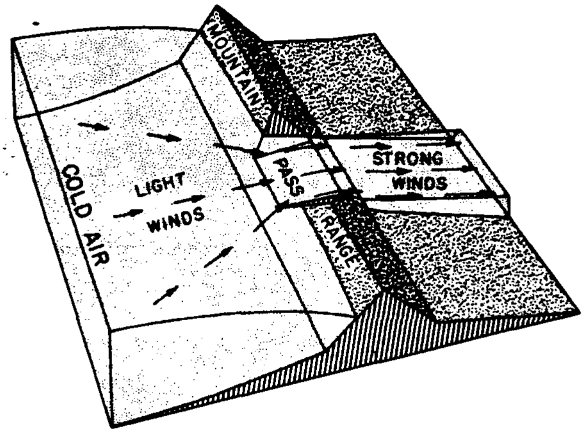


Fig. 3.5—As a cold air mass pours through a mountain pass, strong winds are produced.

## 5. WIND ROSES

Long periods of wind records may be summarized in a wind rose, such as the one shown in Fig. 3.6. The wind rose may be used to estimate the probability that material may move in a particular direction and at a certain range of speed. These summaries may be constructed for specific elevations, seasons, times of day, or meteorological conditions to provide data for specific problems.

The configuration of a wind rose integrates the results of air currents on a planetary scale, the passing of high- and low-pressure systems, and local winds. [Note that in standard practice winds are shown as direction from which they occur and are measured clockwise from north with north as 360° (or 0°). Thus a southwest wind is at the 225° position on the circle.]

## 6. LOCAL WINDS

The most important local winds from the viewpoint of air pollution are likely to be thermally produced. Outstanding are the sea-breeze and valley-slope circulations.

6.1 *Sea Breeze.* In the case of the sea (or lake) breeze, the strong heating of air over land (and the greater expansion of a column of air over land as compared with a similar volume over water) leads to an inflow of air at the surface from sea to land, which, in turn, causes a return circulation aloft from land to sea. At night a reverse flow occurs. Principal among the factors which favor a sea breeze is a relatively high intensity of solar radiation; however, a weak general pressure gradient is required to permit formation of a true sea breeze. Thus, in tropical regions one might expect the sea breeze to occur throughout the year, whereas in temperate latitudes the sea breeze is most frequent during spring and summer. Ordinarily, the sea breeze begins early in the day with relatively low wind speeds and attains its maximum about 2 p.m. Its depth in temperate latitudes is usually less than 2000 ft. As the sea breeze penetrates inland, its speed and depth are reduced considerably. Speeds

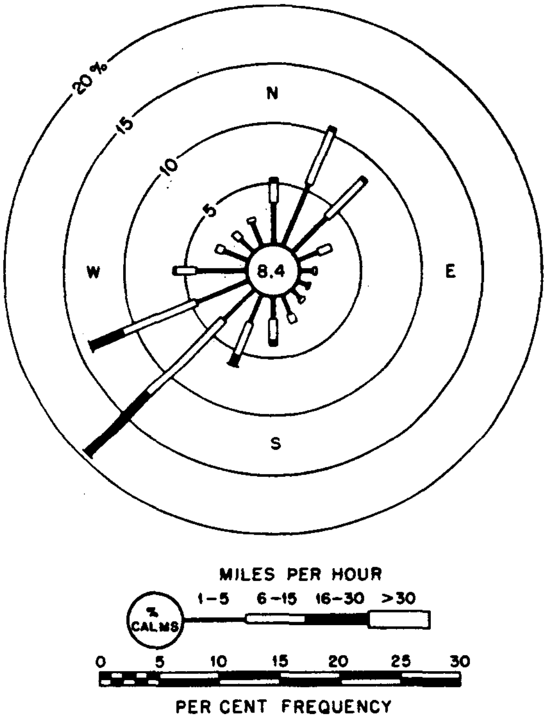


Fig. 3.6—Annual wind rose for two-year period, June 1950 to May 1952. Wind at 20-ft level. Radial lines show direction from which wind blows (NRTS).

measured 10 to 15 miles inland may be about one-half the value at the coast line, and the depth is correspondingly reduced. The land breeze, the return flow from land to sea, begins about 2 hr after sunset and continues until about 2 or 3 hr after sunrise. The land breeze is not so well marked a wind phenomenon as the sea breeze, and its depth is only a few hundred feet.

6.2 *Valley-slope Circulations.* Local winds caused by differential heating of the terrain are often the dominant circulation over a site. Although valley-slope winds may occur over gently sloping terrain, they are most pronounced and frequent in mountainous areas.

During the day the air over a slope will be warmer than air at the same height over the valley. The rising of this warmer air creates a well defined wind up the slope. The reverse is true at night, and the cooler air over the slope flows downward into the valley.

The essentially cross-valley-slope winds are an integral part of the larger and deeper circulation along the longitudinal axis of the valley. This wind too is caused by differential heating, this time between the air over the valley and that over the plain. Now it is the air within the valley that becomes warmer during the day and, rising, is replaced by a flow into the valley from the plain. During the night a reversal occurs, and air flows down the valley out to the plain. Figure 3.7 is an idealized representation of the circulation which might occur in a typical valley. It should be noted that the slope and valley circulations decrease with height, disappearing entirely at about the height of the tops of the ridges forming the valley. The annual wind rose for the National Reactor Testing Station shown in Fig. 3.6 shows the great influence of terrain winds. The southwesterly winds are primarily up-valley, and the opposing northeasterly winds, the nocturnal return, flow down the valley.

A very localized feature, but one which can result in rapid distribution of contaminants, is the heating of one side of a valley, as by the morning sun, while the other side remains in shadow. This may result in overturning of the air as shown in Fig. 3.8.

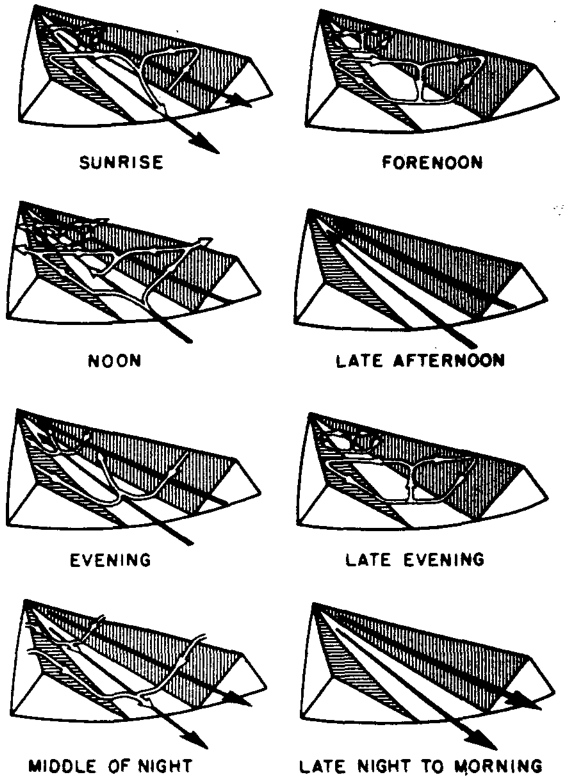


Fig. 3.7—Idealized representation of the circulation which might be expected in a typical valley (Defant[40]).

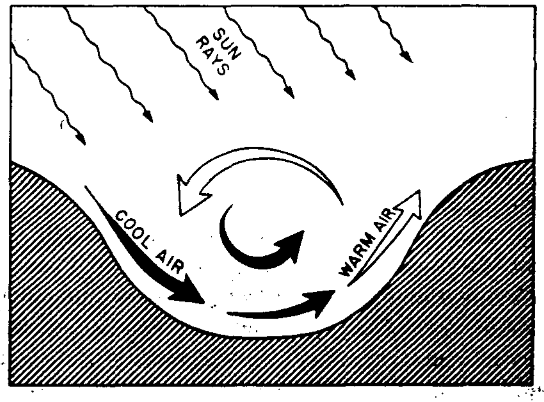


Fig. 3.8—The heating of one side of a valley while the other side is relatively shady may produce overturning of the air in the valley.

A coastal location may be subjected to a combination of sea breeze and up-slope winds. The effects which produce local winds also combine with the effects of the large scale pressure systems to increase or decrease wind speed and to alter wind direction.

## 7. EFFECTS OF SURFACE FRICTION

The frictional drag of the earth's surface on the air moving over it results in a velocity increase with altitude from the surface upward. This increase of speed with height may vary according to a logarithmic or power law. At Hanford it was shown[87] that the wind profile is logarithmic about 93% of the time during daylight hours. At night such a formula is less applicable, probably owing to the thermal stratifications of the air.

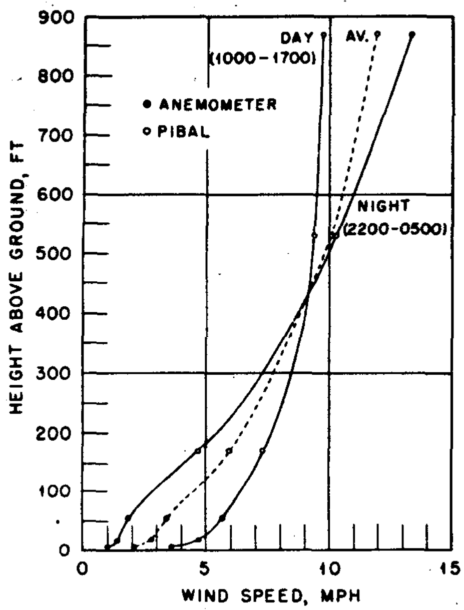


Fig. 3.9—Annual wind speed profiles showing that winds near the surface are stronger during the day and winds aloft are stronger at night. The observations were made at Oak Ridge[81] September 1949 to August 1950.

During the day energy from moving air aloft is rapidly brought to the ground by eddy motion. At night the eddies are damped out. Therefore surface winds are stronger during the day, and the winds aloft are stronger at night (Fig. 3.9).

## 8. MIXING PROCESSES

These motions may result in a change of location of material within an air mass, or they may result in the mixing of clean air with the material. The latter decreases the concentration of material per unit volume and is of primary concern. In the preceding parts of this chapter, with an entire air mass in mind, we have considered motions which are nondiffusive. Consider now those which may be regarded as diffusive. Since a mathematical approach to the diffusion process is given in the chapters to follow, we will consider the subject qualitatively here. A puff of material, if actually injected into a volume of air, will seem to grow larger. This is due almost entirely to eddy motions. Molecular motion also produces diffusion, but, compared to eddy diffusion, molecular diffusion is hardly noticeable at the scale in which we are interested.

Eddy motions may result from mechanical effects, as when objects protrude into the volume and interrupt smooth air flow (Fig. 3.10), from the effects of convective or thermal eddies due to unstable density stratification, or from the combined effects of both. Mechanical eddies may be favored or damped out by the vertical density gradient.

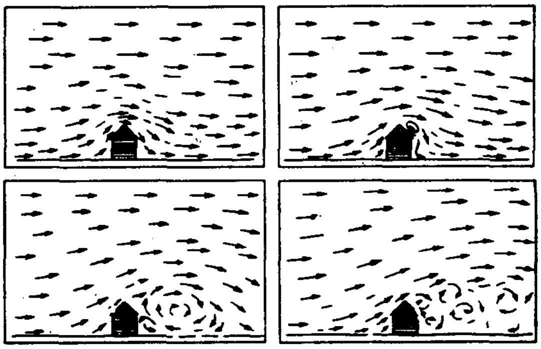


Fig. 3.10—Mechanical eddies form when smooth flow is interrupted by objects. The four examples show the effect of wind speed on eddy formation (Sherlock and Stalker[130]).

8.1 *Dimensions of Eddies.* An eddy in the atmosphere can range in size from molecular dimensions to the diameters of great cyclonic storms covering large portions of the earth's surface. The effect of eddy sizes on diffusion is of great interest and practical significance. However, our knowledge is limited by the technical difficulties in collecting observational data. The study of eddy motions by instruments is greatly complicated by the three dimensional character of the eddies and by the speed of response necessary in instruments for their measurement.

Vertical diffusive motions in the lower levels are subject to the damping effect of the ground, but above 100 ft such motions are usually treated as though they were equal vertically and horizontally. (In other words, turbulence is now usually regarded as isotropic at the level of most stack tops. Further investigations may modify this concept materially.)

8.2 *Convection*. Our ability to estimate quantitatively the effects of convection on airborne material is limited. From observations of clouds and smoke and from the experiences of glider pilots, it appears that convective "cells" take various forms. The classical Bénard cell of the laboratory has fluid rising in the central section and then descending. Such cells form in liquid or air and are easily produced. They are characteristic of a shallow layer of fluid with a pronounced vertical density gradient that is not disturbed by the effect of shear or by eddies due to other causes, and they may be responsible for some of the regular patterns of clouds often observed. With proper shear, a single line of Bénard cells in a vessel becomes two rotating rollers oriented in the direction of the shear. Rising motions occur between the two rollers, with descending motions along the outer edges. Similar motions probably cause the so-called "cloud streets" (long parallel rows of clouds), seen sometimes over the open ocean.

Glider pilots and some meteorologists (notably R. S. Scorer[100]) discuss another type of convection which, for want of a better name, is called the "bubble-type." With this type, hot bubbles of air, which form because of unequal heating of the ground, rise independently; thus the descending motion is indefinite and is not easily detected. The pilots call the rising bubbles and the column of air trailing the bubbles "thermals." The difference between circulation in a Bénard cell and air motion according to the bubble theory is shown in Fig. 3.11. Experience indicates that most natural convection combines features from both models.

Convection may lift and disperse material or, in the case of stack effluent, may bring it to the ground in concentrations higher than would otherwise be expected.

8.3 *Surface Roughness*. Keeping all other factors constant, the contribution to the diffusive power of the atmosphere which is due to mechanical turbulence is relatively larger over rough surfaces than when the surface is smooth.

Ground types can be ranked according to roughness almost completely intuitively, and the roughness can be checked experimentally with smoke; a wheat field is rougher than mown grass, and the grass is rougher than a snow surface. In atmospheric pollution work we are also interested in roughness due to terrain and objects, such as trees, walls, and buildings. For the most part in industrial problems, roughness is dealt with without assigning a numerical value (such as the micrometeorological parameter "roughness" length) to surfaces and objects. It is considered indirectly in terms of its effects on the coefficients of the diffusion equations.

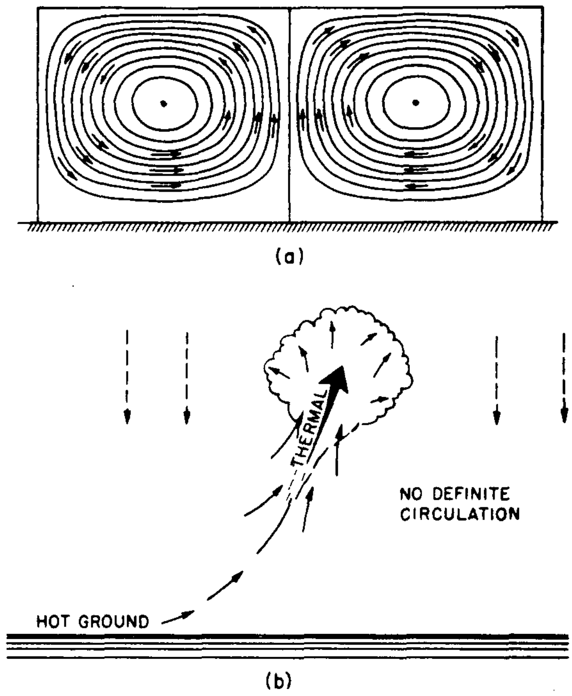


Fig. 3.11—Comparison of circulation in a Bénard cell with air motion according to the bubble theory. (a) Circulation in a Bénard cell (cross section). (b) Convection bubble.

8.4 *Gustiness*. Gustiness, usually referring to a variability in the force of the wind, is physical evidence of eddy motion, as is the swinging from side to side of a wind vane. With gusts due to mechanical eddies, the greater the mean wind speed the greater the mean amplitude of the gusts.

## 9. EFFECTS OF MIXING PROCESSES

If material is released as a puff, the diffusive action of a particular eddy depends upon its size relative to the size of the puff. If the puff is small, a large eddy may only transport the material from one part of an air mass to another, with a minimum of diffusion. However, since eddy sizes may range from a few centimeters to thousands of meters, diffusion to some degree will begin almost instantly after the material is released into the atmosphere.

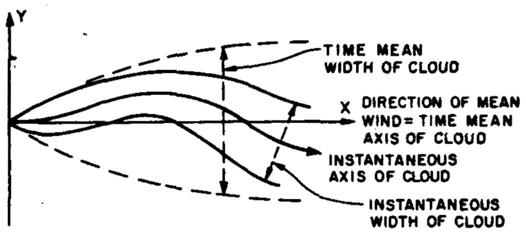


Fig. 3.12—Instantaneous width of a cloud from a continuous source vs. the time mean width.[32]

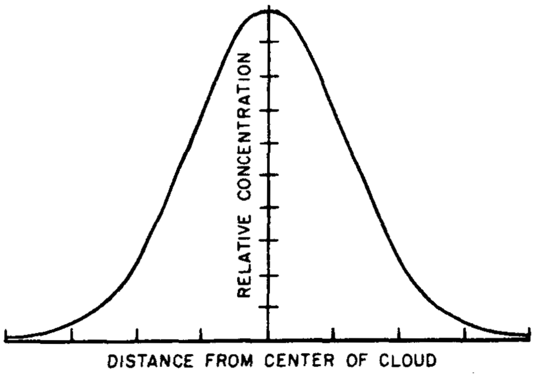


Fig. 3.13—Concentrations across the time mean width.

Internal motions within an air mass must be considered somewhat differently when referring to the diffusion of material from a stack or vent, i.e., a continuous source. Some eddies are effective in producing diffusion of the smoke plume, and some move the plume in a serpentine fashion horizontally or vertically. In this case, to estimate concentrations downwind, sampling time becomes important. For any continuous source, since a time interval is considered instead of an instantaneous event, eddies of many sizes affect concentrations. Figure 3.12 shows schematically the instantaneous width of a cloud from a continuous source vs. the time mean width. Figure 3.13 shows schematically relative concentrations across the mean width as obtained by time averages, and Fig. 3.14 shows ground concentrations over a sufficient time interval (30 min or more) downwind from a stack.

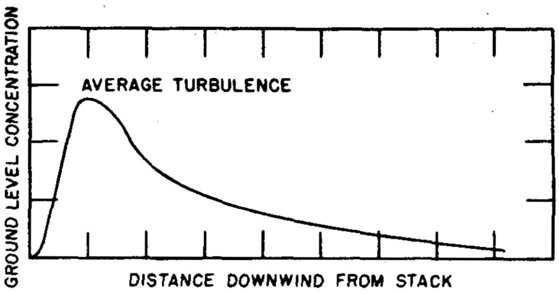


Fig. 3.14—Ground concentrations over a sufficient time interval downwind of a stack (elevated continuous source).

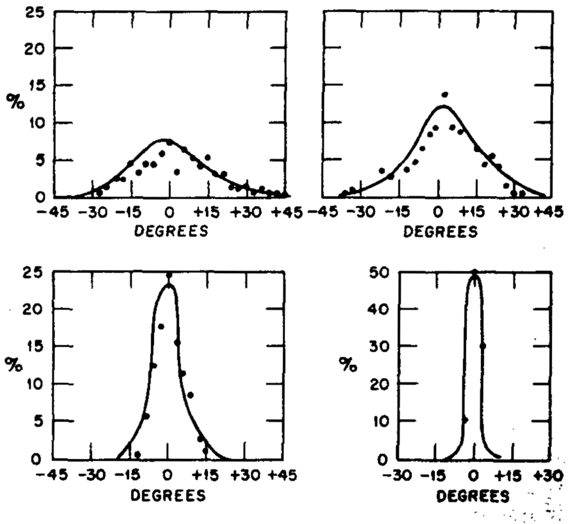


Fig. 3.15—Representative variations of wind direction form the 10-sec mean for the wind trace types (Lowry[34]).

The variations of wind direction from the mean for the wind trace types are shown in Fig. 3.15. Note the similarity of these curves to the curve for the relative concentrations across the time mean width from a continuous source. The relation between the wind fluctuations and the time mean concentrations downwind from a source is inferred from these curves.

## 10. TEMPERATURE PROFILES

The diffusive capacity of an air mass is strongly influenced by its vertical thermal structure. When the temperature of the air is plotted as a function of height above surface, the curve is conveniently referred to as a temperature profile.

At a given pressure and specific volume, the temperature of a gas is inversely related to its density, and its acceleration due to buoyancy force is proportional to the difference between its density and that of the medium in which it is submerged. Buoyancy alone is not sufficient to account for the motions which actually occur, but the temperature profile, together with its associated buoyancy effects, is a necessary consideration when estimating concentrations of airborne material downwind from a source.

The rate of decrease in the value of any meteorological element with elevation is usually referred to as its lapse rate. With a normal or standard lapse rate (e.g., U. S. Standard Atmosphere), the rate that temperature decreases with height is specified as 3.5°F/1000 ft and 0.65°C/100 meters.

If the lapse rate is such that it shows no change of temperature with height, it is isothermal. A stratum with an "inverted" (or positive) gradient, in which the temperature increases with elevation, is designated an inversion (Fig. 3.16).

Of particular interest is the unique atmospheric lapse rate which permits a parcel of air to be displaced from one level to another so that the parcel always has the same density as its environment (assuming unsaturated air and that changes of temperature within the parcel take place without an exchange of heat with its surroundings). Since a change of state, i.e., of the temperature, pressure, and density, of a gas is said to be adiabatic if it takes place without heat being supplied or withdrawn, the lapse rate referred to is known as the dry adiabatic lapse rate or sometimes as just the adiabatic rate. Numerically, it is equal to a decrease with elevation of 1°C/100 meters and 5.4°F/1000 ft.

If the temperature in the atmosphere decreases at a rate greater than the adiabatic, the lapse rate is superadiabatic. With a superadiabatic lapse rate, a parcel of air which is displaced upward from a level at which it has the same temperature and pressure as the surrounding atmosphere will undergo a decrease of temperature corresponding to the adiabatic rate and will have a higher temperature than its environment at the new level. It will be of lower density than the surrounding air, and the force of buoyancy which results will tend to cause the volume to continue to ascend. In like manner, if the parcel should be displaced downward, it will have a lower temperature than its surroundings and will tend to sink further. Therefore, when the lapse rate is more than the adiabatic, all vertical motions are accelerated, and the atmosphere is said to be unstable. On the other hand, if a lapse rate is less than dry adiabatic, a parcel of air displaced upward will have a temperature lower than its surroundings or, if displaced downward, a temperature higher. In this case, buoyancy forces tend to restore the parcel to its original level, and the atmosphere is said to be stable. If the lapse rate is exactly dry adiabatic, the air is neither stable nor unstable, and conditions are said to be neutral (Fig. 3.17). (The neutral lapse rate is often referred to as "average" conditions. This may give an incorrect impression since measurements show that in a continental area the temperature profiles in the

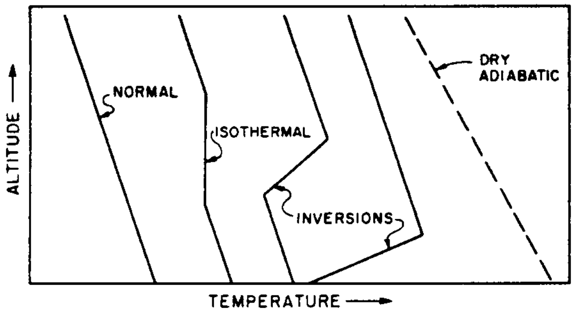


Fig. 3.16—Temperature profiles illustrating the normal lapse rate, an isothermal lapse rate, and inversions. The dashed line is the dry adiabatic lapse rate.

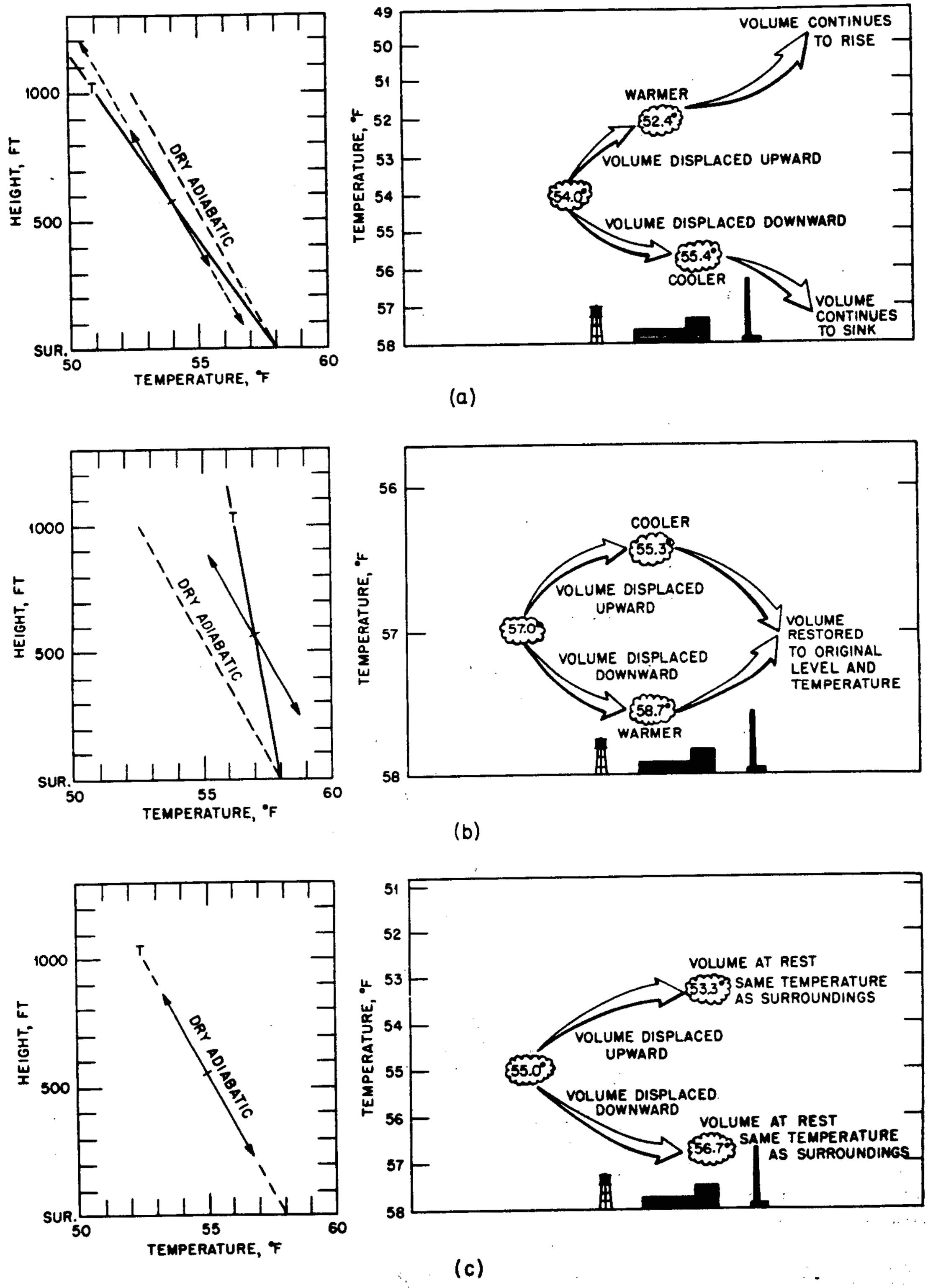


**Fig. 3.17—Effects of lapse rate on displaced air volumes. (a) Unstable lapse rate. (b) Stable lapse rate. (c) Neutral lapse rate.**

lower layers are most frequently superadiabatic by day and isothermal or inversions at night.)

As water changes phase from a vapor to a liquid, heat will be released; and, if the water is condensing in a rising volume of air, the rate of cooling of the air will be changed. The lapse rate produced, which is less than the dry adiabatic, is known as the moist or pseudoadiabatic lapse rate. However, in air pollution problems it is seldom necessary to consider the lifting of air high enough to produce condensation by adiabatic cooling.

When dealing with conditions near the surface, e.g., in stack effluent problems, it is usually considered that condensation is not occurring within the stratum of interest even though there may be fog or precipitation. The actual lapse rate is compared with the dry adiabatic to determine stability. The error introduced is negligible.

## 11. EFFECTS OF TURBULENT MIXING

During windy weather, when the atmosphere is well mixed and clouds prevent incoming and outgoing radiation, lapse rates which are nearly equal to the dry adiabatic are observed to moderate elevations.

Since the dry adiabatic rate is greater than that of the atmosphere generally at these heights, at the upper limit of the mixed layer there will be a turbulence inversion (Fig. 3.18). Such inversions are common on the coast of California and are a factor in air pollution there. Under strong inversion conditions gentle mixing has the effect shown in Fig. 3.19. Any motion at the surface will tend to stir the air and make the noctural inversion deeper and less intense.

## 12. DIURNAL EFFECTS

Figure 3.20, drawn from actual data, shows the changes in the temperature profile which may be expected to occur on a typical day with light winds and few clouds. During the middle of the day (note 0900 and 1500 hours), the lapse rate is superadiabatic. The superadiabatic rate will be nearly constant because of the mixing action of the convective currents which are automatically generated. Additional mixing due to turbulence created by wind does not greatly change a superadiabatic profile when there is strong surface heating. During the day the air is heated initially by molecular conduction at the surface, but that heat is transported to a considerable height by convection. However, superadiabatic lapse rates are usually maintained only in the lowest few hundreds of feet, occasionally reaching 1000 to 2000 ft over bare ground in midsummer. The midafternoon profile is similar to that of midmorning, except that it is displaced toward warmer temperatures.

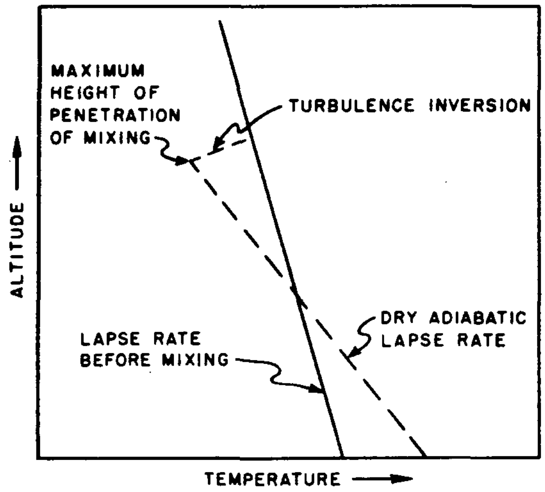


Fig. 3.18—Development of a turbulence inversion.

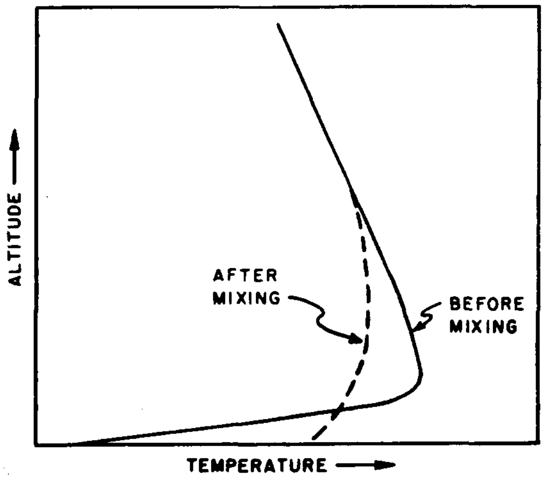


Fig. 3.19—Effect of gentle mixing on a nocturnal temperature inversion.

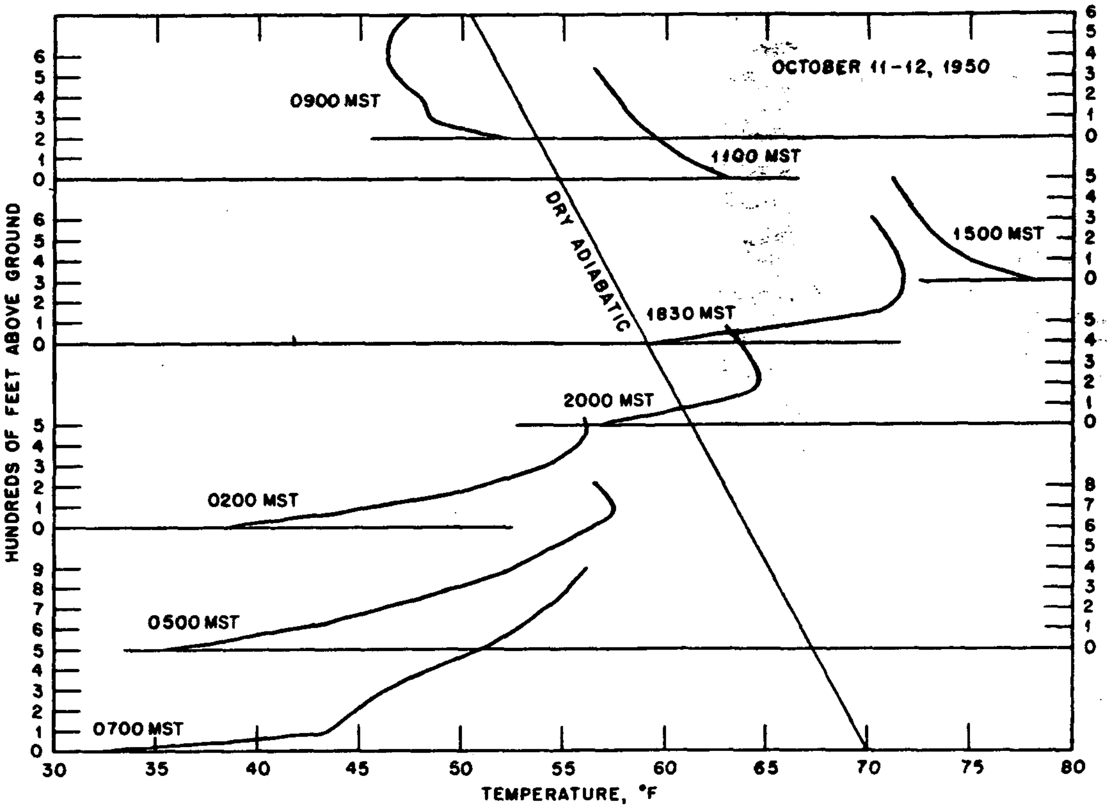


Fig. 3.20—Temperature soundings on a day with clear skies and light winds.

As the sun sets, the ground begins to cool rapidly; as a result an intense but shallow inversion is formed (1830). Throughout the night the surface temperature will continue to decrease; therefore the surface inversion will continue to become more pronounced. Other factors remaining the same, still air will contain the most intense, although shallow, inversions. Above such inversions the air will cool slowly.

At sunrise, heating at the surface begins immediately, and a shallow but gradually deepening superadiabatic layer develops (0900). Convective eddies are soon established in this layer; thus, by the time it is a few hundred feet thick, stack effluent may be brought to the ground and mixed within the layer to produce high ground concentrations. This particular profile is said to produce "fumigation" conditions and is discussed in greater detail in Chap. 5. Thereafter, the profile becomes, for all practical purposes, superadiabatic.

Figure 3.21 shows similar data obtained at Oak Ridge, Tenn., but, in addition, the frequency of the various lapse rates and profiles is illustrated. The general diurnal trend is quite similar, although the higher, drier regime at the Idaho station results in higher values of both the daytime superadiabatic lapse rate and the nighttime inversions. This figure also shows that the large diurnal range of lapse rate decreases rapidly with increasing height above the ground.

Figure 3.22 shows the temperature difference between 100 ft and 5 ft for a winter and a summer month. In July, surface heating begins about sunrise, or shortly before, and within about 2 hr the temperature at the two levels is the same. Then, a few minutes afterward, a superadiabatic lapse rate is established. The strongest lapse rate occurs about midmorning, before strong convective currents or mixing occurs. During the latter part of the morning, after convective currents are established, the

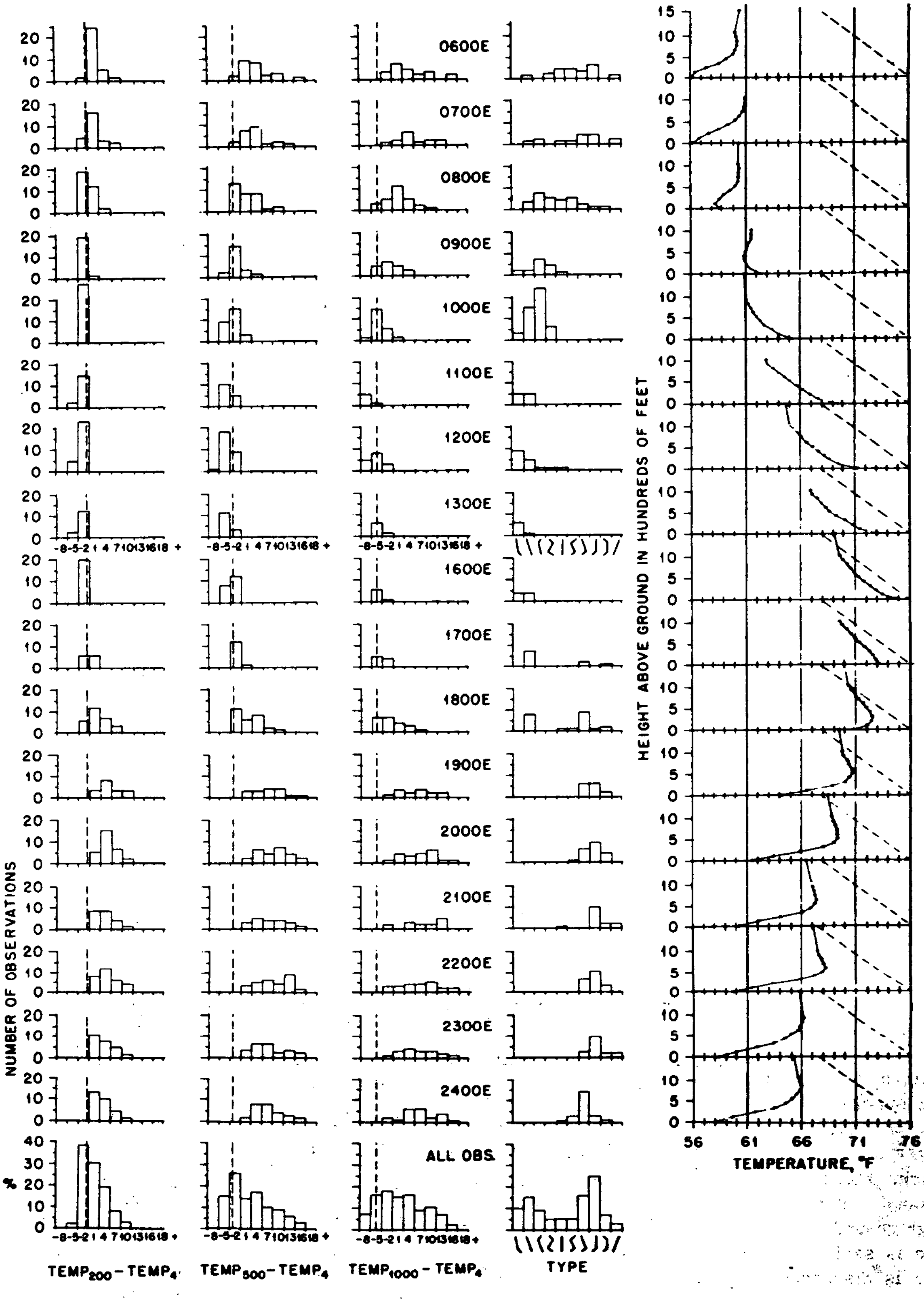


Fig. 3.21—Lapse rate frequencies (Oak Ridge[31]).

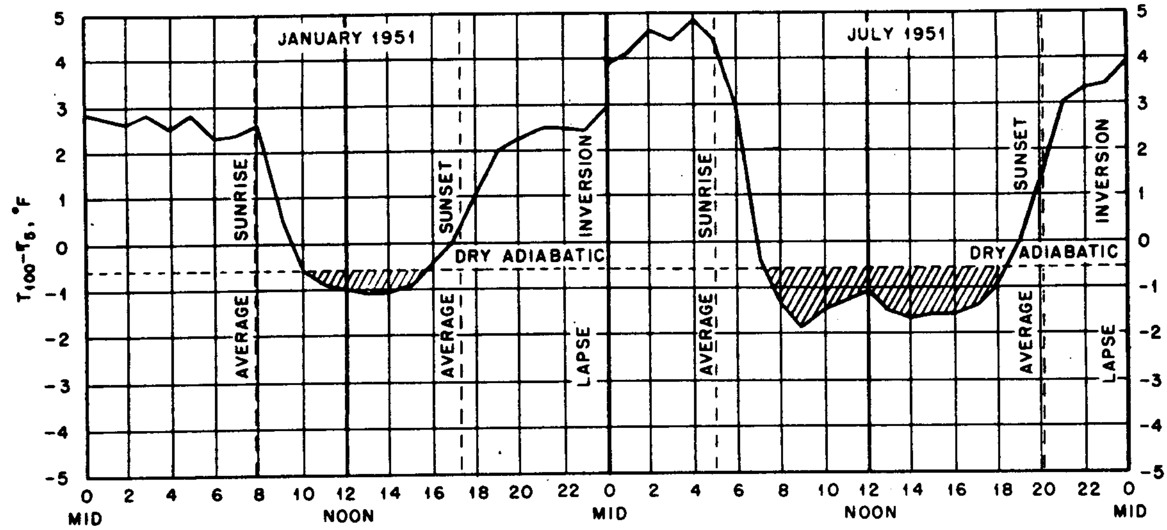


Fig. 3.22—Average vertical temperature gradients (NRTS).

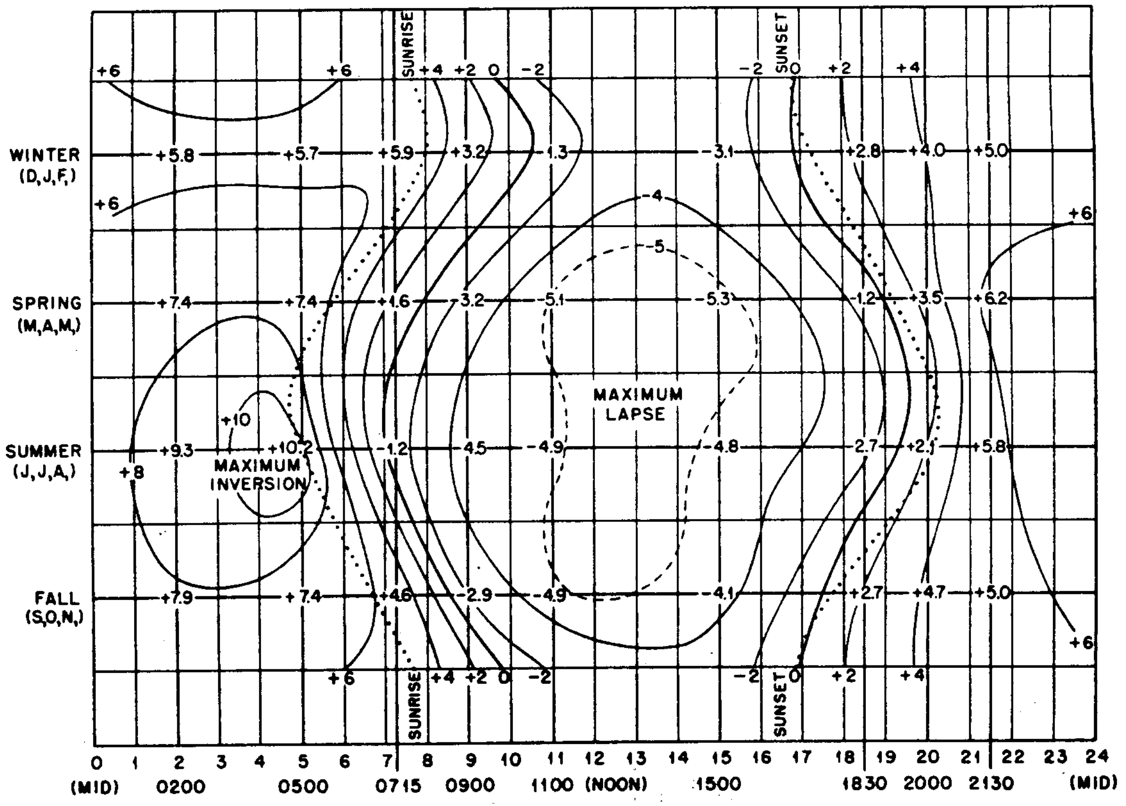


Fig. 3.23—Seasonal variations in the average thermal gradient between 5- and 400-ft levels. Temperature sounding data for two-year period, September 1950 to August 1952 (NRTS).

lapse rate is less superadiabatic; however, it becomes more unstable again as surface heating progresses. During the early afternoon surface temperatures reach a maximum, and the lapse rate may be as superadiabatic as any other time during the day. With enough heating, convective processes are inadequate for maintaining a constant lapse rate. Cooling at the ground begins before midafternoon, and, for most of the remainder of the afternoon, the lapse rate gradually decreases. In the example shown, inversion conditions are established about 1 hr before sunset. In a shallow layer near the ground, the most intense inversion will occur in the evening since the air is still relatively warm with respect to the cooling ground.

## 13. SEASONAL EFFECTS

The difference between the amount of solar radiation received at the surface in summer as compared to winter is greater than is generally realized. On clear days in winter there is not only less sunshine per unit area because of the lower elevation of the sun but the duration of sunshine is much less. For example, at about 45°N, the solar period is almost twice as long on June 21 as on December 21. A secondary effect of the elevation of the sun is that at low angles the sunlight must penetrate a much greater depth of atmosphere; thus there is much more opportunity for radiation to be lost owing to scatter and absorption by water vapor, dust, smoke, and other turbidity factors.

Actual seasonal profiles are greatly affected by local conditions and will vary greatly; but, in general, the seasonal differences in solar radiation will favor longer inversion periods during colder months. At a continental station with pronounced seasonal effects, a maximum of only a few hours of definitely superadiabatic conditions will occur consecutively during midwinter, whereas sometimes an unbroken period of inversion conditions will occur for several days. At the same station throughout summer months, superadiabatic conditions will be the rule during daylight hours.

In addition to the seasonal effects directly caused by the solar angle, there is also an important effect which is caused by the lag in the heating of the atmosphere as a whole. This is illustrated in Fig. 3.23. It is easy to see by means of this diagram that, on the average, the strongest lapse rates occur during the spring, whereas the strongest inversions occur during late summer or fall. In spring there is likely to be cool air over a warming surface, whereas after midsummer the reverse is true.

From the preceding discussion of seasonal effects, it would seem that there would be more inversion hours during the colder months. Actually, at most locations conditions are just the opposite. Although the lack of sunshine greatly favors inversion conditions during winter, in northern continental latitudes there is also much more windy, cloudy weather than in summer. For the United States as a whole, spring months have the least number of inversion hours, whereas fall months have the most. It should be noted, however, that winter conditions favor the persistence of inversions.

Other factors contribute to the modification of the thermal structure of the atmosphere and hence to the diffusion. Since they are rarely considered separately or measured directly, they will be mentioned briefly.

## 14. RADIATION SURFACES

Surfaces also differ greatly in their ability to radiate heat. Snow is an especially good radiator and for all practical purposes may be regarded as a black body. The most pronounced inversions are likely to be found over snow surfaces. Note the effects of snow shown in Fig. 3.24.

## 15. CONDUCTIVITY AND SPECIFIC HEAT

Air temperatures above a surface are affected materially by its conductivity and specific heat. In general, highly porous dry materials have low conductivity, whereas materials containing the most water have the highest specific heats. The combined effects of these properties are most evident in the minimum temperatures observed over various surfaces. Other conditions being equal, minimum temperatures should be slightly lower over freshly fallen snow and dry sandy soil than over humus, ice, or concrete.

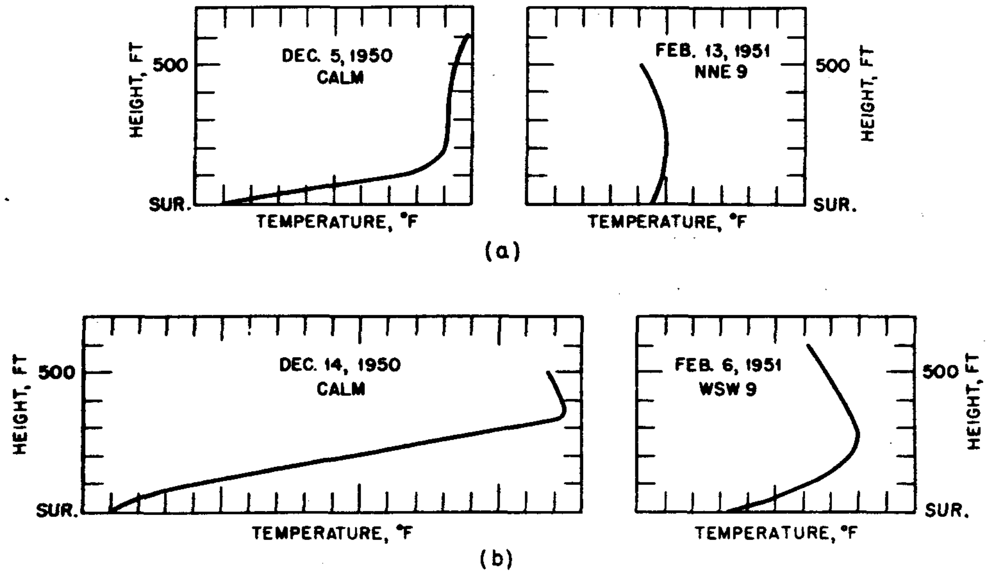


Fig. 3.24—Bare ground (a) vs. snow cover (b).

## 16. PHASE CHANGE OF SURFACE WATER

It is possible to observe superadiabatic gradients during the early morning hours, the time when air is usually especially stable, under the following combination of circumstances:

1. When there is a low, heavy overcast lasting throughout the previous day and continuing through the night.
2. When a mass of freezing air is brought in over a wet and relatively warm surface.
3. When wind speeds are light (between 4 and 8 mph).

The air very near the ground is warmed by the latent heat of fusion given off as the water on the ground freezes. Figure 3.25 shows a temperature profile obtained under the conditions described.

Evaporation, as on the day following a heavy rain, will also exert a cooling effect that may be significant. The cooling effects of evaporation are likely to be more pronounced during the daytime. Evaporation at night is primarily a function of wind speed; thus its effects on the temperature profile are somewhat masked.

16.1 *Vegetation*. The daily range of temperature is smaller over vegetation. Neither lapse nor inversion conditions are as pronounced as over bare ground.

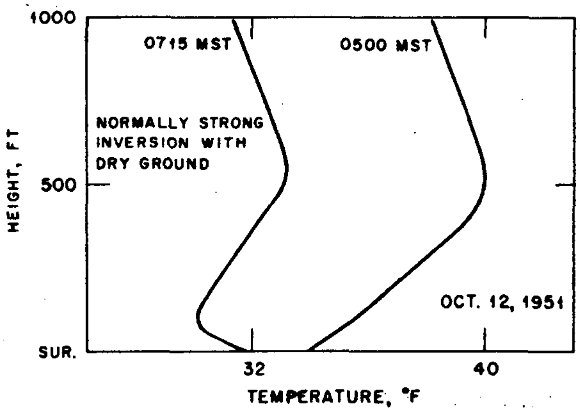


Fig. 3.25—The heat of fusion as surface water freezes can produce a superadiabatic (unstable) lapse rate in a layer of air that might otherwise be completely stable.

16.2 *Cities and Other Built-up Areas.* Investigations[41,120] have shown that cities or large industrial areas do indeed produce significant temperature effects and consequently have a different temperature profile than exists over the surrounding countryside. Built-up areas frequently cause instability up to about three times roof height in otherwise stable air. This

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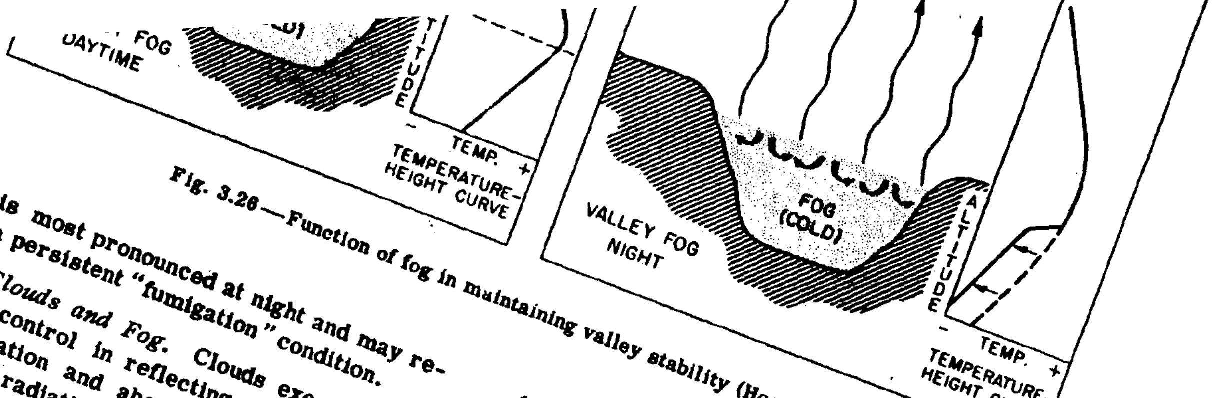

Fig. 3.26—Function of fog in maintaining valley stability (Hoecker[71]).

effect is most pronounced at night and may result in a persistent "fumigation" condition.

16.3 *Clouds and Fog.* Clouds exert a thermostatic control in reflecting the short-wave solar radiation and absorbing the long-wave terrestrial radiation. With clouds the surface temperature changes less, and consequently the temperature profile is likely to be more constant and less extreme. The thicker and lower the cloud layer the more effective is the damping of diurnal changes.

The top of a cloud or fog layer will reflect sunlight regardless of the angle of the sun. At night this surface also acts as a radiator. When clouds or fog occur beneath an inversion layer, the drop in temperature with radiation may intensify the inversion and increase the lapse rate just below it. This effect of fog or low clouds on the temperature profile is important to air pollution since, combined with stagnant conditions, it will result in increased pollution concentrations (Fig. 3.26).

Fog also has an important effect on stack gases. A nocturnal surface inversion is destroyed by the formation of a dense radiation fog (Fig. 3.27). Ordinarily, under inversion conditions, stack effluents will stay aloft, but within fog the lapse rate becomes such that effluents are carried downward more easily. It is a well-known fact that city smoke mixes easily with fog. This is in part due to the lapse rate in the fog itself and in part due to the effect of the city as mentioned in Sec. 16.2.

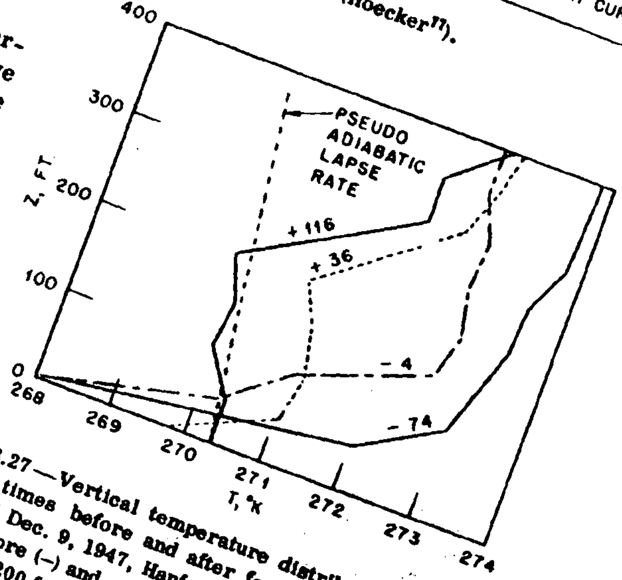

Fig. 3.27—Vertical temperature distribution at selected times before and after fog formation on the night of Dec. 9, 1947, Hanford, Wash. Time in minutes before (−) and after (+) fog is presumed to have reached 200 ft is indicated by numbers on soundings (Fleagle, Parrott, and Barad[41]).

16.4 *Terrain Contours.* Concave topography (valleys) tend to increase the daily and annual temperature ranges because the minimum temperatures are lower. Cold air tends to drain; thus inversion intensities are increased (Fig. 3.28). The effect can be very pronounced even though the valley is not deep and the slope of its sides is gentle.

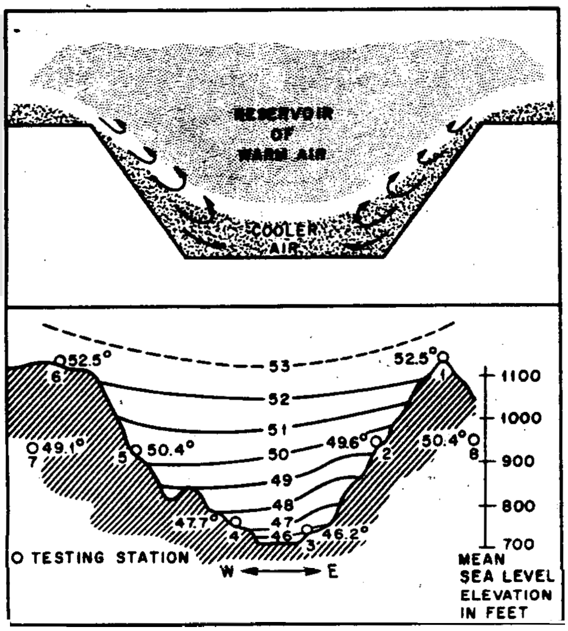

Fig. 3.28—Cold air drains to lower elevations, producing colder temperatures on the valley floor and intensifying temperature inversion conditions. An actual temperature distribution resulting from drainage is shown (Hoecker[77]).

Convex topography (crests of hills or mountains) tends to decrease the daily and annual temperature ranges since cold air drains away. Slope stations are the least exposed to temperature extremes, but southern slopes receive much more and northern slopes receive much less radiation than nearby stations on a level surface. Consequently, the temperature profile on one side of a high hill may be greatly different from that on the other.

16.5 *Altitude*. The greatest diurnal effects are likely to be observed on level plains and large plateaus which are high above sea level. The drier less dense air favors strong surface heating during the day and maximum radiation at night.

16.6 *Advection*. Marked changes in air temperature, humidity, and turbidity may result from the large scale horizontal transport of warm or cold air masses. If a warm air mass moves over a cool surface, the air will become more stable, and, conversely, if a cool volume moves over a warm surface, it will become more unstable. When air moves over a warmer surface, the heating effects are promptly carried to considerable heights. However, air brought over a colder surface is modified but little except in the lowest layers, but there the cooling effect may result in a strong inversion.

16.7 *Water Surfaces*. The surface temperature of a large body of water changes very slowly. Diurnal effects are small. The temperature profile over such a surface is for the most part due to advection. Fog is sometimes the visible effect of a water surface on the air above it. A classic example is the fog of the Grand Banks which results when warm moist air passes over the cold currents. Steam fog, on the other hand, forms when cold relatively dry air passes over warm water. Weather forecasters around the Great Lakes predict snow showers, resulting from instability, when otherwise stable arctic air masses cross the unfrozen lakes.

16.8 *Precipitation*. A precipitation condition which may result in high concentrations at the ground is important when radioactive materials are involved. Here we consider very briefly the kinds of precipitation and the stability conditions under which precipitation occurs. (For further information see Chap. 7 on wash-out and deposition of radioactive debris.)

In practically all instances precipitation is the result of air being lifted. Lifting may take place when air is forced up over a mountain or over a wedge of cooler more dense air or when it rises through convective processes. When a stable air mass moves up a slope, the vertical component of velocity is likely to be determined by the angle of the slope; on the other hand, when there are convective currents, vertical velocities can be comparatively large. Since precipitation falls when the cloud particles become so large that they cannot be supported by the upward-directed currents, drop sizes in a shower are usually larger than those in a steady rain. Table 3.1 shows the variation in drop sizes from fog, a stable condition, to a cloudburst, perhaps the most unstable.

Rates of rainfall are also related to atmospheric stability, though not in a simple way.

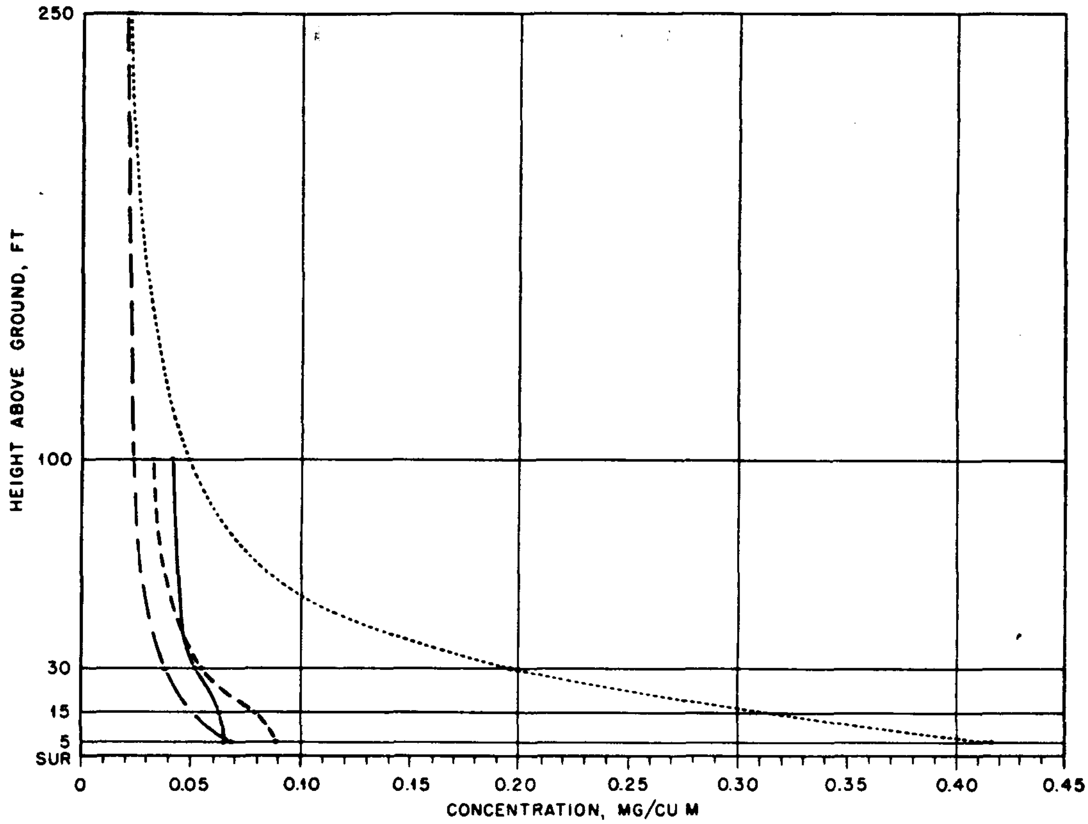

Fig. 3.29—Tower measurements of dust concentration, test period August 4 to August 28, 1953. — —, lapse and inversion. ——, inversion, light winds. - - -, lapse, light winds. ····, lapse, strong winds.

When estimating the effects of precipitation on ground concentrations, the type of precipitation, rate of fall, and the lapse rate associated with such precipitation should be taken into account. The effect of the fine winter rain of Seattle is quite different from that of a Miami thundershower. Furthermore a sudden shower calculated to bring dangerous amounts of airborne material to the ground is not likely to occur when diffusion conditions are poor.

Table 3.1—Variation in Drop Sizes*

| Popular name | Diameter, mm |
|---|---|
| Dry fog | 0.01 |
| Mist | 0.1 |
| Drizzle | 0.2 |
| Light rain | 0.45 |
| Moderate | 1.0 |
| Heavy rain | 1.5 |
| Excessive rain | 2.1 |
| Cloudburst | 3.0 |

* Data taken from Humphreys.[84]

16.9 *Dust.* Some atomic facilities are unusually sensitive to atmospheric dust, e.g., air-cooled reactors. Dust can harm a reactor in various ways, but perhaps the most important aspect is that in passing through a reactor it can become radioactive and radioactive airborne particles may result. It is customary to include air cleaning devices, such as filters and precipitrons, in a design to clean the air before it enters a reactor. Where the air is particularly dusty, the expense of operating air cleaning equipment increases. Some observations of dustiness are available from Weather Bureau offices in instances when dust restricts visibility; however, dustiness must often be inferred from state of ground and wind data.

Where quantitative information on dustiness is required, special observations must be taken at the site. Average dust concentrations run from 0.05 to 0.5 mg/m$^3$ in a rural or suburban district to 0.2 to 0.5 mg/m$^3$ for industrial districts.[2] Amounts of dustiness decrease significantly with elevation above surface. The results of a series of measurements using a 250-ft tower are shown in Fig. 3.29.

Troublesome dustiness is often not entirely a meteorological problem but results when the ground surface is broken up by activity, such as site construction. Dustiness can be, and is, controlled by the planting of shrubs and grass and by surfacing roads, parking lots, etc.

Although the preceding material has discussed the various meteorological parameters separately, and mostly from the standpoint of nomenclature, these variables are inextricably interrelated and often complex. The interested reader is referred to the Bibliography for additional information. This list, although not complete, should serve as a useful guide.

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# 4

# An Outline of Atmospheric Diffusion Theories

Qualitatively speaking, the notion of diffusion† in the atmosphere is not a particularly difficult one. Photographs in Chap. 5 on stack effluents illustrate strikingly the spreading of smoke plumes; and, in general, their characteristic behavior is not surprising, agreeing as it does with our intuitive idea of what ought to take place. In a puff or plume, smoke is relatively concentrated near the central portion; the concentration quite evidently decreases toward the edges and diminishes with time or with distance from the source. Reference to the smoke pictures, furthermore, verifies that the windiness and degree of thermal stability of the lower layers of air markedly affect this process of diffusion; and once again this is seen to occur in a way that is qualitatively very reasonable, high winds and unstable thermal stratification favoring rapid diffusion. The problem is to express these facts quantitatively in a theory so that predictions can be made.

An outline of the significant practical results of the various meteorological diffusion theories will be attempted in this chapter. Since there is no general agreement on a best theory and since several approaches are currently available, the comparative advantages and shortcomings of each will be discussed. No exhaustive treatment is, however, possible here. Rather, an attempt is made to collect and present concisely, and in a logical way, the results that appear to be germane to those problems of greatest interest to the atomic energy industry.

The original objective, that of a brief presentation, has been abandoned. Even so it has not been possible to do justice to all phases of the diffusion problem, with its multiplicity of approaches and many ramifications. In particular, emphasis has been placed on the presentation of final results, with references serving instead of proofs; mathematical details can, of course, be found in the original papers. Fortunately several excellent general discussions of the atmospheric diffusion problem are available which provide rather complete coverage of just those areas that have had to be slighted in the present report. Treatments emphasizing mathematical formulations and derivations have been given by Calder[18] and Frenkiel,[52] and Sutton's recent text[142] contains much valuable material along this line. The discussions of Hewson,[74] Davidson,[32] and Holland[81] emphasize the practical applications of the various theoretical results, providing useful guidance for the field worker.

## 1. THEORIES OF ATMOSPHERIC DIFFUSION

1.1 *Historical Background: Fickian and Non-Fickian Diffusion.* Historically, the earliest meteorological theory of diffusion was presented independently by Taylor[144] and Schmidt,[128] who derived the following differential equation of the problem:

$$\frac{d\chi}{dt} = \frac{\partial}{\partial x}\left(K_x \frac{\partial \chi}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial \chi}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial \chi}{\partial z}\right) \quad (4.1)$$

where $\chi$ is the concentration of some quantity expressed, for example, in grams per cubic centimeter. $K_x$, $K_y$, and $K_z$ are coefficients of diffusion in the x-, y-, and z-directions, called "austauch-koeffizienten" or "exchange coefficients," by Schmidt. This austauch theory of diffusion is rooted in still earlier ideas, based

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†The distinction between diffusion, as of fluid (air) parcels, and dispersion, as of particulate matter suspended in the atmosphere, such as smoke clouds, is sometimes made, but it will not be made here.

on Fourier's treatment of the conduction of heat, about which there is extensive literature. Fourier's theory of conduction was first applied to the case of diffusion by the physiologist Fick. Thus, by analogy with Fourier's law of heat conduction, one may state Fick's law of molecular diffusion, *diffusion of material is in the direction of decreasing concentration and is proportional to the concentration gradient*, and also Fick's equation,

$$\nabla^2\chi = \frac{1}{d}\frac{\partial\chi}{\partial t} \tag{4.2}$$

where the constant of proportionality, d, is the molecular diffusivity. Since Eq. 4.1 is a generalization of Eq. 4.2, Richardson[123] refers to Eq. 4.1 as an equation of Fick's type; both the above laws are commonly referred to as Fickian. The K's in Eq. 4.1 are called "eddy diffusivities."

Under this analogy with conduction theory, the problem of atmospheric diffusion becomes that of solving Eq. 4.1 with appropriate boundary conditions. Realistic meteorological conditions result in mathematical problems of considerable difficulty, some of which are not yet solved. Several meteorologists, principally Roberts, Calder, and Deacon, have been active in developing this so-to-speak generalized Fickian theory, which is often termed the "K theory of atmospheric diffusion."

The Fickian analogy has been very fruitful in problems of atmospheric diffusion, as we will see; but it appears to contain a fundamental shortcoming, which was (characteristically) first pointed out by L. F. Richardson in 1926. Richardson noticed that, if the eddy diffusivity, K, is evaluated by fitting observations to Eq. 4.1, the resulting K values vary from about 0.2 cm$^2$/sec for molecular diffusion to $10^{11}$ cm$^2$/sec for diffusion due to large-scale cyclonic storms in the atmosphere. Thus the ability of the atmosphere to diffuse properties appears to depend fundamentally on the controlling scale of meteorological events, a contingency with which Fickian theory is not directly prepared to cope since the dispersion of a concentrated cloud of particles may be successively affected by molecular agitation while the cloud is quite small, small-scale turbulent wind gusts when the cloud grows to a few meters in size, and so on until its ultimate dispersion throughout the whole of the atmosphere by the large-scale cyclonic and anticyclonic currents. This circumstance led Sutton[135–137] and, more recently, Frenkiel[50–52] to develop their "statistical" theories of turbulent diffusion, following Taylor's statistical theory of turbulence.[145]

In the paragraphs which follow, the salient features of both the K theory and the statistical theories of diffusion will be summarized. It should be clearly understood that these do not represent fundamentally conflicting viewpoints but rather are the logical results of emphasizing different aspects of the diffusion problem. Nevertheless it is an interesting fact that certain differences between the two approaches have not yet been entirely resolved, as discussions at a recent international turbulence symposium clearly verify.[73]

Fortunately each theory has its place in current meteorological practice. It may be said, arbitrarily but with some justification, that essentially in the atmosphere one faces diffusion problems on three characteristic scales. One scale, extending in length up to perhaps a kilometer, is exemplified by certain aspects of the chemical warfare problem, where precise information on the concentrations close to sources at or near the ground is required. The second, which reaches out to perhaps tens of kilometers, is that of air pollution and stack and reactor hazard meteorology. A third, involving great horizontal distances up to continental limits, becomes important in treating the diffusion of an atomic bomb cloud. Now for certain source types and for relatively small distances, Calder's extension of the K theory will be seen to be most appropriate. For the very large scale problem, an adaptation of Roberts' theory has been used (see Chap. 6, Sec. 4). Sutton's statistical theory, on the other hand, has been the one most generally applied to the intermediate scale, that of diffusion on a length scale of from hundreds of meters to kilometers, as in stack meteorology.

1.2 *The K Theory*. The term "K theory" actually describes a wider class of atmospheric problems than diffusion, including evaporation and, in fact, the atmospheric transport problem in general. It is a well developed theory of atmospheric turbulence, of which a concise account has been given by Sutton.[134] The present discussion is restricted to applications of K theory to atmospheric diffusion, the earliest example of which is to be found in the work of Roberts.[125]

From the standpoint of turbulent diffusion, the total instantaneous meteorological wind vector is thought of as being divided into two parts: a mean part, which does not contribute to the diffusion phenomenon, and a turbulent part, which does. Thus one writes

$$\mathbf{V} = \overline{\mathbf{V}} + \mathbf{V}' \tag{4.3}$$

where $\overline{\mathbf{V}}$ is averaged in time. It follows that $\overline{\mathbf{V}'} \equiv 0$. Also, the mean wind, $\overline{\mathbf{V}}$, may be considered to be horizontal for the purpose of diffusion study.

Roberts gave the following equation for the concentration distribution due to the instantaneous release of a quantity Q of material released at a time t = 0 from a point.

$$\chi(x,y,z,t) = \frac{Q}{(4\pi t)^{3/2}\,(K_x K_y K_z)^{1/2}} \times \exp\left[-\frac{1}{4t}\left(\frac{x^2}{K_x} + \frac{y^2}{K_y} + \frac{z^2}{K_z}\right)\right] \tag{4.4}$$

The z-direction is taken to be positive upward, and the x- and y-directions are conveniently chosen to be along and across the mean wind. Thus in this system $\overline{\mathbf{V}} = \overline{u}$, and $\overline{v} = \overline{w} = 0$. For simplicity, the coordinate axes are affixed to the center of the cloud in the case of the instantaneous point source. Equation 4.4 is often written in terms of $\overline{x}$, the distance downwind the cloud travels during the time interval 0 to t, where $x = \overline{x} - \overline{u}t$. Furthermore, if the origin of the cloud is at point $(\xi,\eta,\zeta)$ instead of (0,0,0), one has $(x - \xi)^2$ in place of $x^2$, and so on.

Equation 4.4 expresses the diffusion of an instantaneous point cloud in an infinite homogeneous atmosphere. The central concentration in the cloud decreases as the negative $^3/_2$ power of time, and the concentration through the cloud follows a Gaussian distribution. For nonisotropic diffusion, characterized by

$$K_x \neq K_y \neq K_z$$

the cloud will have ellipsoidal symmetry. For isotropic diffusion, characterized by equal values of the eddy diffusivity in each direction, i.e.,

$$K = K_x = K_y = K_z$$

the symmetry is spherical, and Eq. 4.4 becomes

$$\chi(x,y,z,t) = \frac{Q}{(4\pi K t)^{3/2}} \exp\left(-\frac{r^2}{4Kt}\right) \tag{4.5}$$

where $r^2 = x^2 + y^2 + z^2$

Both equations satisfy the differential equation of Fickian diffusion (Eq. 4.1) and the boundary conditions

$$\begin{aligned} &\chi \to 0 \text{ as } t \to 0,\ r > 0 \\ &\chi \to 0 \text{ as } t \to \infty \end{aligned} \tag{4.6}$$

as well as the continuity condition

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \chi\, dx\, dy\, dz = Q \tag{4.7}$$

These results do not represent a working theory of diffusion until the K values are determined. Also, solutions corresponding to other source types likely to occur in practice, such as lines, areas, volumes, and continuous sources, need to be built up. These considerations will be temporarily deferred in favor of some further development of the basic theory.

Equations 4.4 and 4.5, considered as formal consequences of Eq. 4.1 and the boundary conditions, cannot of course represent diffusion in a medium which is observed to be as complex as the lower layers of the atmosphere. In truth, although these solutions have been of great help in opening up the atmospheric diffusion problem, they contain little that is different from the molecular diffusion model. The real atmosphere, by contrast to the infinite homogeneous one that was assumed, has certain important characteristics bearing critically on diffusion.

In the first place, the layers of air near the ground (to a height of several thousand feet) exhibit a pronounced shear of the mean wind, both in direction and magnitude. The wind must increase from zero at some level at or very near the ground to a value, at several thousand feet in elevation, characteristic of the free atmosphere, which is relatively uninfluenced by the presence of the ground surface. Moreover the presence of the ground itself, with its varying geometrical properties, must influence diffusion, as must the pronounced variation of the vertical thermal structure of the air near the ground, from neutral or unstable values during the daytime to very stable values on clear calm nights. Consideration of these problems has led to the later developments of the K theory.

1.3 *Effect of Vertical Wind Shear.* It was suggested by Schmidt that the increase of the mean wind velocity, $\bar{u}$, with height near the ground might be approximated by a power law

$$\bar{u} = \bar{u}_1 \left(\frac{z}{z_1}\right)^m \qquad m \geq 0 \tag{4.8}$$

where the subscript 1 refers to some reference level. For the layer in which such a law applies, it was shown by Ertel[44] that the eddy diffusivity must also vary with height

$$K_{(z)} = K_1 \left(\frac{z}{z_1}\right)^{1-m} \tag{4.9}$$

Equations 4.8 and 4.9 are known as the conjugate power laws. The depth of the layer through which they will apply can be of the order of tens of meters at most (about 30 meters, according to Ertel); this is the layer through which the vertical variation of the stress is negligible.

For the problem of two-dimensional steady-state diffusion, i.e., for Eq. 4.1 with

$$\frac{\partial \chi}{\partial t} \equiv 0 \tag{4.10}$$

and

$$\frac{\partial}{\partial y}\left(K_y \frac{\partial \chi}{\partial y}\right) \equiv 0 \tag{4.11}$$

and neglecting

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial \chi}{\partial x}\right)$$

by comparison with

$$\bar{u} \frac{\partial \chi}{\partial x}$$

the diffusion equation becomes

$$\bar{u} \frac{\partial \chi}{\partial x} = \frac{\partial}{\partial z}\left(K_z \frac{\partial \chi}{\partial z}\right) \tag{4.12}$$

This equation may be used to compute diffusion from a continuous infinite line source oriented cross-wind along $x = z = 0$. A solution to Eq. 4.1 subject to the boundary conditions

$$\chi \rightarrow 0 \text{ as } x \rightarrow \infty \tag{4.13}$$

$$K_z \frac{\partial \chi}{\partial z} \rightarrow 0 \text{ as } z \rightarrow 0 \text{ (zero flux at ground)}$$

$$\int_0^\infty \bar{u}\chi \, dz = Q \qquad \text{(continuity condition)}$$

$$\chi = \infty \text{ at } x = z = 0 \qquad \text{(condition for a source)}$$

was given by Roberts for the case where Eqs. 4.8 and 4.9 apply. His solution, as stated by Sutton,[138] is

$$\chi_{(x,z)} = \frac{Q}{\bar{u}_1 \Gamma(S)} \left[\frac{\bar{u}_1}{(m-n+2)^2 K_1 x}\right]^S \times \exp\left[-\frac{\bar{u}_1 z^{(m-n+2)}}{(m-n+2)^2 K_1 x}\right] \tag{4.14}$$

where $S = (m+1)/(m-n+2)$, $n = 1 - m$, and $\Gamma$ represents the gamma function. Equation 4.14 takes into account the effects of wind shear near the ground and of the presence of the ground as a barrier to the flux, but it considers neither varying conditions of ground roughness nor varying thermal stability. Thus it could be expected to apply only over "aerodynamically smooth" terrain and at times of neutral thermal stratification (adiabatic lapse rate of temperature).

1.4 *Effect of Varying Surface Roughness.* It is perhaps not so important to distinguish between flow over aerodynamically "smooth" and "rough" surfaces in the atmosphere as it is in airfoil theory. Rough flow is in principle characterized by the idea that the roughness elements protrude through the laminar boundary layer, a few millimeters thick, next to the surface. It is doubtful whether a truly smooth type of flow ever exists in this sense in the atmosphere; and the aerodynamic theory of rough surface flow can be directly applied. This theory gives the well-known logarithmic velocity profile law, that

$$\bar{u} = \frac{w_*}{k} \ln \frac{z + z_0}{z_0} \tag{4.15}$$

where $w_* \equiv \sqrt{\tau_0/\rho}$, $\rho$ is air density (constant), $\tau_0$ is the (constant) eddy stress defined by Prandtl's formula

$$\tau_0 = \rho l^2 \frac{d\bar{u}}{dz} \cdot \left|\frac{d\bar{u}}{dz}\right| \qquad (4.16)$$

$l$ is Prandtl's mixing length ("mischungsweg"), k is von Karman's universal constant, equal (see Montgomery[73,112]) to 0.43, and $z_0$, the "roughness length," is a geometrical parameter proportional to the height of the roughness elements of the ground surface. Figure 4.1, after Deacon,[38] gives typical $z_0$ values for various natural surfaces.

Equation 4.15 has the advantage over Eq. 4.8 that it contains parameters with clear physical meanings which can be evaluated independently; but it has not yet been possible to incorporate Eq. 4.15 directly into the solution of Eq. 4.12. Instead, Calder[19] used the approximation

$$\bar{u} = w_* q \left(\frac{w_* z}{\nu}\right)^{\alpha} \qquad \text{(smooth flow)} \qquad (4.17)$$

$$\bar{u} = w_* q' \left(\frac{z}{z_0}\right)^{\alpha} \qquad \text{(rough flow)} \qquad (4.17a)$$

choosing q, q′, and $\alpha$ so that Eq. 4.17 agrees most closely with Eq. 4.15. From this work, it follows that

$$\tau_0 = \epsilon\, \rho\, \bar{u}^{2B} \left(\frac{\delta}{z}\right)^{2\alpha B} \qquad (4.18)$$

and

$$K_z(z) = \left(\frac{\epsilon}{\alpha}\right) \delta^{2\alpha B}\, \bar{u}_1^{\,2B-1}\, z_1^{\,\alpha(1-2B)}\, z^{1-\alpha} \qquad (4.19)$$

The new parameters have the values:

$$B = \frac{1}{1+\alpha}$$

$$\delta = \nu \qquad \text{(smooth flow)} \qquad (4.20)$$

$$\epsilon = \left(\frac{1}{q}\right)^{2/(1+\alpha)}$$

$$B = 1$$

$$\delta = z_0 \qquad \text{(rough flow)} \qquad (4.21)$$

$$\epsilon = \frac{1}{(q')^2}$$

where $\nu$ is the kinematic molecular viscosity of air and q and q′ are determined by reference to the velocity profiles of aerodynamic theory.

Calder's solution of Eq. 4.12, subject to the laws expressed by Eqs. 4.18 and 4.19, and the boundary conditions in Eq. 4.17a, is

$$\begin{aligned}\chi = &\Big\{Q \exp\Big[-\bar{u}_1^{\,2(1-B)}\, z^{2\alpha+1/(\epsilon/\alpha)}\, \delta^{2\alpha B}(2\alpha+1)^2 \\ &\times z_1^{\,2\alpha(1-B)}\, x\Big]\Big\}\Big\{(2\alpha+1)^{½(\alpha+1)} \\ &\times \Big[(\epsilon/\alpha)\, \delta^{2\alpha B}\Big]^{(\alpha+1)/(2\alpha+1)} \\ &\times \Gamma\Big[(\alpha+1)/(2\alpha+1)\Big]\, u_1^{\kappa}\, z^{-\alpha\kappa} \\ &\times x^{(\alpha+1)/(2\alpha+1)}\Big\}^{-1} \end{aligned} \qquad (4.22)$$

where

$$\kappa = \frac{2\alpha B + 2B - 1}{2\alpha + 1} \qquad (4.23)$$

The effects of both wind shear and surface roughness appear in this result.

1.5 *Effect of Thermal Stability.* Extension of Calder's theory to nonadiabatic thermal stratification is based on Deacon's "generalized velocity profile" formula

$$\bar{u} = \frac{w_*}{k(1-\beta)} \left[\left(\frac{z}{z_0}\right)^{1-\beta} - 1\right] \qquad (4.24)$$

which reduces to a logarithmic law for $\beta \to 1$ and expresses the effect of varying thermal stratification by varying values of $\beta$. Thus

| | |
|---|---|
| $\beta > 1$ | for thermal instability |
| $\beta = 1$ | for neutral conditions (adiabatic lapse-rate) |
| $\beta < 1$ | for thermal stability |

Figure 4.2 indicates the variation of $\beta$ with stability, according to Deacon. As a result of Eq. 4.24 it follows that

$$K_z(z) = k w_* z_0 \left(\frac{z}{z_0}\right)^{\beta} \qquad (4.25)$$

Calder solved the system of Eqs. 4.12, 4.13, 4.24 and 4.25, expressing the effects of shear, surface roughness, and stability, finding (reference 32, p. 174) that

$$\begin{aligned}\chi = &\left\{Q\, q^{(\beta-1)/n} \exp\left[\frac{-q z^n z_0^{(\beta-\alpha-1)}}{k n^2 x}\right]\right\} \\ &\times \Big[w_*\, k^{(1+\alpha)/n}\, n^{(\beta+\alpha)/n}\, \Gamma \frac{1+\alpha}{n} \\ &\times x^{(1+\alpha)/n}\, z_0^{(1-\beta)/n}\Big]^{-1}\end{aligned} \qquad (4.26)$$

where $n = 2 + \alpha - \beta$.

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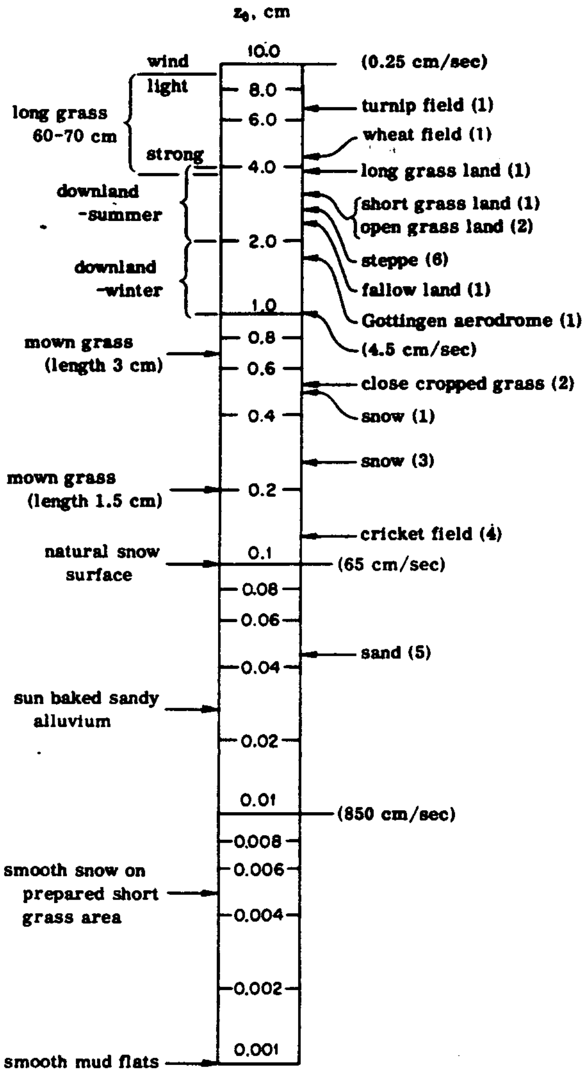


Fig. 4.1—The roughness parameter of various surfaces (Deacon). (1) Paeschke, 1937. (2) Rossby and Montgomery, 1935. (3) Sverdrup, 1936. (4) Best, 1935. (5) Bagnold, 1941. (6) Laikhtman, 1944.

Essentially, the K theory rests with this result. Attempts to extend it to the more general case of the point source have not been successful. The diffusion equation governing the point source is

$$\bar{u}\,\frac{\partial \chi}{\partial x} = \frac{\partial}{\partial y}\left(K_y\,\frac{\partial \chi}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\,\frac{\partial \chi}{\partial z}\right) \qquad (4.27)$$

For a point source located at the ground, Calder (according to Davidson,[32] see also Calder[20]) derived a formula which satisfies the boundary conditions and which reduces to the line source formula when integrated with respect to y, although it does not directly satisfy Eq. 4.27.

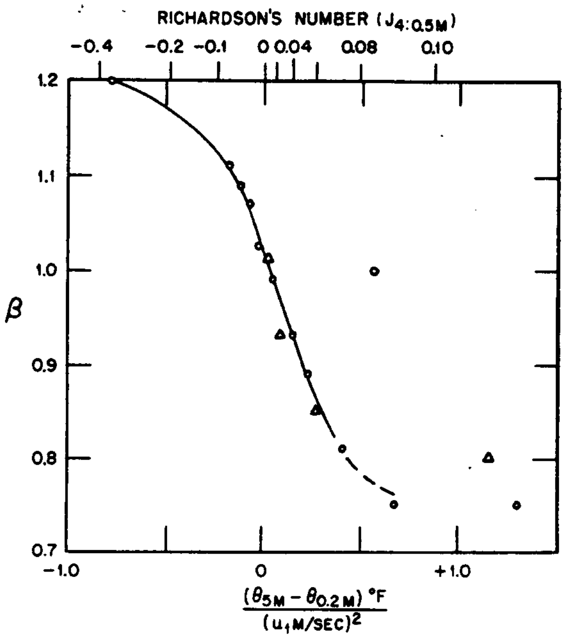


Fig. 4.2—The variation of β with stability (Deacon). O, short grass surface; $z_0$ = 0.27 cm. Δ, from Sverdrup's observations over snow; $z_0$ = 0.25 cm.

Davies[36] also has discussed the three-dimensional problem and has given some results for area sources, applicable mainly to evaporation. He also has treated[38] the equation

$$0 = \frac{\partial}{\partial y}\left(K_y\,\frac{\partial \chi}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\,\frac{\partial \chi}{\partial z}\right) \qquad (4.28)$$

a special case of Eq. 4.27 valid for large x, and obtained the solution for an infinite line source parallel to the mean wind, i.e., in the x-direction. Knighting[39] gives a useful general mathematical discussion of the diffusion equation in the form

$$\frac{\partial}{\partial z}\left(a z^{1-m}\,\frac{\partial \chi}{\partial z}\right) = \frac{\partial \chi}{\partial t} + \bar{u}\,\frac{\partial \chi}{\partial x} \qquad (4.29)$$

The mathematical achievements of the K theory are certainly impressive, but its practical utility is clearly limited. The various velocity profile expressions are not valid to very great heights, and thus the diffusion formulae can be expected to hold over very modest horizontal distances only. Experience indicates that the lateral spread of a diffusing cloud is rarely more than about ten times its vertical extent. Consequently, results of the K theory utilizing a variable velocity profile should not be expected to apply to distances greater than several hundred meters. Furthermore, these same results are limited to the case of continuous cross-wind line sources located at the ground level. Within these limits good experimental verification[142] is claimed for Eqs. 4.22 and 4.26.

1.6 *Statistical Theories.* In his basic and very helpful work, Taylor[143] considered the time history of representative parcels of air in a region where the statistical properties of the turbulence are homogeneous and isotropic and proved the fundamental theorem, *the rate at which diffusion takes place depends on the variance,* $\overline{x^2} = \overline{y^2} = \overline{z^2}$, *of the wind velocity fluctuation distributions according to the formula*

$$\overline{y^2} = 2\overline{(u')^2} \int_0^t d\tau \int_0^\tau R_\xi(s)\, ds \tag{4.30}$$

The components of the fluctuations in the x-, y-, and z-directions are u′, v′, and w′, and Eq. 4.3 again applies; $\xi$ denotes time interval, t is time and must be chosen sufficiently long to give Eq. 4.30 a meaning; $R_\xi$, the Lagrangian autocorrelation coefficient, is defined by

$$R_\xi = \frac{\overline{u'(t)\, u'(t+\xi)}}{\overline{(u')^2}} \tag{4.31}$$

Assuming that the mean concentrations within a diffusion cloud are distributed according to a three-dimensional Gaussian law (a proof of this was recently given by Ogura[118]), Frenkiel[49] gave the following equation for the concentration distribution from an instantaneous point source in an infinite region:

$$\chi_{(x,y,z,t)} = \frac{Q}{(2\pi\overline{y^2})^{3/2}} \exp\left(-\frac{r^2}{2\overline{y^2}}\right) \tag{4.32}$$

As in Eqs. 4.4 and 4.5, the coordinate axes are imagined to be affixed to the center of the cloud, which is translated with the speed $\bar{u}$ of the mean wind.

In the nonisotropic case, i.e., where

$$\overline{(u')^2} \neq \overline{(v')^2} \neq \overline{(w')^2}$$

$$\overline{x^2} \neq \overline{y^2} \neq \overline{z^2}$$

$$R_{\xi_x} \neq R_{\xi_y} \neq R_{\xi_z}$$

one has, corresponding to Eq. 4.4,

$$\chi = \frac{Q}{(2\pi)^{3/2}\,(\overline{x^2}\;\overline{y^2}\;\overline{z^2})^{1/2}} \times \exp\left[-\frac{1}{2}\left(\frac{x^2}{\overline{x^2}} + \frac{y^2}{\overline{y^2}} + \frac{z^2}{\overline{z^2}}\right)\right] \tag{4.32a}$$

Notice that Eqs. 4.32 and 4.5 are equivalent if

$$\overline{y^2} = 2Kt \tag{4.33}$$

Frenkiel[50] points out that, as a result, K is in effect an apparent turbulent viscosity (or, in our terms, eddy diffusivity), whose value is different for each value of time t. As Frenkiel indicates, Eq. 4.32 reduces to Eq. 4.5 when the time of diffusion t is very large. In other words, Fick's law can apply only at great distances from the source, i.e., after a large diffusion time. On the other hand, the same modifications must be considered in connection with the application of the statistical theory to atmospheric diffusion near the ground as were found to be so important in the extension of the K theory, namely, the effects of ground surface condition, wind shear, and thermal stability. Furthermore, information on $\overline{y^2}$, or else on $R_\xi$, is required, and very few observations of these have been reported (cf. Gifford[59] for an attempt along this line).

Reasoning dimensionally, Sutton, in 1932, proposed the following expression for $R_\xi$:

$$R_\xi = \left[\frac{\nu}{\nu + \overline{(u')^2}\xi}\right]^n \tag{4.34}$$

where $\nu$ is the kinematic viscosity of air and n is a number varying between zero and 1, usually defined by reference to the following velocity profile law:

$$\bar{u} = \bar{u}_1\left(\frac{z}{z_1}\right)^{n/(2-n)} \tag{4.35}$$

For this choice of $R_\xi$, Eqs. 4.30 and 4.32 yield the instantaneous point source equation

$$\chi(x,y,z,t) = \frac{Q}{\pi^{3/2} C^3 (\bar{u}t)^{3(2-n)/2}} \times \exp\left[-\frac{r^2}{C^2(\bar{u}t)^{2-n}}\right] \tag{4.36}$$

Sutton refers to C as a "virtual diffusion coefficient" and obtains its value by substituting Eq. 4.34 into Eq. 4.30, integrating, and ignoring terms of the order of $\nu$ by comparison with $\overline{(u')^2}t$. If $C^2$ is defined by

$$C^2 = \frac{4\nu^n}{(1-n)(2-n)\,\bar{u}^n}\left[\frac{\overline{(u')^2}}{\bar{u}^2}\right]^{1-n} \tag{4.37}$$

it develops, since for the isotropic case $\overline{x^2} = \overline{y^2}$, that

$$\overline{x^2} = \frac{1}{2}C^2(\bar{u}t)^{2-n} \tag{4.38}$$

For the nonisotropic case, separate values of the autocorrelation are defined using $\overline{(u')^2}$, $\overline{(v')^2}$, and $\overline{(w')^2}$, and the result is that $C \equiv C_x$ and that

$$C_y^2 = \frac{4\nu^n}{(1-n)(2-n)\,(\bar{u})^n}\left[\frac{\overline{(v')^2}}{\bar{u}^2}\right]^{1-n} \tag{4.39}$$

and

$$C_z^2 = \frac{4\nu^n}{(1-n)(2-n)\,(\bar{u})^n}\left[\frac{\overline{(w')^2}}{\bar{u}^2}\right]^{1-n} \tag{4.40}$$

Then Sutton's instantaneous point source equation for the nonisotropic case is

$$\chi(x,y,z,t) = \frac{Q}{\pi^{3/2} C_x C_y C_z (\bar{u}t)^{3(2-n)/2}} \times \exp\left[-(\bar{u}t)^{n-2}\left(\frac{x^2}{C_x^2} + \frac{y^2}{C_y^2} + \frac{z^2}{C_z^2}\right)\right] \tag{4.41}$$

Sutton considered that the ground would act as a perfect reflector of diffusing particles and accounted for it in his theory by using the "method of images"; the result of this is to double the right hand side of Eqs. 4.36 and 4.41 for a source located at the ground. The effect of ground surface roughness is also accounted for by replacing $\nu$ by a quantity Sutton[142] calls the macroviscosity, N, where

$$N \equiv w_* z_0 \tag{4.42}$$

The effect of thermal stability is presumably introduced into Sutton's theory through the definition of the number n in Eq. 4.35. He describes n as follows: "In very turbulent air n approaches zero and in conditions of low turbulence n tends toward its upper limit of unity. In ... conditions, corresponding to a small gradient of temperature in the vertical, the value of n is approximately $^1\!/_4$."

Sutton's formulation is thus able to satisfy, in principle, most of the desiderata of a theory of low-level atmospheric diffusion. It has been objected that Eq. 4.35 defining n is inconsistent with Eq. 4.36, for which $\bar{u}$ is assumed to be constant, but Sutton[142] maintains that the error introduced is small. Sutton's formulation has successfully, under certain meteorological conditions, predicted diffusion over distances up to several kilometers. Probably for this reason his theory is widely accepted in practice; and many formulae for special applications have been deduced from those given above.

1.7 *The Non-Fickian Theories of Richardson, Lettau, and Bosanquet.* (a) *Richardson's Distance-Neighbor Theory.* Richardson, as a result of his observation of the tremendous variation of K with scale, to which we have already referred, was led to introduce his "distance-neighbor" theory of turbulence.[123] He illustrates the essential point in the following way:[124] Suppose seven people live on a road at certain intervals, perhaps like these:

A      BC      DE      F      G

How are they fixed for neighbors? Richardson considers the "average number of neighbors per unit length." Take Mr. A, lay off a scale from his house and count how many neighbors he has between 1 and 2 units, between 2 and 3, 3 and 4, and so on. Repeat for Messrs. B, C, etc. Then take for each range of separation L, (of 0 to 1, 1 to 2, etc., units) the average number of neighbors, P. Richardson's "distance-neighbor graph" is then a graph of L vs. P. If the objects under consideration are not people but are diffusing parcels of air, wandering at random, the graph of P vs. L will change with time, ultimately becoming a straight line parallel to the L-axis (neighbors equally common at all distances, i.e., parcels distributed at random). The process has every appearance of the diffusion of the quantity P in L-space. Richardson obtained as the governing differential equation

$$\frac{\partial P}{\partial t} = \frac{\partial}{\partial L}\left(F(L)\,\frac{\partial P}{\partial L}\right) \qquad (4.43)$$

and was able to deduce that

$$F(L) \cong \sigma L^{4/3} \qquad (4.44)$$

thus anticipating a fundamental result of Kolmogoroff's theory of "locally isotropic turbulence" by some 15 years. The diffusion parameter σ, in the range $10\text{ cm} < L < 10^8$ cm varies between 0.1 and 15, a far smaller range than that of K.

Richardson's theory has not lead directly to practical diffusion formulae, but it is mentioned for the deep influence it has had on later investigators, such as Sutton and, more recently, Batchelor[7] and Brier.[15] It was the first attempt to explain the fact that the diffusion phenomenon, rather unexpectedly, appears to depend on the degree of separation of the parcels, i.e., upon scale.

(b) *Lettau's Shearing Advection Theory.* Lettau[73] considers that the difficulty with the Fickian Eq. 4.1 lies in its failure to take into account "shearing advection," i.e., the separation of air parcels owing to the action of the vertical wind shear characteristic of the surface layer.

For adiabatic conditions consideration of the shearing advection term produces the following interesting definition of an apparent eddy-diffusivity, $K_{app}$, which turns out to be related to the ordinary eddy-diffusivity, K, by

$$K_{app} = K + K\,\frac{\partial u}{\partial z}\,\frac{(x - x_0)}{u}$$

$$= k w_* (z + z_0)\left[1 + \frac{(x - x_0)}{(z + z_0)\ln\dfrac{(z + z_0)}{z_0}}\right] \qquad (4.45)$$

where $(x - x_0)$ is the distance from the source. This result evidently explains observations of the spreading of smoke plumes which clearly indicate an increase in K with distance. Lettau's shearing advection theory, unfortunately, leads to a differential equation for which general solutions have not yet been found; but it appears to have illuminated a difficult point of the earlier K theories.

The opinion of Priestley (reference 73, p. 442) is that shearing advection is an additional effect to the increase in diffusivity with scale. If this is true, which seems reasonable, future advances in diffusion theory will have to account for the points raised by both Richardson and Lettau. (See also a recent discussion by Davies.[38]

(c) *Bosanquet and Pearson's Theory for Elevated Sources.* With the exception of Sutton's theory, which is readily adapted to elevated sources (e.g., stacks), the foregoing theories all result in diffusion formulae which apply to sources either at the ground level or else in the free atmosphere well above the surface layers of air. Reasoning statistically, and employing some dimensional arguments, Bosanquet and Pearson[13] derived the following formula for the ground level concentration distribution due to a continuous elevated point source near the ground.

$$\chi = \frac{Q}{(2\pi)^{1/2}\, p q \bar{u} x^2}\,\exp\left(-\frac{h}{px} - \frac{y^2}{2q^2x^2}\right) \qquad (4.46)$$

This was the first formula that applied directly to diffusion from stacks and has consequently been very important in applications; p and q are vertical and lateral diffusion coefficients. Equation 4.46 is nearly identical with Sutton's continuous point source Eq. 4.51 for the special case of n = 0; in particular, the maximum ground concentrations predicted by each formula differ only by a constant factor. Note that the Bosanquet and Pearson formulation does not directly take into account atmospheric stability.

## 2. EXTENSIONS OF THE POINT SOURCE FORMULAE

The various formulae for diffusion from an instantaneous point source, Eqs. 4.4, 4.5, 4.32, 4.32a, and 4.41, represent fundamental solutions from which, by the process of integration with respect to one or more of the coordinate directions and time, other diffusion formulae for more complex sources may be built up, in the same way as is done in heat conduction theory. The sources most often encountered in practical applications are

| Source type | Application |
|---|---|
| Continuous point | Smokestack, vent |
| Continuous line | Array of stacks or vents |
| Instantaneous volume | Explosion |

Another class of useful formulae involves certain geometrical properties of any of these results, namely, the maximum concentration and its location and the plume width or height. Finally, a group of special results and extensions involving corrections for radioactive decay, ground surface deposition, diffusion in very stable atmospheres, and many other important modifications can be deduced; most of these latter have been given in terms of Sutton's theory, which is the most widely used in practical applications.

2.1 *Continuous Point Source Formulae.* The various point source formulae may be integrated with respect to time to give equations for the concentration distribution downwind from continuous point sources. For continuous point sources, Q is the emission rate, expressed for example in grams per second. The atmosphere considered by Roberts and Frenkiel is always infinite; that of Sutton is semiinfinite, i.e., the ground is present. Sutton's results are given for elevated sources at a height h above the ground. Thus in his formulae $\chi$ is the ground concentration at a distance x, downwind, and y, crosswind, from the source at height h. The most important of the continuous point source equations are:

*Roberts:* (a) *Isotropic*

$$\chi_{(x,y,z)} = \frac{Q}{4\pi Kr} \exp\left[-\frac{\bar{u}(y^2 + z^2)}{4Kr}\right] \tag{4.47}$$

(b) *Anisotropic*

$$\chi_{(x,y,z)} = \frac{Q}{4\pi r(K_y K_z)^{1/2}} \times \exp\left[-\frac{\bar{u}}{4r}\left(\frac{y^2}{K_y} + \frac{z^2}{K_z}\right)\right] \tag{4.48}$$

*Frenkiel:*

$$\chi_{(x,y,z)} = \int_0^\infty \frac{Q}{(2\pi\overline{y^2})^{3/2}} \times \exp\left[-\frac{(\bar{x} - \bar{u}t)^2 + y^2 + z^2}{2\overline{y^2}}\right] dt \tag{4.49}$$

*Sutton:* (a) *Isotropic*

$$\chi_{(x,y)} = \frac{2Q}{\pi C^2 \bar{u} x^{2-n}} \exp\left(-\frac{y^2 + h^2}{C^2 x^{2-n}}\right) \tag{4.50}$$

(b) *Anisotropic*

$$\chi_{(x,y)} = \frac{2Q}{\pi C_y C_z \bar{u} x^{2-n}} \times \exp\left[-x^{n-2}\left(\frac{y^2}{C_y^2} + \frac{z^2}{C_z^2}\right)\right] \tag{4.51}$$

2.2 *Continuous Line Source Formulae.* If the continuous point source formulae are integrated with respect to some direction, usually the y-direction (crosswind), equations describing the concentration distribution downwind of a continuous line source result. In practice, line sources may be rows of stacks or of hood vents on laboratory buildings, or smoke screens, and so on. Some formulae which have been given are:

*Roberts: Continuous infinite crosswind line source*

$$\chi_{(x,z)} = \frac{Q}{2(\pi\bar{u}\sqrt{x^2 + z^2})^{1/2}} \times \exp\left(-\frac{\bar{u}z^2}{4K\sqrt{x^2 + z^2}}\right) \tag{4.52}$$

*Sutton: Continuous infinite elevated crosswind line source*, (a) *Isotropic*

$$\chi_{(x)} = \frac{2Q}{\pi^{1/2} C \bar{u} x^{(2-n)/2}} \exp\left(-\frac{h^2}{C^2 x^{2-n}}\right) \tag{4.53}$$

(b) *Anisotropic*

$$\chi_{(x)} = \frac{2Q}{\pi^{1/2} C_z \bar{u} x^{(2-n)/2}} \exp\left(-\frac{h^2}{C_z^2 x^{2-n}}\right) \tag{4.54}$$

Units of Q = g/sec/meter, etc.

2.3 *Instantaneous Volume Source Formulae.* The approximation of the point source is a good estimation of the concentration distribution downwind of a burst or explosion provided the distance from the scene of the explosion is great enough. The effect of the size of the source on close-in concentrations may be large, however, and this has been studied by several writers by integrating the various instantaneous point source equations over infinite and finite initial volumes.

Kellogg[88] integrated Roberts' instantaneous point source formula, Eq. 4.5, to produce the following equation for the concentration distribution due to an instantaneous spherical volume source having a uniform distribution of material, obtaining

$$\chi_{(r,t)} = \frac{Q_{av}\,(4Kt)^{1/2}}{2r\pi}\Bigg(e^{-(R+r)^2/4Kt} - e^{-(R-r)^2/4Kt} + \frac{\pi^{1/2}\,r}{(4Kt)^{1/2}}\left\{\operatorname{erf}\left[\frac{(r+R)}{(4Kt)^{1/2}}\right] + \operatorname{erf}\left[\frac{(r-R)}{(4Kt)^{1/2}}\right]\right\}\Bigg) \qquad (4.55)$$

where R is the radius of the volume source, and where Q is the source strength per unit volume.

Similarly Frenkiel[51] integrated Eq. 4.32 and obtained a fully equivalent solution for the statistical theory

$$\chi_{(r,t)} = \frac{Q_{av}}{2}\left\{\operatorname{erf}\left[\frac{R-r}{(2\overline{y^2})^{1/2}}\right] + \operatorname{erf}\left[\frac{R+r}{(2\overline{y^2})^{1/2}}\right]\right\} - Q_{av}\left(\frac{\overline{y^2}}{2\pi}\right)^{1/2}\frac{1}{r}\left\{\exp\left[-\frac{(R-r)^2}{2\overline{y^2}}\right] - \exp\left[-\frac{(R+r)^2}{2\overline{y^2}}\right]\right\} \qquad (4.56)$$

Holland[81] suggested the idea of a "virtual point source" in connection with the volume source problem. This is an imaginary point source located upwind of the real source just far enough to produce the required volume source at point (0,0,0) and at t = 0. The initial distribution of material in this volume source formula is of course Gaussian. Defining the distance upwind to the virtual source, $x_0$, by

$$x_0 = \left(\frac{2Q/\chi(0)}{\pi^{3/2}C^3}\right)^{2/3(2-n)} \qquad (4.57)$$

where $\chi(0)$ is the central ground concentration at instant t = 0, Holland obtains the formula

$$\chi = \frac{2Q}{\pi^{3/2}C^3(x_0 + \bar{u}t)^{3(2-n)/2}} \times \exp\left[-\frac{h^2}{C^2(x_0 + \bar{u}t)^{2-n}}\right] \qquad (4.58)$$

for an instantaneous volume source having a Gaussian distribution, in terms of Sutton's theory.

Real distributions within a volume source are probably neither uniform nor Gaussian. Gifford[60] has studied more general initial distributions and has solved in particular the case where the initial distribution of material has a maximum at some distance from the center of the spherically symmetrical volume cloud, according to the equation

$$Q(\delta) = Q(0)\left(1 + b_2\,\delta^2\right)e^{-b_1\delta^2} \qquad (4.59)$$

where δ is distance from the center of the initial cloud. For this eccentric maximum initial distribution, Gifford found the concentration distribution, in terms of the statistical theory, to be

$$\chi_{(r,t)} = Q\,\frac{2b_1^{5/2}e^{-r^2/[2\overline{y^2}+(1/b_1)]}}{\pi^{3/2}(2b_1 + 3b_2)}\left[\frac{1}{(2b_1\overline{y^2} + 1)^{3/2}} + \frac{3\overline{y^2}b_2}{(2\overline{y^2}b_1 + 1)^{5/2}} + \frac{r^2b_2}{(2\overline{y^2}b_1 + 1)^{7/2}}\right] \qquad (4.60)$$

and indicated how more complicated volume source initial distribution may be treated. The distance of the initial maximum concentration from the center of the source, $R_{max}$, is

$$R_{max} = \left(\frac{b_2 - b_1}{b_2b_1}\right)^{1/2} \qquad (4.61)$$

Furthermore the radius, R, of the initial cloud containing a fraction Q − Q(R) of the total material Q is given in terms of the central concentration, Q(0), by

$$Q - Q(R) = Q(0)\left[\frac{\pi^{3/2}}{b_1^{3/2}}P(2b_1R^2;3) + \frac{3}{2}\pi^{3/2}\frac{b_2}{b_1^{5/2}}P(2b_1R^2;5)\right] \qquad (4.62)$$

when $P(\chi;k)$ is the chi-square probability function for k degrees of freedom.

**2.4** ***Formulae for Some Geometrical Properties of Effluent Clouds.*** In practical work it is often more convenient to use a formula which expresses only a certain geometrical property of the concentration distribution. Those most often used are the maximum ground concentration, the distance of this from the source, and the cloud or plume "width" or "height." These latter are defined in terms of some percentage of the central concentration since mathematically the width and height of theoretical plumes is infinite. Such formulae are much simpler than the complete equations, containing as they do less information.

The following formulae have been obtained by differentiating and maximizing certain of Sutton's results. The distance of the maximum concentration downwind of a source is $d_{max}$, and the maximum concentration there is $\chi_{max}$. For the isotropic case

*Instantaneous point source:*

$$d_{max} = \left(\frac{2h^2}{3C^2}\right)^{1/(2-n)} \tag{4.63}$$

$$\chi_{max} = \frac{2Q}{\left(\frac{2}{3}e\pi\right)^{3/2} h^3} \tag{4.64}$$

*Continuous point source:*

$$d_{max} = \left(\frac{h^2}{C^2}\right)^{1/(2-n)} \tag{4.65}$$

$$\chi_{max} = \frac{2Q}{e\pi\bar{u}h^2} \tag{4.66}$$

*Continuous, infinite crosswind line source:*

$$d_{max} = \left(\frac{2h^2}{C^2}\right)^{1/(2-n)} \tag{4.67}$$

$$\chi_{max} = \frac{2Q}{(2e\pi)^{1/2}\, h\bar{u}} \tag{4.68}$$

For the nonisotropic case, the most widely used formula is that for the maximum concentration from a continuous point source

$$\chi_{max} = \frac{2Q}{e\pi h^2\bar{u}}\,\frac{C_z}{C_y} \tag{4.69}$$

Formulae for the plume width and height from a continuous point source may be written by defining the "boundary" of the plume as the point at which the concentration falls to p per cent of its axial value. For Sutton's continuous elevated source theory, the following equations are easily demonstrated:

*Cloud width, $2y_0$, continuous point source:*

$$2y_0 = 2\left(\ln\frac{100}{p}\right)^{1/2} C_y x^{(2-n)/2} \tag{4.70}$$

*Cloud height, $z_0$, continuous point or infinite line source:*

$$z_0 = \left(\ln\frac{100}{p}\right)^{1/2} C_z x^{(2-n)/2} \tag{4.71}$$

2.5 *The Effect of Stability on Diffusion.* Although in theory it is possible to treat the effect of atmospheric stability on diffusion, either by means of Sutton's n or Deacon's $\beta$, verification of the theoretical formulations in stable atmospheres have not been obtained. This is due in part to the difficulty of making suitable measurements, but there is evidence that the problem of diffusion under stable conditions is so unusual as to require a completely separate treatment. Photographs of diffusion from elevated sources under stable and unstable conditions are shown in Chap. 5. It is evident that, as compared with unstable conditions, the effect of a stable vertical temperature stratification is to decrease the horizontal eddy diffusion and practically eliminate entirely the vertical eddy diffusion.

Barad[4] has discussed diffusion under stable conditions and suggested that, because of the limited range of eddy sizes then, the K theory may be expected to apply more closely than in the case of neutral or unstable atmospheres. Barad suggests, from visual observations at Brookhaven, that either Eq. 4.48 or a nearly equivalent one which he derives will describe the diffusion if $\bar{u}/2K_y \approx 0.1\ \text{cm}^{-1}$ and $K_y/K_z \approx 10$.

2.6 *Special Applications of Sutton's Theory.* Certain problems arise in practice which require corrections to, or variations upon, the diffusion equations that have been presented. In this section a number of these useful special results will be listed. Most of these have been given by Holland,[31] in terms of Sutton's theory, although in each case the general idea could be applied to one of the alternative formulations of the diffusion problem. Clearly each of the following topics is worthy of an extended individual discussion, the presentation of which cannot be attempted here. Including the equations will, however, make this enumeration of theoretical results on diffusion fairly complete.

(a) *Total Integrated Dosage (TID) at the Ground Downwind of an Instantaneous Elevated Point Source.* This is the maximum amount of airborne material to which a point at the ground may be exposed as the result of the passage of a cloud of diffusing substance. Integration of Eq. 4.36 (right side doubled) with respect to $t (= x/\bar{u})$, with $y = 0$ and $z = h$, gives

$$\mathrm{TID} = \frac{2Q}{\pi C^2 \bar{u} (\bar{u}t)^{2-n}} \exp\left[\frac{-h^2}{C^2 (\bar{u}t)^{2-n}}\right] \tag{4.72}$$

Also

$$\mathrm{TID}_{\max} = \frac{2Q}{\pi e \bar{u} h^2} \tag{4.73}$$

and

$$d_{(\text{max dosage})} = \left(\frac{h^2}{C^2}\right)^{1/(2-n)} \tag{4.74}$$

The integrated dosage from an instantaneous source is, in other words, identical in form with the concentration from a continuous source (cf. Eqs. 4.50, 4.65, and 4.66).

(b) *Maximum Ground Concentration During "Looping."* The term "looping" has been used to characterize a certain behavior of the plume from an elevated source which is common during typical daytime, light wind conditions (the Brookhaven type A conditions; see Chap. 5). During this condition the plume is deformed into a serpentine shape, doubtless as a result of the presence of larger thermal eddies in the lower layers. The result is that concentrations characteristic of the center of the plume may occur at the ground momentarily. To estimate these concentrations, Holland[81] has suggested substituting the minimum distance from the source to the point of measurement, $x'$, for $x$ and assigning the value of 1 to the exponential terms in Sutton's Eqs. 4.50 or 4.51. For "large downdrafts" of velocity $\bar{w}$, $x = h\bar{u}/\bar{w}$, and $x' = \sqrt{x^2 + h^2}$. For downdrafts in the lee of large buildings, $x' = x + h$. Such deformations would be expected to be accompanied by extraordinarily large values of $C_y$ and $C_z$. Situations of this type have probably produced the majority of the "least dilutions" reported by Church, "eddy peak concentrations" reported by Gosline, and "downwash" or "blowdown" concentrations reported by steam power plant investigators, according to Holland.

(c) *Concentration During a "Fumigation" Condition.* The term "fumigation" was introduced by Hewson[72] to describe the mixing downward to the ground of effluent material which has accumulated aloft during a period of thermal stability; such an occurrence is common after dawn, when the nocturnal ground temperature inversion is rapidly dissipated by warming due to the rising sun. To estimate this effect, Holland[81] integrates Eq. 4.51 between 0 and ∞ with respect to z and distributes the resulting amount of material uniformly through a layer of depth H, obtaining

$$\chi = \frac{Q}{(2\pi)^{1/2} C_y \bar{u} H x^{(2-n)/2}} \tag{4.75}$$

*Average concentration over a long period of time, from a continuous elevated source:*

$$\chi_{av} = \frac{0.02Qf}{\pi^{1/2} C_z \bar{u} x^{(2-n)/2}} \exp\left(\frac{-h^2}{C_z^2 x^{2-n}}\right) \tag{4.76}$$

where f is the wind direction frequency (in per cent) toward the location during the period. A similar idea was advanced by Lowry.[84]

(d) *Deposition of Particles.* The effect of gravitational settling of particles (fall-out) and scavenging of particles by precipitation (rainout and wash-out) is not always negligible, as has been assumed to be the case in all the foregoing formulae. It is appropriate to mention the subject here since, in practice, it is dealt with as a special application of the point source diffusion formulae; however, because the concept is so complicated it will be the subject in Chap. 7.

2.7 *Correction for Radioactive Decay.* Computed concentrations may be corrected for decay in the case of radioactive effluents by multiplying the source strength Q by the factors:

| | |
|---|---|
| $\exp\left(-0.693 \frac{t}{T}\right)$ | (single isotope of known half life) |
| $\left(\frac{t}{t_1}\right)^{-1.2}$ | [short lived mixed fission products (as from a power excursion)] |
| $\left(\frac{t}{t_1}\right)^{-0.2}$ | [long lived mixed fission products (as from a reactor operating for an extended period)] |

where T is the half life in seconds, t is the elapsed time in seconds between the completion of the nuclear incident and the passage of the cloud over the point for which the concentration is computed, and $t_1$ is a time in seconds after completion of the nuclear incident at which the radioactivity of the source strength Q is known. Note that in the case of a continuous source t may be represented by [$(x/\bar{u})$ + the containment time before release to air].

## 3. PARAMETERS AND COEFFICIENTS OF THE DIFFUSION THEORIES

All theories of atmospheric diffusion contain certain parameters and coefficients which have to be evaluated by recourse to some hypothesis or else by direct or indirect measurement, usually the latter. In fact, to this extent, all existing theories are partially empirical, at least in actual practice. It is true that Calder's development of the K theory via the mixing-length hypothesis for the special case of flow over certain types of terrain can be evaluated independently of direct physical measurements; and good verification has been obtained. Nevertheless, in practice, some empiricism will nearly always be employed in determining the appropriate parameters. For this reason the problem of evaluating these various parameters needs some elaboration.

3.1 *Parameters of the K Theory.* (a) *Constant K.* Richardson's values[123] of the eddy diffusivity, K, are given in Table 4.1. It is with these measurements that Richardson discovered the law $K = 0.2\ L^{4/3}$ to which reference has been made, L being the length scale to which the K value applies, analogous to a mixing length.

Table 4.1 —K and L Values (Richardson[123])

| K, $cm^2/sec$ | L, cm | Source of measurements |
|---|---|---|
| $3.2 \times 10^3$ | $1.5 \times 10^3$ | W. Schmidt; anemometers at 2, 16, and 32 meters |
| $1.2 \times 10^5$ | $1.4 \times 10^4$ | Akerblom; anemometers at 21 to 305 meters |
| $6 \times 10^4$ | $5 \times 10^4$ | Taylor and Hesselberg; pilot balloons at 100 to 800 meters |
| $10^8$ | $2 \times 10^6$ | Richardson; manned and unmanned balloons |
| $5 \times 10^8$ | $5 \times 10^6$ | Richardson; volcanic ash |
| $10^{11}$ | $10^8$ | Defant; diffusion due to cyclones regarded as deviations from the general circulation |

Recently, Lettau[91] has summarized present knowledge of vertical eddy-diffusion coefficients by means of Fig. 4.3. His D is equivalent to $K_z$, which, for the isotropic assumption, is equal to K. The eddy diffusivity, D, is taken as equal to the product of a characteristic mixing length, $\lambda$, and mixing velocity, $\zeta$, by analogy with the definition of the molecular diffusivity.

Data for diffusion from continuous point and line sources at ground level in nearly adiabatic conditions have enabled Sutton[142] to determine that $K_y = 1.6 \times 10^4 cm^2/sec$ and $K_z = 10^3 cm^2/sec$. The distance from the source for these measurements was 100 meters and $\bar{u} = 5$ m/sec. Various other measurements of eddy diffusivity, K, have been obtained by measuring heat and moisture transport. For example, Taylor[143] estimated the magnitude of K to be between $1 \times 10^3$ and $3 \times 10^3$ $cm^2/sec$ from observations of fog over the Grand Banks. These all roughly confirm the order of magnitude of the above estimates of K.

(b) *Variable K.* The parameters of Calder's theory are evaluated by means of Eqs. 4.17a and 4.19 and Fig. 4.1. It has been found necessary to introduce a factor d, the so called "zero point displacement," into Eq. 4.17a, namely,

$$\bar{u} = w_* q' \left(\frac{z - d}{z_0}\right)^{\alpha} \qquad (4.77)$$

This is done to account for the effect of packing of certain types of roughness elements at the surface, such as long grass, which displaces the effective surface upward a distance d, so far as the surface turbulence is concerned; d is a func-

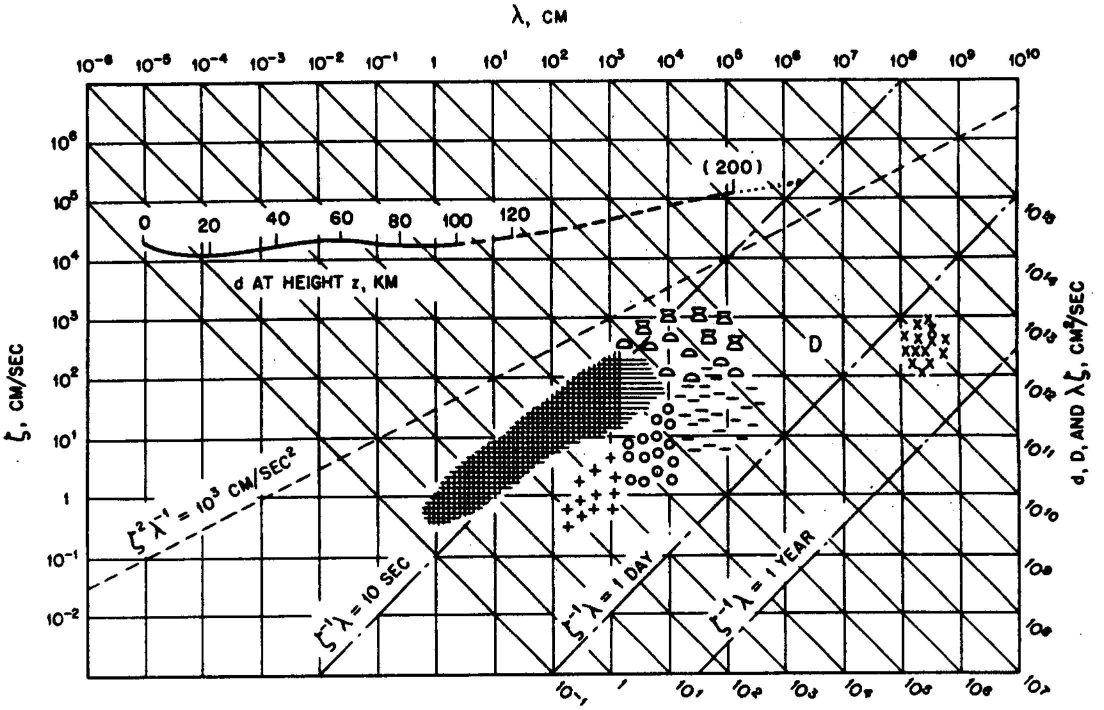


Fig. 4.3—Diffusion diagram. Each point of the λ, ζ plane determines a diffusion coefficient (cm²/sec). In molecular diffusion λ ≈ free path and ζ ≈ mean molecular speed; d = λ ζ is fixed by the density and temperature of the atmosphere; consequently, the height variation of d is marked by a curve. In eddy diffusion, λ ≈ mixing length and ζ ≈ mixing velocity; owing to the variability of these elements, D = λ ζ, and its variations with height are denoted by characteristic areas when the possible variability of D is narrowed by the consideration of limiting values of eddy accelerations (ζ²/λ) and time terms (λ/ζ) (Lettau). ——, 1–10 km for ordinary turbulence. ⌓, 1–10 km for cumulus convection. ⊟, 1–10 km for cumulonimbus convection. ○, 10–25, 35–45, and 80–100 km. ×, horizontal gross austausch of the general circulation. ▦, 0–1 km. +, 25–35 km. —, 45–80 km.

tion, moreover, of wind speed. Calder's examples of values of q′ and α over long and short grass plots are given in Table 4.2.

3.2 *Parameters of Sutton's Theory.* This theory contains the diffusion coefficient $C_x$, $C_y$, and $C_z$; the turbulence parameter n; and the macroviscosity N. According to the theory, these are completely determined by Eqs. 4.35, 4.37, 4.39, 4.40, and 4.42; but there are certain difficulties and limitations.

In the first place, while measurements of $\overline{(u')^2}$ and $\overline{(v')^2}$, the mean-squared values of the turbulent wind speed fluctuations in the downwind and crosswind directions, are readily obtained from standard anemometer installations, measurements of w′ depend on special instrumentation and are not common. In the case of isotropic turbulence, with $C_y = C_z$, Holland[81] reasoned that

$$\frac{\overline{(w')^2}}{\bar{u}^2} = \frac{\overline{(v')^2}}{\bar{u}^2} \simeq \sigma^2_{\tan\theta} \tag{4.78}$$

where θ is the instantaneous angular deviation of the horizontal wind direction from the mean wind and σ is the standard deviation; for θ < 20°

$$\sigma_{\tan\theta} \simeq \tan\sigma_\theta$$

Thus an approximation to Eqs. 4.39 and 4.40 is

$$C_y^2 = C_z^2 \simeq \frac{4\nu^n}{(1-n)(2-n)\,\bar{u}^n}\,(\tan\sigma_\theta)^{2(1-n)} \tag{4.79}$$

providing a means for obtaining diffusion coefficients from readily obtainable measurements of $\theta$, the instantaneous deviation from the mean wind direction. For flow over aerodynamically rough surfaces, the kinematic viscosity, $\nu$, would be replaced by the macroviscosity, N.

Table 4.2—Values of $\alpha$ and q (Calder[19])†

| | Long grass‡ | | | Short grass§ | | |
|---|---|---|---|---|---|---|
| z, cm | $\bar{u}$, cm/sec | $\alpha$ | q' | $\bar{u}$, cm/sec | $\alpha$ | q' |
| 200 | 500 | | | 500 | | |
| 300 | 556 | | | 531 | | |
| 500 | 624 | 0.220 | 4.14 | 574 | 0.153 | 6.01 |
| 1,000 | (715) | (0.205) | (4.42) | (632) | (0.146) | (6.28) |
| 2,000 | (803) | (0.194) | (4.61) | (690) | (0.140) | (6.50) |
| 5,000 | (917) | (0.179) | (4.91) | (766) | (0.132) | (6.82) |
| 10,000 | (1002) | (0.170) | (5.10) | (824) | (0.128) | (6.97) |

† Values in parentheses are calculated; all others are observed.
‡ $w_* = 49.5$ cm/sec, d = 30 cm, $z_0 = 3$ cm.
§ $w_* = 33.3$ cm/sec, d = 0, $z_0 = 0.5$ cm.

The wind fluctuations to which the above equations refer are, of course, a function of height as, consequently, are the diffusion coefficients. Sutton gives this formula for the vertical variation of C (as corrected by Wanta[150])

$$C = C(0) - 0.0422 \log_{10} z \qquad (4.80)$$

applying to adiabatic conditions. The value of C(0) is 0.18. This value was obtained by extrapolating downward to the surface the value of C found at 1.8 meters over smooth grassland using Eq. 4.37.

Sutton[137] states that "The virtual diffusion coefficients $C_y$ and $C_z$ depend primarily upon the value of n and the magnitude of the 'gustiness'... the diffusion coefficient (decreases) with height in consequence of the normal steady fall of turbulence with height..." The basic values of $C^2$ as a function of atmospheric stability, as represented by the turbulence index n, and of source height above the ground, h, have been derived from Sutton's work (Table 4.3).

The extension of these coefficients was undertaken by Barad and Hilst,[5] who give values as a function of source height and of atmospheric stability conditions. All these values of $C_y$, $C_z$, and n are essentially related to the very few published estimates and suggestions in Sutton's papers.

Table 4.3—Sutton's Value for $C^2$ as a Function of Stack Height, (h), and Stability Parameter (n)

| | | $C^2$ [at various h values (meters)], (meters)$^n$ | | | |
|---|---|---|---|---|---|
| | n | h = 25 | h = 50 | h = 75 | h = 100 |
| Large lapse rate | 0.20 | 0.043 | 0.030 | 0.024 | 0.015 |
| Zero or small temperature gradient | 0.25 | 0.014 | 0.010 | 0.008 | 0.005 |
| Moderate inversion | 0.33 | 0.006 | 0.004 | 0.003 | 0.002 |
| Large inversion | 0.50 | 0.004 | 0.003 | 0.002 | 0.001 |

3.3 *Experimental Determinations of Sutton's Parameters: Effect of Sampling Time.* Holland[81] has studied the question of the Sutton parameter values, using data obtained over rough hilly terrain (Oak Ridge, Tenn.). His main conclusions about n are that (1) the wind profile index of Sutton is, in general, related to stability, but that a large scatter of the values of n is found at any given value of the vertical temperature gradient; (2) n values determined experimentally are, in general, greater than Sutton's suggested values (Table 4.3); and (3) daytime observations (or observations under neutral or unstable conditions) show more uniformity of n with height (see Table 4.4).

Using observed values of wind gustiness and values of n for various stabilities, Holland calculated $C_x$, $C_y$, and $C_z$. The results of this work are summarized in Fig. 4.4, and the $C_y$ values he found are compared with Sutton's values in Fig. 4.5.

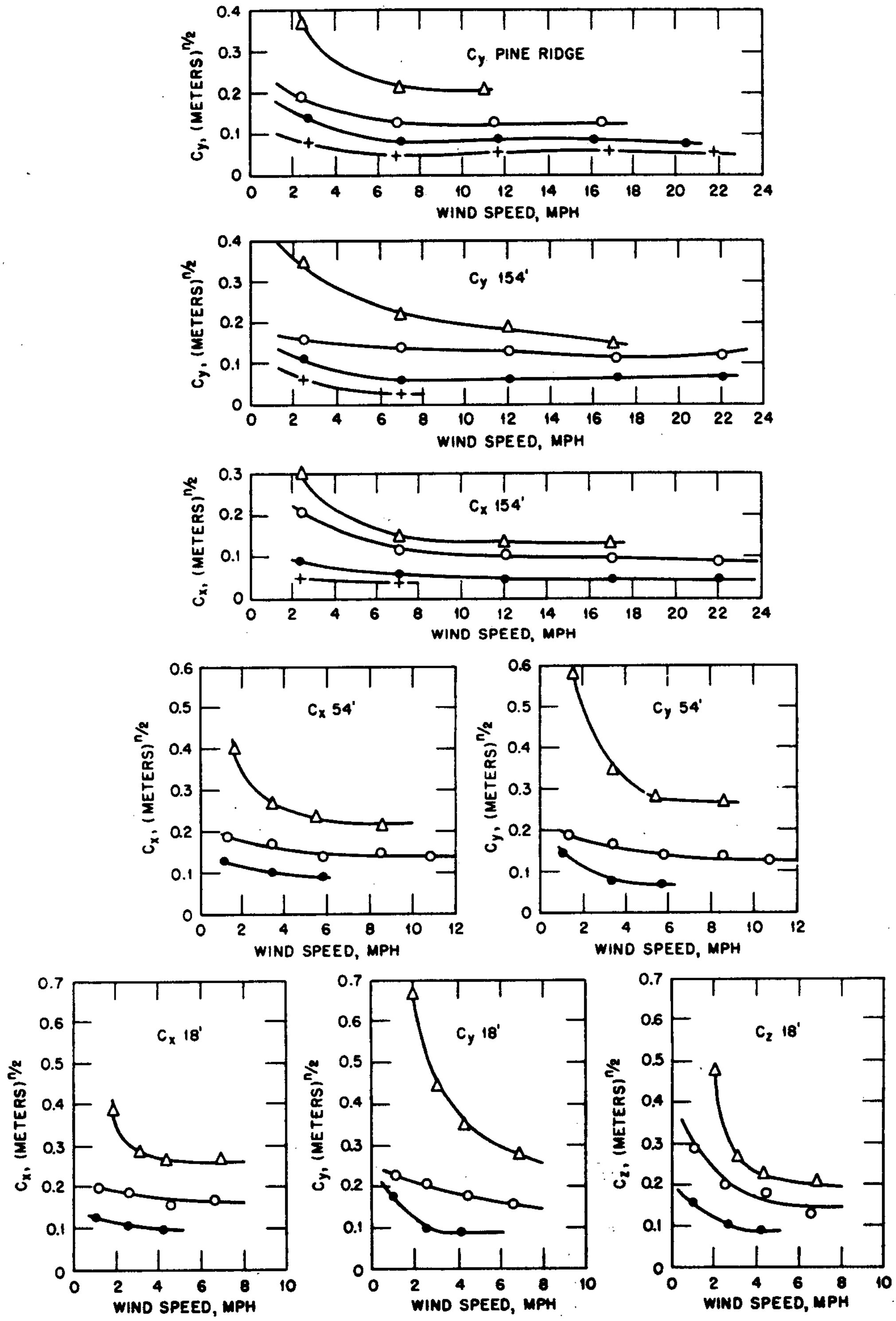


Fig. 4.4—Observed $C_x$, $C_y$, and $C_z$ vs. wind speed and stability (Holland). Δ, lapse (≤ −1°F/100 ft, n = 0.15 to 0.20). ○, neutral (−0.5 to 0°F/100 ft, n = 0.25). ●, moderate inversion (≤ 2°F/100 ft, n = 0.30 to 0.40). +, large inversion (>2°F/100 ft, n = 0.50).

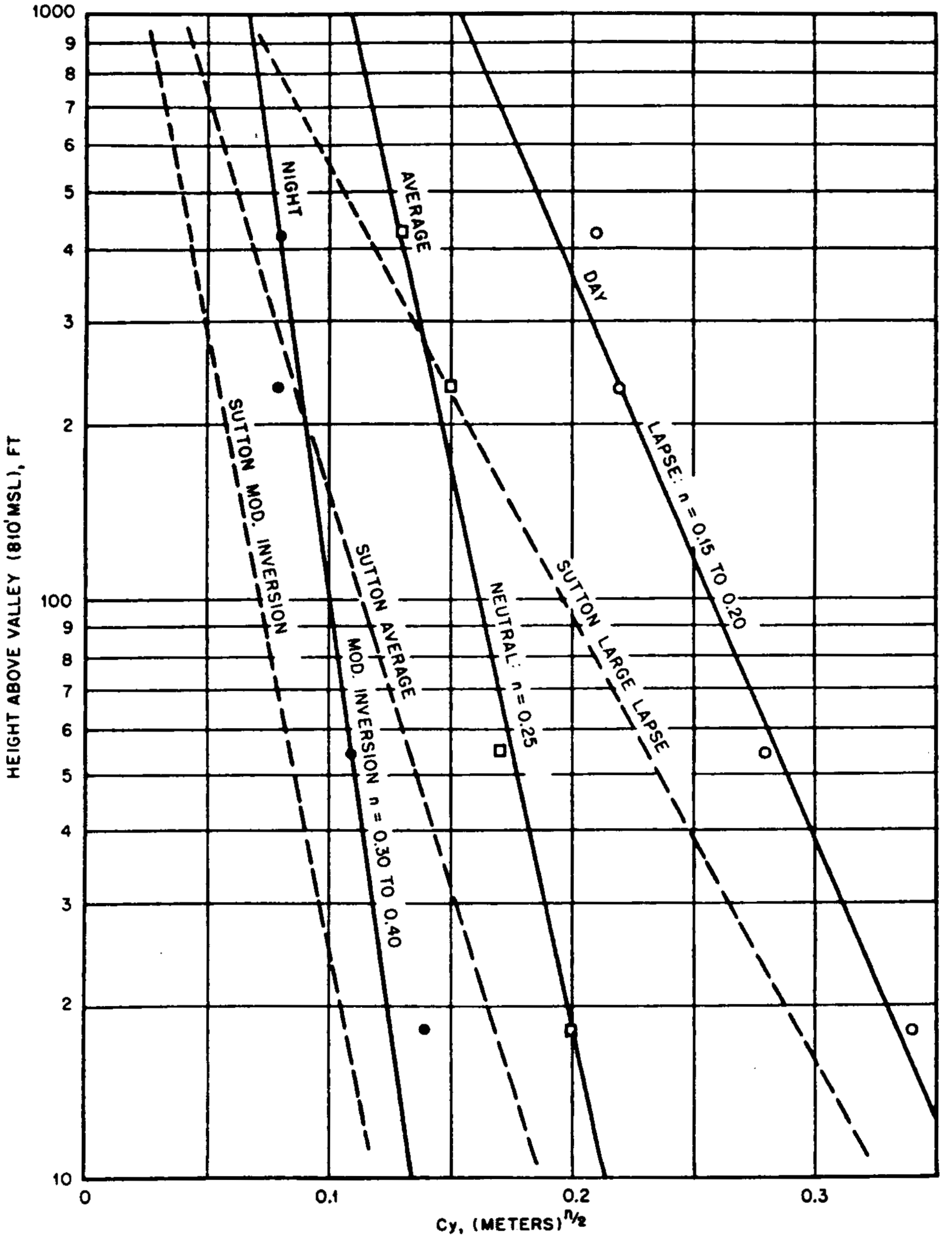


**Fig. 4.5**—Variation of $C_y$ with height (Holland). ○, lapse. □, neutral. ●, moderate inversion.

Table 4.4—n from Average Wind Speed Profiles (Oak Ridge)

| | Day | Night | Average |
|---|---|---|---|
| 10 to 40 ft | 0.3 to 0.4 | 0.3 to 0.7 | 0.3 to 0.5 |
| 25 to 100 ft | 0.3 to 0.4 | 0.5 to 0.9 | 0.4 to 0.6 |
| 100 to 400 ft | 0.2 to 0.5 | 0.8 to 0.9 | 0.5 to 0.7 |

The differences between the values of Sutton and of Oak Ridge are interpreted by Holland as being due to the following facts: (1) the Oak Ridge observations represent 15-min samples of the wind gustiness, whereas Sutton's are based on 3-min values; (2) the Oak Ridge wind speeds are much less than those used by Sutton; and (3) the terrain at Oak Ridge is rougher.

The lateral diffusion coefficient, $C_y$, has also recently been studied by Friedman,[53] employing the equation

$$C_y^2 = \frac{4}{(1-n)(2-n)} \left(\frac{N}{\bar{u}}\right)^n \left[\frac{\overline{(v')^2}}{\bar{u}^2}\right]^{1-n} \tag{4.81}$$

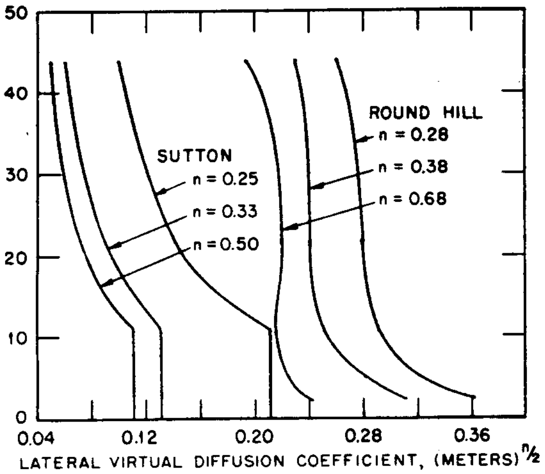


Fig. 4.6—Lateral virtual diffusion coefficient, $C_y$, plotted against height (Friedman).

obtained by replacing $\nu$ and n in Eq. 4.39 with values of the wind gustiness observed at Round Hill, Mass. N was evaluated by means of Eq. 4.42. The roughness length at Round Hill equalled 8.5 cm, and the stress was evaluated by the formula

$$\tau_0 = 0.006\, \rho\, \overline{u^2}_{(10\ \text{meters})} \tag{4.82}$$

Friedman's values are compared with Sutton's in Fig. 4.6. The differences are at least in part attributable, according to Friedman, to the use of the macrovisicosity, to the fact that terrain at Round Hill is rougher than the ground of Sutton's work, and to the fact that Sutton's values for other than neutral stability conditions are estimates only.

In confirmation of the effect of terrain roughness on the lateral diffusion coefficient, $C_y$, Wilkins at the National Reactor Testing Station has found the value $C_y = 0.061$ at a height of 250 ft for $\bar{u} = 6.2$ m/sec and $n = 0.37$. Terrain at that site is remarkable for its smoothness.

## 4. SUTTON'S EQUATIONS AS INTERPOLATION FORMULAE

Many of the difficulties of diffusion theories could be by-passed simply by the use of diffusion observations and suitable interpolation formulae. Unfortunately, reliable measurements of concentrations are very rare. Some, made at Brookhaven National Laboratory (BNL) by Lowry et al.,[37] have been published, and it occurred to Gifford to use these in a direct attempt to determine the parameters of Sutton's theory.

The difficulty is that Eq. 4.51 contains three parameters, namely, $C_y$, $C_z$, and n, to be determined given measurements of concentrations $\chi$ at various downwind points (x,0,0) from the stack of height h. One way out is to obtain a different equation involving only, say, $C_z$, by integration; then measure the "crosswind integrated concentration." A few such measurements are being obtained, but the observational technique is not simple. A second possibility is the direct fitting of data to Eq. 4.51, which can be accomplished as follows.

For the case of y = 0 (downwind concentrations), rearranging Eq. 4.51 and taking logarithms gives

$$\log_{10}\left(\frac{\chi}{Q}\,\frac{\pi}{2}\,\bar{u}\,x^{2-n}\right) = \log_{10} C_y C_z - \frac{0.4343 h^2}{C_z^2 x^{2-n}} \tag{4.83}$$

This is a linear equation in certain functions of the variables, in which $C_y$ and $C_z$ appear as coefficients, say of the form

$$y = a + bz \tag{4.84}$$

provided n is regarded as known or defined. The variation of n is, however, small, supposedly between zero and 1, suggesting the following procedure: assign various values to n over (and if necessary, beyond) its theoretical range, perform for each assigned value the usual linear least-squares curve fitting calculations, and examine the resulting series of standard errors. If there is a minimum standard error value corresponding to some value of n, this value of n and the corresponding value of $C_y$ and $C_z$ are regarded as best fits to the data.

The BNL data are in the form of measured surface values of oil-fog smoke concentrations made at various distances up to about 5 km downwind of a 355-ft stack. Inspection shows that the observations may be grouped conveniently into cases representing nearly neutral meteorological conditions and cases representing stable conditions, depending on whether the temperature difference $(T_{410'} - T_{37'})$ lies between −1.0 and −1.4°C or is less than −1.0°C. The BNL concentrations include values corresponding to three sampling intervals:

(1) Peak concentrations: the highest reading during the passage of a smoke puff.

(2) Average concentrations: the average concentration while smoke was present.

(3) Time-mean concentrations: the average concentration during the sampling period.

Group (1) represents an average value of very short duration, perhaps a few seconds, representing the response of the sampling apparatus; (2) is an average of several minutes duration, and (3) may represent a 20- to 60-min average. Only groups (1) and (2), for near neutral conditions, contained enough data for the present statistical treatment.

The significant results of the least-squares analysis appear in the tabulation below, where estimates of $C_y$, $C_z$, and n from BNL concentration data for nearly adiabatic conditions are given:

Peak concentrations:
$n = 0.4$, $C_y = 0.75$, $C_z = 0.63$, $C_z/C_y = 0.83$
(77 observations)
Eddy mean concentrations:
$n = 1$, $C_y = 23$, $C_z = 5.5$, $C_z/C_y = 0.239$
(for $n = 0.4$, $Cy = 2.3$, $C_z = 0.60$, $C_z/C_y$ 0.260)
(77 observations)

These values require some comments. Figure 4.7 shows the variation of the standard error of the least-squares fits as a function of assumed n value. For the peak concentration data, a minimum of n = 0.4 was determined, but for the eddy-mean data n = 1 was the minimum value. The explanation evidently lies in the structure of turbulence in the lower layers. The vertical gustiness of the lower atmosphere is evidently bounded by the presence of the ground, but this is not true of the lateral eddy motion. Thus over a longer and longer period of time the influence of larger and larger lateral turbulent fluctuations will be felt; but the vertical turbulence should not be strongly influenced by sampling time. Thus the effect on measured concentrations of increasing the sampling time is not unlike that of increasing the stability. This is also shown by the "coefficient of isotropy," $C_z/C_y$, which, for the peak concentration data was nearer to unity, the isotropic value, but for eddy-mean data was equal to between 0.24 and 0.26.

These parameter values are not directly comparable with those determined from the defining equations. There are several good reasons why this is so. In the first place the oil-fog concentrations contain all the sources of variability that were present, including any instrumental and calibration errors and so on, in addition to the variability produced by air turbulence. Furthermore, the method used for determining n is not really sensitive. As shown in the tabulation above, if n is selected to be 0.4, a reasonable value, rather than the value 1 corresponding to the minimum standard error, in the case of the eddy-mean data, values of $C_y$ and $C_z$ are altered radically but their ratio remains much the same. Even so, the parameter values derived for the peak concentration data are not unreasonable.

## 5. THE RELIABILITY OF DIFFUSION PREDICTIONS

The standard error values given in Fig. 4.7 provide quantitative information which bears on the controversial question, "How reliable are concentration predictions based on theoretical diffusion formulae?" Since Eq. 4.83 is in terms of common logarithms of relative concentration, $\chi/Q$, interpretation of the standard error values is particularly convenient. If all the variability of the measurements is attributed to the concentrations, then, for example, a standard error value of 0.5 means that 68% (one standard error unit) of the observed $\chi$ values lay within ±5 times the value predicted by Sutton's theory and 95% lay within an order of magnitude. The work of Holland[79] shows somewhat better agreement; however, the measured and computed concentrations were for relatively short (<500 meters) distances. Of course, all the variability may not (as has been noted) be blamed upon the concentrations themselves; but certainly most of it

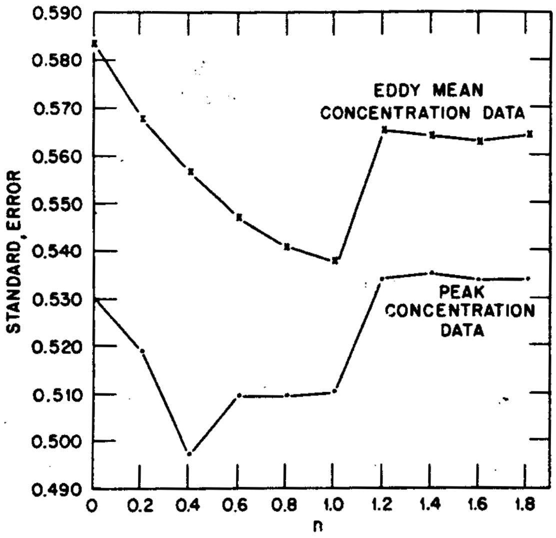


Fig. 4.7—Standard error as a function of n value, BNL data, adiabatic conditions (Gifford).

must be, and the measurements give some idea of what to expect in practical applications of Sutton's formula.

The point source formulae of Bosanquet and Pearson (Eq. 4.46) and Roberts (Eq. 4.48) were also fitted to the BNL data by the same least-squares process. The resulting standard errors permit a comparison of these with Sutton's formula.

| Theory | Standard error value |
|---|---|
| Sutton (n = 0.4) | 0.497 |
| Bosanquet and Pearson | 0.534 |
| Roberts | 0.564 |

This result is not surprising inasmuch as, considered purely as an interpolation formula, Sutton's is the most adjustable of the three.

The above results are not definitive, and many more observational comparisons need to be made; but there is no reason to doubt that they fairly represent the general level of accuracy to be expected of diffusion estimates from the various formulae, particularly in working field conditions.

# 5

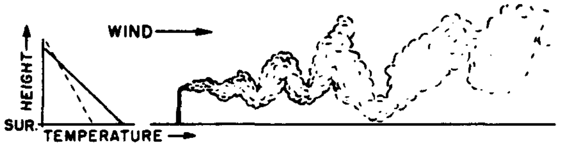
# Behavior of Stack Effluents

Although most people have observed that smoke plumes from a chimney have a different appearance at different times of day or during various weather conditions, it has been through the work of meteorologists that various kinds of plume behavior have been correlated with instrumental measurements of meteorological conditions. Stack emissions, except in rare cases, will usually be treated as continuous sources, and the continuous source equations, Eqs. 4.46 to 4.59, can be applied. Where several stacks are located together and more or less aligned or where multiple short stacks on a large building may merge effluent (see Fig. 1.2), better agreement may be achieved by the use of the continuous line source equations, Eqs. 4.52 to 4.54.

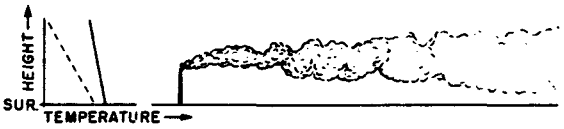
Parameters for use with the various equations may, if a sufficiently comprehensive meteorological program exists, be computed from Eqs. 4.79 and 4.81. It is more likely, however, that adequate representation of these parameters will have to be obtained from considerations of the diffusion climate and the terrain of the site and reference to Tables 4.3 and 4.4 and Figs. 4.4 and 4.5. Other sources, many of which have been referenced in Chap. 4, may also be consulted for parameter information.

Where the entire picture of the effluent concentrations is not required, the "hot" spots can be quickly obtained from Eqs. 4.65 to 4.68 and plume dimensions from Eqs. 4.69 to 4.71.

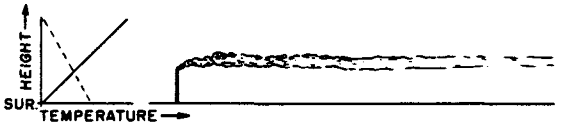
It has been found that the appearance of effluent plumes from stacks is regulated largely by the vertical gradient of air density (as measured by the vertical gradient of air temperature) in the neighborhood of a stack. Since there are a limited number of configurations of the vertical temperature gradient that are likely to occur in nature, the kinds of plume behavior likely to be observed from any particular stack are also limited. Although some variations may be found, it is believed that there are five major types of plume behavior,[23] and these are shown schematically in Fig. 5.1, along with the general form of vertical temperature distribution causing the behavior. These classifications are mostly applicable to single and more or less isolated stacks.



STRONG LAPSE CONDITION (LOOPING)



WEAK LAPSE CONDITION (CONING)



INVERSION CONDITION (FANNING)

INVERSION BELOW, LAPSE ALOFT (LOFTING)

LAPSE BELOW, INVERSION ALOFT (FUMIGATION)

Fig. 5.1—Schematic representation of stack gas behavior under various conditions of vertical stability. ---, dry adiabatic lapse rate.

A description of smoke behavior and accompanying meteorological conditions for each type is given below.

## 1. PLUME TYPES

1.1 *Looping*. Looping occurs with superadiabatic (very unstable) temperature lapse rates. The stack effluent, if visible, appears to loop because of thermal eddies in the wind flow. Gases diffuse rapidly, but sporadic puffs having strong concentrations are occasionally brought to the ground near the base of the stack for a few seconds during light winds. This is usually a fair weather daytime condition since strong solar heating of the ground is required. Looping is not favored by cloudiness, snow cover, or strong winds. Momentary looping concentrations may be computed by the technique described in Chap. 4, Sec. 2.6b. Longer period (e.g., 10 to 30 min) concentrations would be obtained from the continuous point source formulae with the parameters chosen to fit existing stability conditions.

1.2 *Coning*. This type of plume occurs with a temperature gradient between dry adiabatic and isothermal and may occur periodically (between thermals) with a superadiabatic lapse rate. The effluent plume is shaped like a cone with the axis horizontal. The distance from the stack at which the effluent first comes to the ground is greater than with looping conditions because thermal turbulence, and hence vertical motions, is less. It usually is favored by cloudy and windy conditions and may occur day or night. In dry climates it may occur infrequently, and, conversely, in cloudy climates it may be the most frequent type observed. Much of the development of diffusion formulae has been for stability conditions similar to this type of lapse rate; hence the continuous point source formulae should be expected to give good results with plume behavior of this type.

1.3 *Fanning*. Fanning occurs with temperature inversions or near-isothermal lapse rates. This type of plume with its very smooth, almost laminar, flow also depends somewhat on wind speed and the roughness of the terrain. The stack effluent diffuses practically not at all in the vertical. The effluent trail may resemble a meandering river, widening gradually with distance from the stack. Depending on the duration of the stable period and the wind speed at the stack level, the effluent may travel for many miles with very little dilution. The concentration within the stream varies inversely as the wind speed, but the distance that it travels is directly proportional to wind speed, the variation in wind direction, and the duration of this type of flow pattern. Since fanning is usually associated with surface inversions, it is mostly a nighttime condition. It is favored by light winds, clear skies, and snow cover. The condition can persist for several consecutive days in winter in some climates, especially at higher latitudes.

In most cases the fanning behavior of plumes is not considered an unfavorable condition for stack releases, even though the effluent undergoes little dilution after leaving the stack. The important feature is that an effluent of neutral bouyancy tends not to spread to the ground during inversion conditions. This situation might be unfavorable, however, in the following circumstances:

1. Where the stack is short with respect to surrounding buildings or other objects needing freedom from pollution.
2. Where the effluent plume contains radioactive wastes that may radiate harmfully to the ground.
3. Where there is a group of stacks of various heights, giving an extensive cloud of effluent. This is especially bad when long periods of calms occur.
4. Where lateral spread and variability of plume direction are restricted (as by a deep, narrow valley) so that the wastes pass repeatedly over the same places.

The likelihood that effluent will accumulate in the neighborhood of a stack during the inversion situation is smaller than one might expect. Wind speeds so light that they cannot be detected by ordinary wind instruments (1 mph or less) will remove effluent sufficiently fast to prevent accumulation for most stacks regardless of discharge rate. Also, since the tendency is far greater for the plume to spread horizontally than vertically, there is little likelihood that such an accumulation would cause the plume to spread downward to the ground as long as the inversion persists.

The theoretical treatment of diffusion is on the most uncertain ground under these conditions. The assumption of isotropy is probably in error, and the horizontal diffusion, although much less than for unstable regimes, is larger than the vertical spread. Under these circumstances Eqs. 4.48, 4.51, 4.54, and 4.69 would apply. Barad's choice of $K_y$ and $K_z$ (see Chap. 4, Sec. 2.5) could be used. Following Barad's reasoning and some comments by Sutton[142] (for neutral conditions), the ratio of $C_y/C_z = 3$ seems reasonable. This assumption is supported by data presented by Holland.[79] Values of $C_y$ are readily obtainable from wind vane fluctuations (Eq. 4.78), or values of $C_y$ shown in Figs. 4.4 and 4.5 may be used.

1.4 *Lofting.* This type of plume occurs with the transition from lapse to inversion and should thus be observed most often near sunset. Depending upon the height of the stack and the rate of deepening of the inversion layer, the lofting condition may be very transitory or may persist for several hours. It has, infrequently, been found to persist throughout the night for the 250-ft stacks at the National Reactor Testing Station (NRTS), although its usual duration is 1 to 3 hr. The zone of strong effluent concentration, shown by shading in Fig. 5.1, is caused by trapping by the inversion of effluent carried into the stable layer by turbulent eddies that penetrate the layer for a short distance. Except when the inversion is very shallow, the lofting condition may be considered as the most favorable diffusion situation. The inversion prevents effluent from reaching the ground, and at the same time the effluent may be rapidly diluted in the lapse layer above the inversion.

If sufficient meteorological instrumentation is available to detect lofting conditions, it can be used for "dumping" an effluent that would cause trouble during other meteorological conditions. Obviously the duration of lofting conditions depends on the rate of increase in depth of the nocturnal inversion and the height of the stack. Since this type of lapse rate will prevent the effluent from reaching the ground, diffusion computations would not often be required. However, if the air concentration above the inversion is of interest, an approximation could be obtained by assuming the inversion top to be an impermeable surface and, choosing the stability parameters appropriate to the layer above the inversion, computing concentrations at the inversion top. The height, h, in this instance would be the distance the effective stack height extends above the inversion top. Since the inversion would not be completely impermeable, these values would be extremely crude.

1.5 *Fumigation.* This condition occurs at the time when the nocturnal inversion is being dissipated by heat from the morning sun. The lapse layer usually begins at the ground and works its way upward, less rapidly in winter than in summer. At some time the inversion is still present just above the top of the stack and acts as a lid, while convective eddies mix the effluent plume within the shallow lapse layer near the ground. This condition may also develop in sea breeze circulations during late morning or early afternoon. Large concentrations are brought to the ground along the entire effluent stream (which may be quite long owing to the previous presence of fanning conditions) by thermal eddies in the lapse layer. The zone of strong concentration shown by shading in Fig. 5.1 is that portion of the plume that has not yet been mixed downward.

The fumigation deserves special attention in stack planning since it (1) provides a method whereby strong effluent concentrations can be brought to the ground, at least briefly, at great distances from the stack and (2) gives stronger sustained ground concentrations in the neighborhood of a stack than looping, coning, etc. During smoke experiments at Brookhaven,[94] using a 355-ft stack, it was found that fumigation concentrations averaged 20 times the maximum concentration computed by the Sutton equation over a period of about 15 min. This figure has been used at Brookhaven to compute exposures from the reactor stack effluent. Concentrations thus computed allow the severity of the fumigation to vary with stack height and wind speed and thus should be sufficiently applicable to other stacks; however, a modification of the Sutton equation for the estimation of fumigation concentrations is given by Holland[81] and is discussed in Chap. 4, Sec. 2.6c.

The duration of fumigation conditions may vary widely from place to place. It will depend upon the rate of deepening of the lapse layer as the nocturnal inversion dissipates and upon the height of the stack. In some places inversion "lids" are known to persist for several days. Fumigation conditions may persist for prolonged periods in deep layers of radiation fog. It should be pointed out that the nocturnal inversion does not always break gradually, in the manner that results in the fumigation. It is likely that in some climates fumigation conditions occur almost daily, whereas in others they would occur only rarely.

For stack planning it is well to determine, if possible, the frequency, duration, and severity of fumigations as well as wind directions at

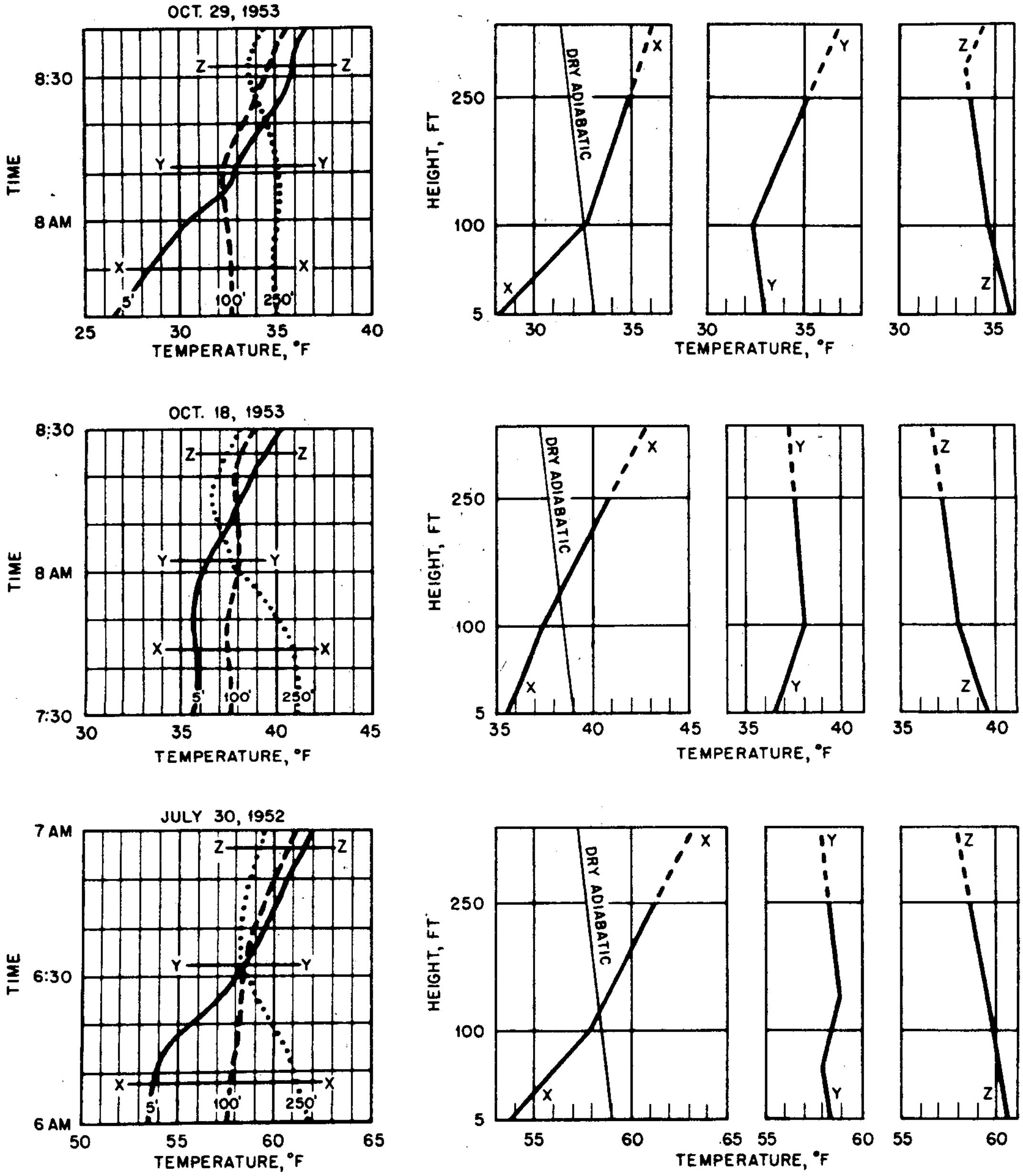


Fig. 5.2—Schematic illustration of inversion breaks. Top: type 1, probable fumigation; inversion breaks from ground upward. Middle: type 2, no fumigation; inversion breaks from top down. Bottom: type 3, fumigation doubtful; combination of types 1 and 2 or indeterminate. Temperature recorder traces are on left; corresponding vertical distributions are on right.

the time they may occur. This, of course, requires suitable instrumentation, the most important component of which is continuous measurement of temperature at two or more levels above the ground. An example of how the fumigation type of inversion break is identified at the NRTS[82] follows.

Temperature traces† at the time of "cross-over," or change from inversion to lapse, can

†Temperatures are recorded on a Brown Electronik strip chart recorder with multipoint markings. Note that this method would not be possible with a temperature difference recorder such as is used for some meteorological towers.

be used as an indication of the nature of the inversion break and hence as an indication of the likelihood that a fumigation will occur. The crossovers are separable into three types, examples of which are illustrated in Fig. 5.2, along with schematic drawings of three stages of the corresponding vertical temperature gradient configurations.

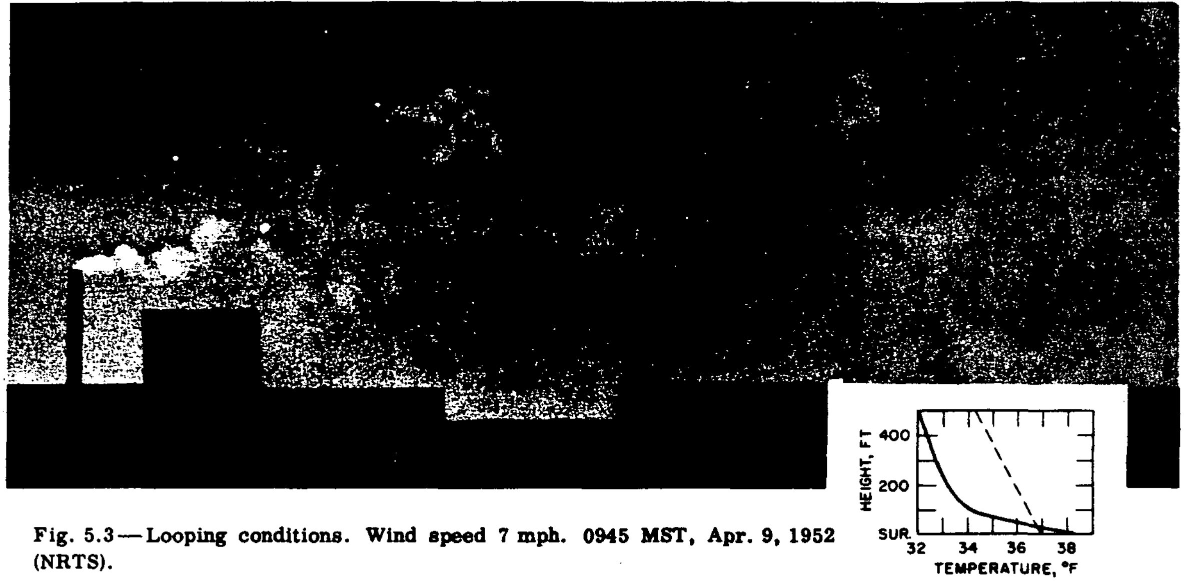


Fig. 5.3—Looping conditions. Wind speed 7 mph. 0945 MST, Apr. 9, 1952 (NRTS).

Note that the type 1 inversion break passes through a stage corresponding to the fumigation condition since the inversion dissipation begins at the ground and works upward. The type 2 break, on the other hand, goes through a stage corresponding to the lofting condition since the inversion apparently dissipates from the top downward. Type 3 is used to designate breaks that appear to be a combination of types 1 and 2 or a crossover that occurs so rapidly that it is not possible to determine whether the inversion dissipates from the ground upward or from the top downward. If a fumigation accompanies this type of break, it must be of very short duration.

Temperature measurements at more points in the vertical, particularly at a level above stack top, would serve better to indicate the nature of these inversion breaks.

The type 2 break needs further qualification. Apparently it is caused by wind shear. The colder, stable pool of air near the ground resists movement; thus a shear zone is introduced at the top of the inversion layer. The turbulent mixing in the shear zone destroys the inversion more or less gradually, depending on wind speed, as the shear zone works downward. A phenomenon similar to this was first remarked by Durst[42] (1933) and also has been observed by Gifford[56] (1952). Gifford associated the dissipation of the surface inversion with the lowering of an upper (turbulence or subsidence) inversion. Unfortunately, there are not sufficient data to resolve the question at the present time. At the NRTS, at least, this type of inversion break is associated with stronger winds and occurs most often after sunrise.

Photographs of each of the plume types are shown in Figs. 5.3 to 5.7, along with coincident temperature gradient data. These pictures were taken during smoke experiments by the Weather Bureau,[83] using the 250-ft chemical plant stack at the NRTS. The smoke was made by two Army M-2 smoke generators. Temperature gradient data were obtained from tethered balloon soundings and from instruments mounted on a 250-ft radio tower. The dashed line on the temperature gradient graphs represents the dry adiabatic lapse rate.

## 2. BROOKHAVEN WIND TRACE TYPES

A system for the classification of diffusion conditions used at Brookhaven is based on characteristics of wind direction fluctuations,

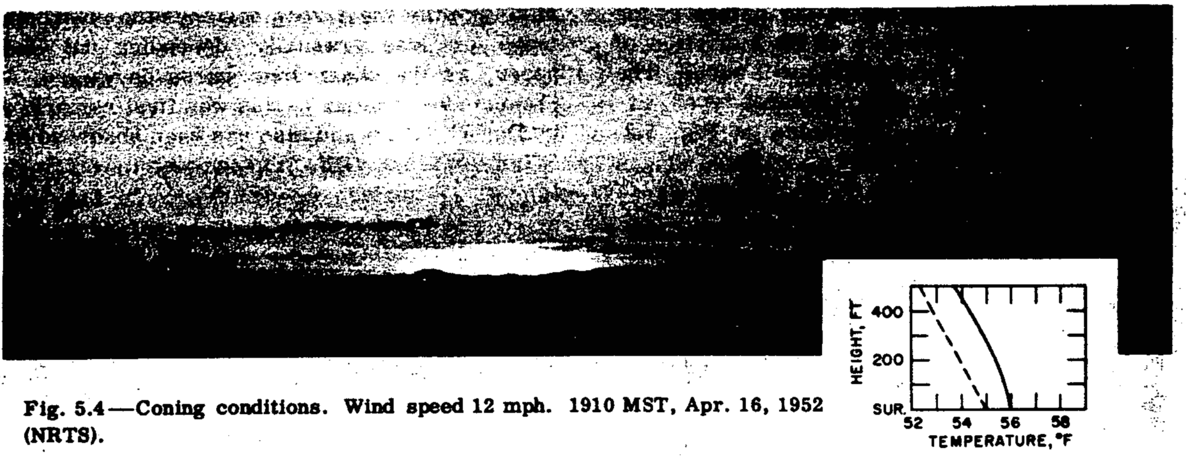


**Fig. 5.4**—Coning conditions. Wind speed 12 mph. 1910 MST, Apr. 16, 1952 (NRTS).

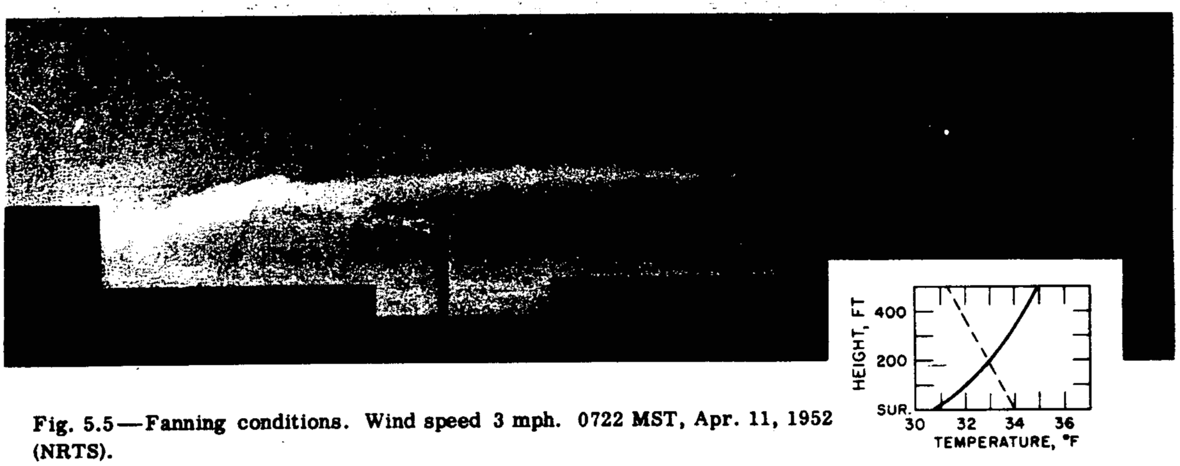


**Fig. 5.5**—Fanning conditions. Wind speed 3 mph. 0722 MST, Apr. 11, 1952 (NRTS).

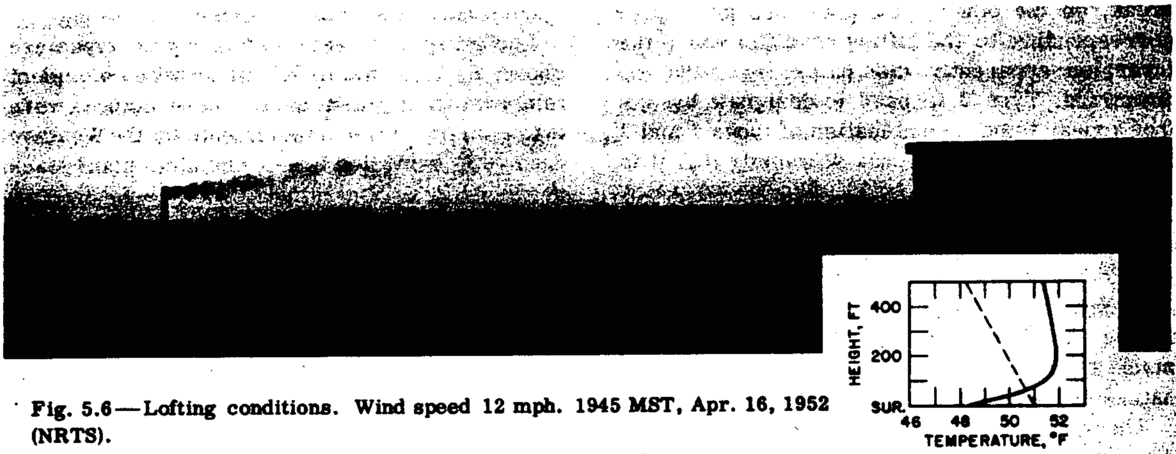


**Fig. 5.6**—Lofting conditions. Wind speed 12 mph. 1945 MST, Apr. 16, 1952 (NRTS).

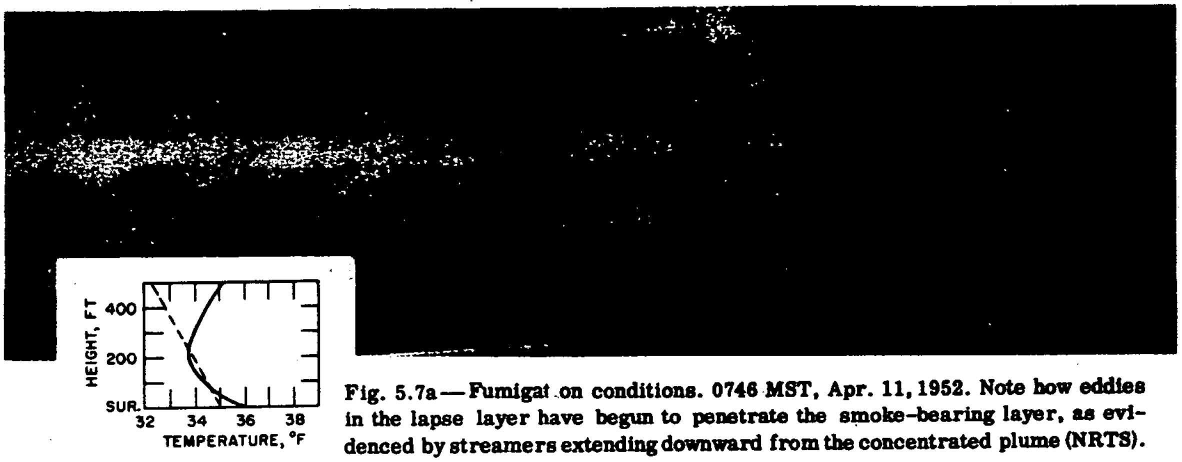


Fig. 5.7a—Fumigation conditions. 0746 MST, Apr. 11, 1952. Note how eddies in the lapse layer have begun to penetrate the smoke-bearing layer, as evidenced by streamers extending downward from the concentrated plume (NRTS).

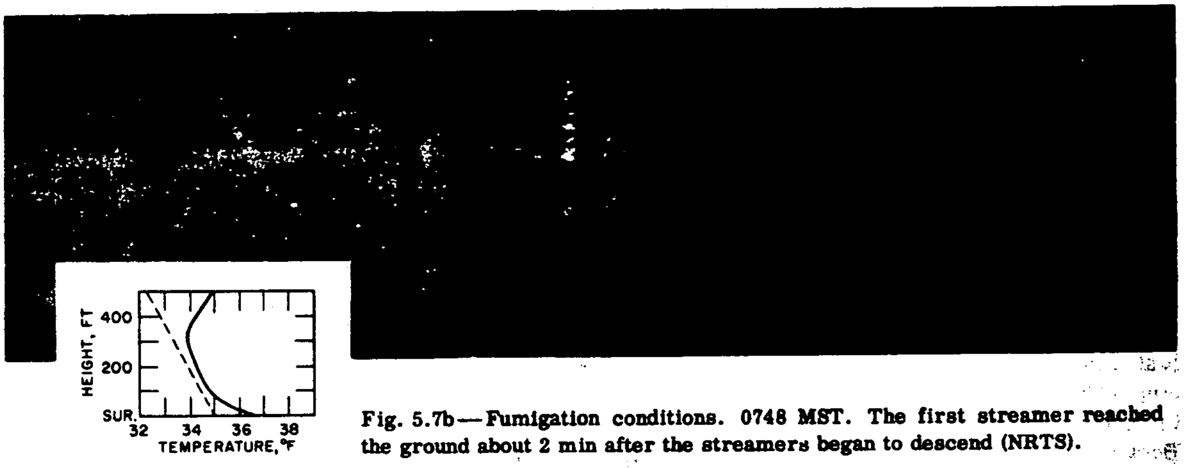


Fig. 5.7b—Fumigation conditions. 0748 MST. The first streamer reached the ground about 2 min after the streamers began to descend (NRTS).

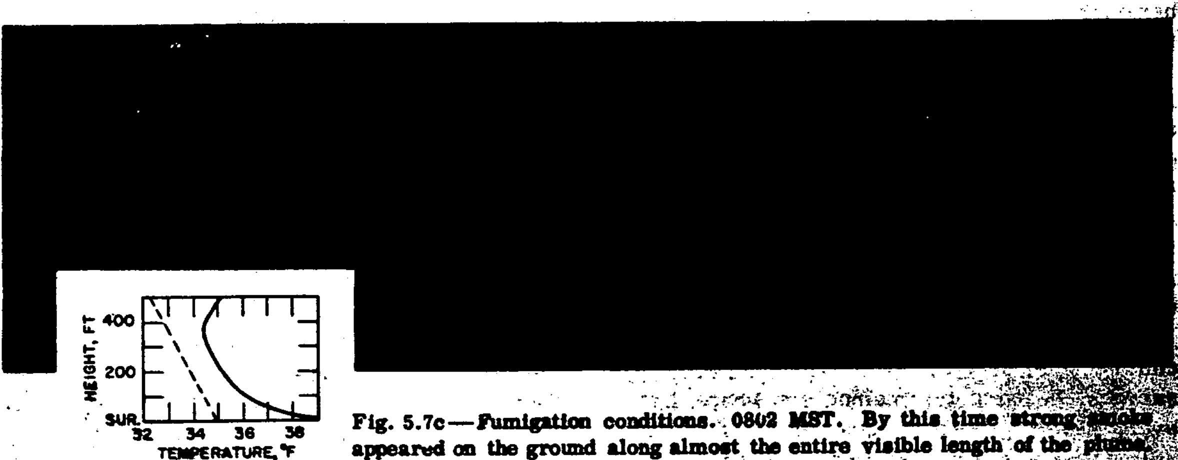


Fig. 5.7c—Fumigation conditions. 0802 MST. By this time strong smoke appeared on the ground along almost the entire visible length of the plume. Note that the concentrated smoke layer aloft visible in Figs. 5.7a and 5.7b has disappeared, and the entire plume appears to have been mixed downward (NRTS).

Table 5.1—Wind Direction Trace Classifications and Related Conditions (Smith)

| Type | Angular width of trace | Type of turbulence | Stability condition | Average stack-height wind, m/sec | Time of day | Season | Remarks |
|---|---|---|---|---|---|---|---|
| A | >90° | Largely thermal (convective) | Great instability | 1.8 | 0900–1500 only | Uncommon in winter | The stronger the lapse the greater the wind speed possible before trace becomes type B |
| $B_2$ | 45°–90° | Largely thermal | Great instability | 3.8 | 0900–1500 only | Mostly summer | Same as above |
| $B_1$ | 15°–45° | Thermal and mechanical | Moderate instability | 7.0 | 0600–1800 (occasionally night with steep lapse) | Any | Generally associated with brisk winds and moderate lapse |
| C | >15° | Mechanical | Moderate stability | 10.4 | Night (or day with heavy cloud cover) | Any | Typical trace under overcast skies and neutral lapse rate |
| D | 0°–15° | None | Great stability | 6.4 | Mostly night | Any | Typical inversion trace |

as traced by a continuous wind recording instrument whose vane is exposed at the 355-ft level. The five major wind trace types are illustrated in Fig. 5.8. According to Smith[132] and Singer[131] these traces are typical of certain turbulence regimes, as shown in Table 5.1. Because of the relations shown in Table 5.1, it may be surmised that certain patterns of smoke behavior also are associated with the trace types.

Figures 5.9 to 5.12 are pictures taken during smoke experiments at Brookhaven in 1949. For these experiments smoke from an Army M-1 generator was piped up to the 355-ft level on the Brookhaven tower. Note that in Figs. 5.9 and 5.10 the plumes are looping, and in Figs. 5.11 and 5.12 they are fanning. No pictures were made during type C wind trace conditions, but this would correspond to the coning type plume.

The "gustiness" classifications offer a simple and economical tool for diffusion climatology surveys. In using the method elsewhere, however, the following points should be remembered:

1. There are patterns of smoke behavior that cannot be detected by inspection of a wind direction trace (i.e., lofting and fumigation).
2. More than one pattern of effluent behavior may occur for a given "gustiness" type.
3. The traces may differ considerably with characteristically different terrain or climate, with different wind instruments, or with instruments exposed at different heights above ground. For example, type D rarely appears, with appreciable wind speeds, at elevations below about 50 to 100 ft.

## 3. NONMETEOROLOGICAL FACTORS

Some aspects of stack plume behavior may be traced to factors that are not meteorological, e.g., stack height, shape, diameter and draft, effluent temperature and density, and nearness of obstacles. When the effluent is ejected at high velocity and/or is buoyant with respect to its surroundings, it may be expected to rise some distance above the stack. If the effluent is dense or cold or contains particles larger than about 1 $\mu$, it may be expected to settle. Unless the effluent rises at least a short distance above the stack top, it will often "crawl" down the lee side of the stack. Nearby obstacles may cause an eddy which will result in "downwash" or a sweeping downward of the effluent plume. In this respect very short stacks or roof vents are particularly affected, and efflu-

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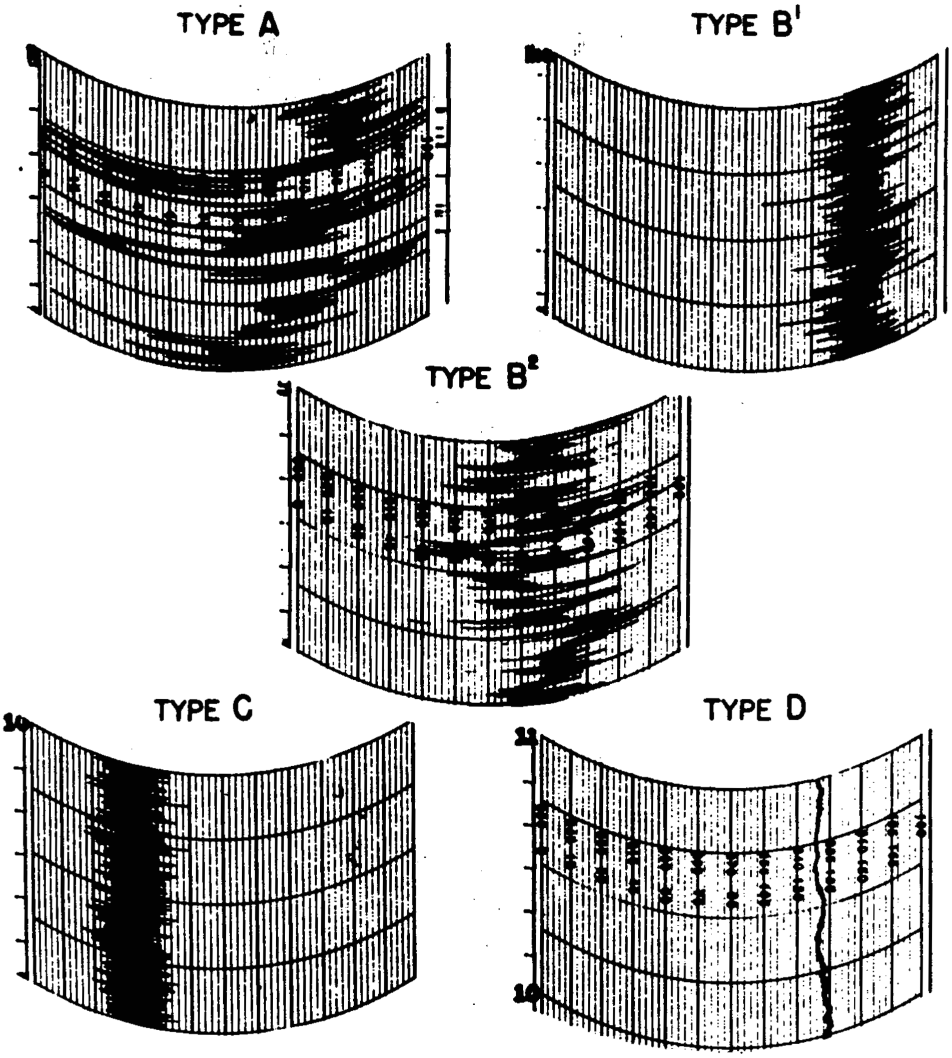

Fig. 5.8—Wind direction trace types (Singer and Smith).

ent from them must be diluted to a tolerable concentration level before it is ejected. In an installation of this type, where the vents extend only a few feet above the roof of a large building, smoke studies have shown that with wind velocities above 3 to 5 mph the effluent is spread across the roof and comes to the ground very close to the building itself. It spreads laterally along the leeward edge of the building in mechanically induced eddies. The whole leeward edge of the roof has been noted to become a line source of smoke in a neutral or slightly unstable atmosphere. A drawing of this type of behavior is shown in Fig. 5.13.

Several rules of thumb have evolved from wind tunnel studies and field investigations to allow for the various nonmeteorological effects on plume behavior. Sherlock and Stalker[130] have found that, while effluent temperature is not particularly important in preventing downwash due to eddies in the lee of isolated stacks, the downwash does not occur to any appreciable extent as long as the wind velocity does not exceed the stack draft velocity. In general, the turbulence generated by obstacles will not cause downwash if the stack is at least $2\frac{1}{2}$ times the height of any structure located within 20 stack lengths of the stack.

Fig. 5.9—Smoke behavior with wind trace type $B_1$ and strong winds. Thermal eddies are present, but the vertical motions are dwarfed by the rapid horizontal motion (BNL).

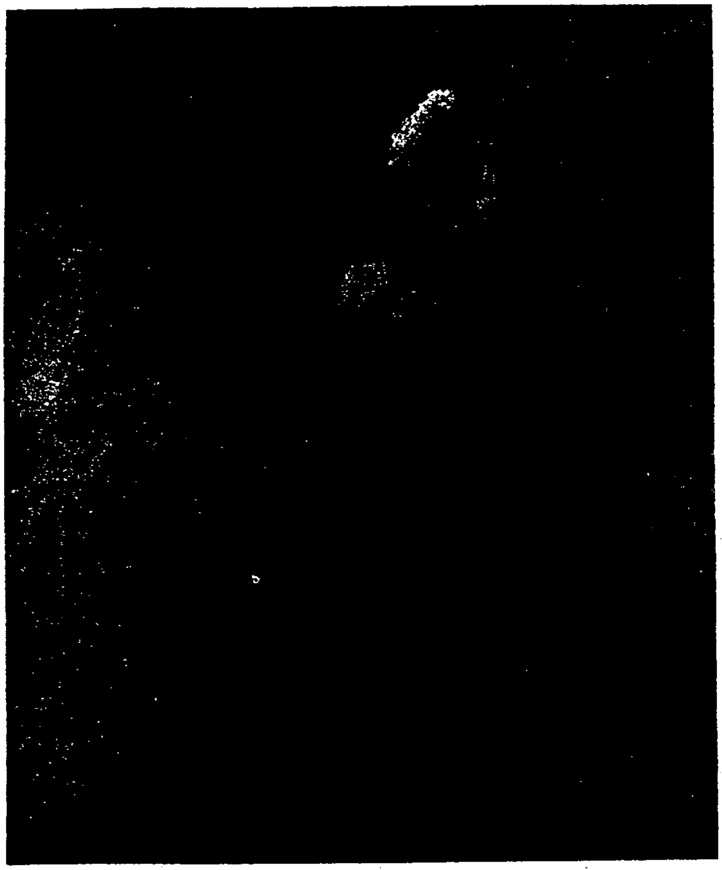

Fig. 5.10—Smoke behavior with wind trace type A (or $B_2$) and very light winds. Thermal eddies bring strong concentrations to the ground very near the stack (BNL).

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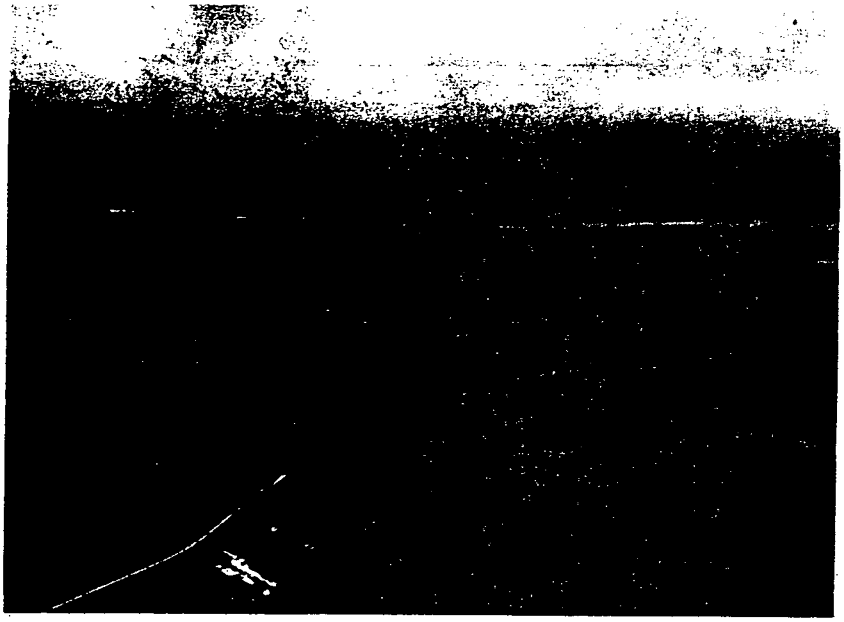

Fig. 5.11—Smoke behavior with wind trace type D. Note how the plume may travel long distances in a temperature inversion without appreciable dilution (BNL).

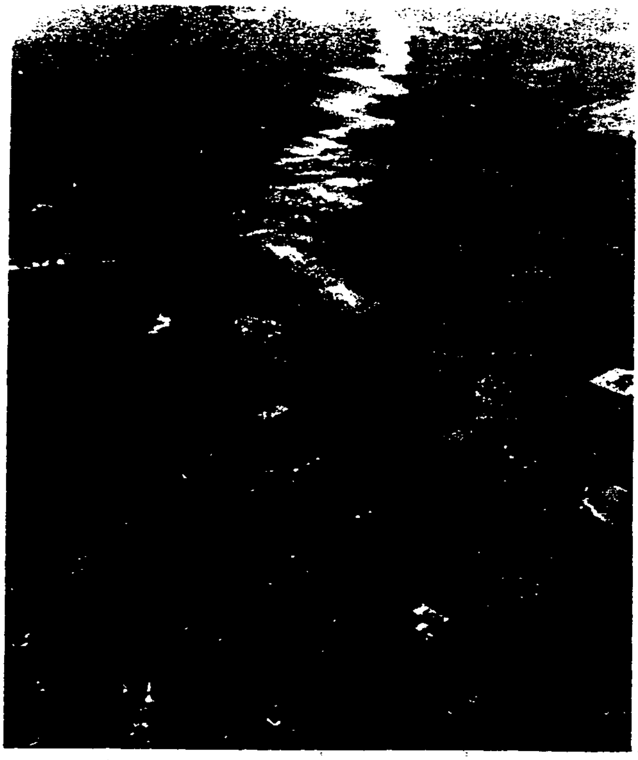

**Fig. 5.12—Smoke behavior in stable conditions. Note that the vertical spread of the plume is negligible but that meandering causes horizontal spreading (BNL).**

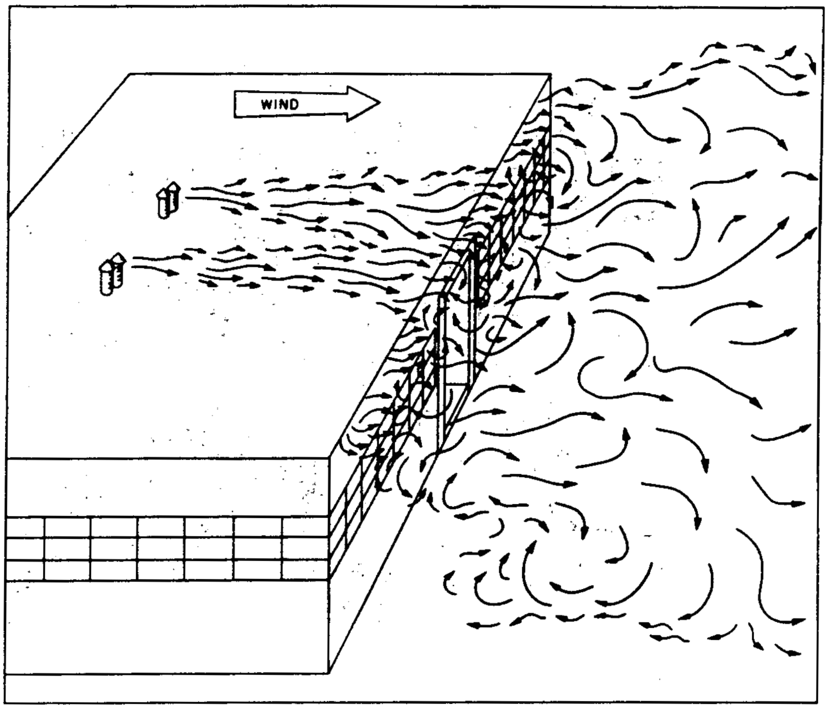

Fig. 5.13—Schematic representation of the effluent behavior near a building when released from short stacks in a light wind.

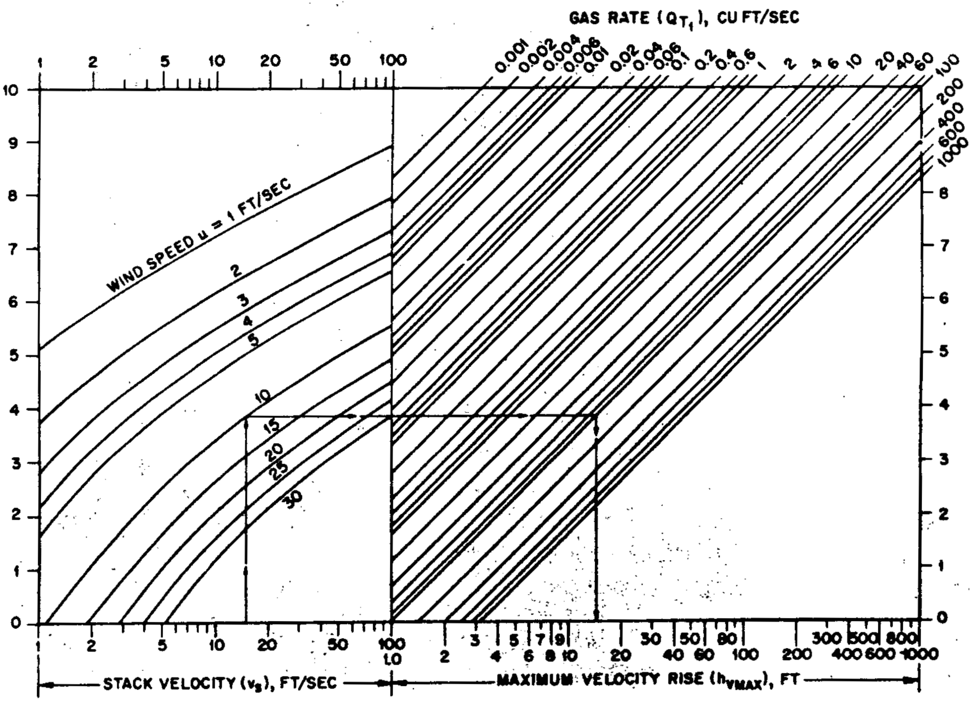

Fig. 5.14—Maximum velocity rise of plume, Bosanquet formula (Helmers).

## 4. EFFECTIVE STACK HEIGHT

The effective stack height is the stack height plus the height that the effluent plume initially rises above the stack owing to stack draft velocity and/or buoyancy of the effluent. The concept involves both meteorological and nonmeteorological parameters and is a very necessary consideration for stack design. Gains in effective stack height are desirable when they can be obtained practicably, and they must be considered in making estimates of ground concentrations by diffusion formulae.

Most investigations of the past have not had to deal with the effects of effluent temperature and velocity together; therefore little information is available on the combined effects. In a practical sense, additional stack height is not needed except when wind speeds are low, and it is then that the effect of excess temperature of the effluent is greatest. Sutton[141] finds from a theoretical treatment that the decrease in ground concentration due to heating varies inversely as the cube of the wind speed.

A rule of thumb frequently used to estimate effective stack height for low wind speeds is due to investigations by O'Gara and Fleming.[117] It states that each degree Fahrenheit of smoke temperature above ambient air is equivalent to 2½ ft of extra stack height.

The atomic energy industry encounters situations in which the effects of both temperature and velocity must be considered, and for this reason further investigations are necessary. When meteorological parameters, such as vertical temperature gradient and wind speed, are taken into consideration as well, the problem becomes quite complicated. For example, the effect of a temperature inversion is to suppress vertical motions; thus it might be expected to reduce the effective stack height. On the other hand, a hot effluent plume might be expected to rise higher if the stability of the air slows turbulent mixing of the plume with its environment since it would thus retain its buoyancy longer.

The only attempt to take all these parameters into account is that of Bosanquet et al.,[12] whose theoretical equation has received some confirmation at several industrial plants. Their model predicts that the effect of a temperature inversion will be to lower the effective stack height, but this part of the theory has not been tested. The maximum rise due to effluent velocity is

$$h_{v\,max} = \frac{4.77}{1 + 0.43\dfrac{u}{v_s}} \, \frac{\sqrt{Qv_s}}{u} \tag{5.1}$$

A graphical solution to this equation (Helmers[71]) is given in Fig. 5.14. The maximum rise due to temperature difference is

$$h_{t\,max} = 6.37g \, \frac{Q\Delta}{u^3 T_1} \, Z \tag{5.2}$$

where

$$Z = \ln J^2 + \frac{2}{J} - 2$$

$$J = \frac{u^2}{\sqrt{Qv_s}} \left( 0.43 \sqrt{\frac{T_1}{gG}} - 0.28 \, \frac{v_s}{g} \, \frac{T_1}{\Delta} \right) + 1$$

$g$ = acceleration due to gravity (ft/sec/sec)
$u$ = mean wind speed (ft/sec)
$v_s$ = stack draft velocity (ft/sec)
$Q$ = gas emission rate at temperature $T_0$ (ft$^3$/sec)
$T_0$ = effluent temperature (°C)
$T_1$ = ambient air temperature (°C)
$\Delta = T_0 - T_1$ (°C)
$J, Z$ = parameters for calculating thermal rise (Bosanquet[12])
$G$ = gradient of potential atmospheric temperature (°C/ft)

The maximum rise of the plume cannot always be used for the height of release in diffusion equations since the calculated rise may occur at a greater distance downwind from the source than the point for which the ground level concentration is being computed. However, the path of the plume can be computed, and the height of the plume at some distance from the stack that is set by the conditions of the problem can be used. The rise at a distance x downwind of the stack due to stack gas velocity is given by

$$h_{vx} = h_{v\,max} \left( 1 - 0.8 \, \frac{h_{v\,max}}{x} \right) \tag{5.3}$$

where $x > \sim 2\, h_{v\,max}$ and the path of the plume for thermal rise in an adiabatic atmosphere is given by the equations

$$h_{tx} = 6.37g \, \frac{Q\Delta}{u^3 T_1} \, Z \tag{5.4}$$

$$x = 3.57 \, \frac{\sqrt{Qv_s}}{u} \, X \tag{5.5}$$

where the relation between X and Z is shown in Fig. 5.15 (Helmers[71]).

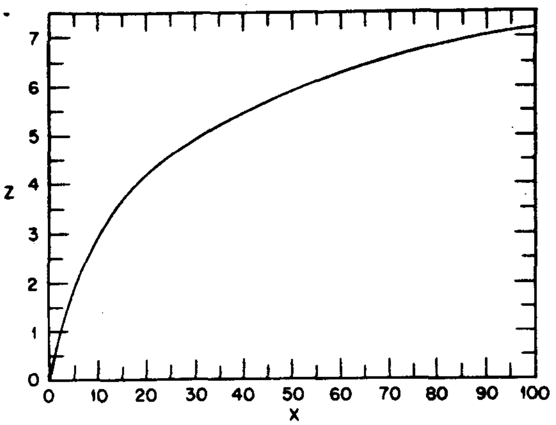

Fig. 5.15—Bosanquet thermal rise parameters for an adiabatic atmosphere (Helmers).

A simpler approach is afforded by an equation empirically derived by Davidson[33] from Bryant's[17] wind tunnel experiments. It does not consider the effect of the vertical gradient of air temperature, but this does not eliminate it in favor of the Bosanquet formula since the effect of air stability on effective stack height is not definitely known for all conditions. The Bryant-Davidson expression is

$$\Delta h = d\left(\frac{v_s}{u}\right)^{1.4}\left(1 + \frac{\Delta T}{T_s}\right) \qquad (5.6)$$

where d is stack diameter, $\Delta h$ is the rise of the plume above the stack, and $\Delta T$ and $T_s$ are the excess and absolute temperature of the stack gas in similar units. Equation 5.6 is graphed in Fig. 5.16 for a wide variety of conditions. In developing the formula, the rise of the plume was taken a short distance from the stack at a point where the plume became almost horizontal and not the maximum height attained by the plume. Thus the value of the rise computed by Eq. 5.6 can be added to the stack height for substitution in diffusion equations. As might be expected, this formula gives somewhat lower effective stack heights than those given by the Bosanquet formula.

Holland[81] found from a study of plumes from three stacks 160, 180, and 200 ft tall that the Bosanquet formula gave estimates that were too high and that the Bryant-Davidson formula gave estimates that, while conservative, fitted the data for some of the lower plume rises that were observed. He found also that plume rises in general were slightly less when a temperature inversion was present. Holland's first approximation formula for his data, based on average conditions, is

$$\Delta h = \frac{1.5 v_s d + 3 \times 10^{-4} Q_H}{u} \qquad (5.7)$$

where u and $v_s$ are in miles per hour and $Q_H$ is in calories per second. This formula might be expected to give more accurate estimates within the range of conditions encountered by Holland; these conditions are given in Table 5.2.

Table 5.2—Stack, Effluent, and Meteorological Parameters for Effective Stack Height Investigation by Holland

| | X-10 pile | X-10 steam plant | Watts Bar steam plant |
|---|---|---|---|
| Stack height, ft | 200 | 180 | 160 |
| Stack orifice diameter, ft | $5\frac{3}{4}$ | 9 | 14 |
| Exit velocity, mph | 45 | 5 | 34 |
| Exit temperature, °F | 180 | 400 | 350 |
| Volume emission rate, cu ft/min | 110,000 | 27,200 | 300,000 |
| Heat emission rate, cal/sec | 830,000 | 710,000 | 6,600,000 |
| Wind speeds:* | | | |
| 1-6 mph | 4 | 19 | 69 |
| 7-15 mph | 4 | 14 | 24 |
| 16-21 mph | 3 | | |
| Temperature lapse* | 10 | 18 | 42 |
| Temperature inversion* | | 16 | 51 |

* Number of observations.

## 5. STACK DRAFT COMPUTATIONS

In engineering terminology the stack draft often is expressed in pounds per second since this quantity is invariable for different atmospheric pressures and effluent densities. The effluent velocity ($v_s$) varies considerably with such values, however, for any fixed discharge

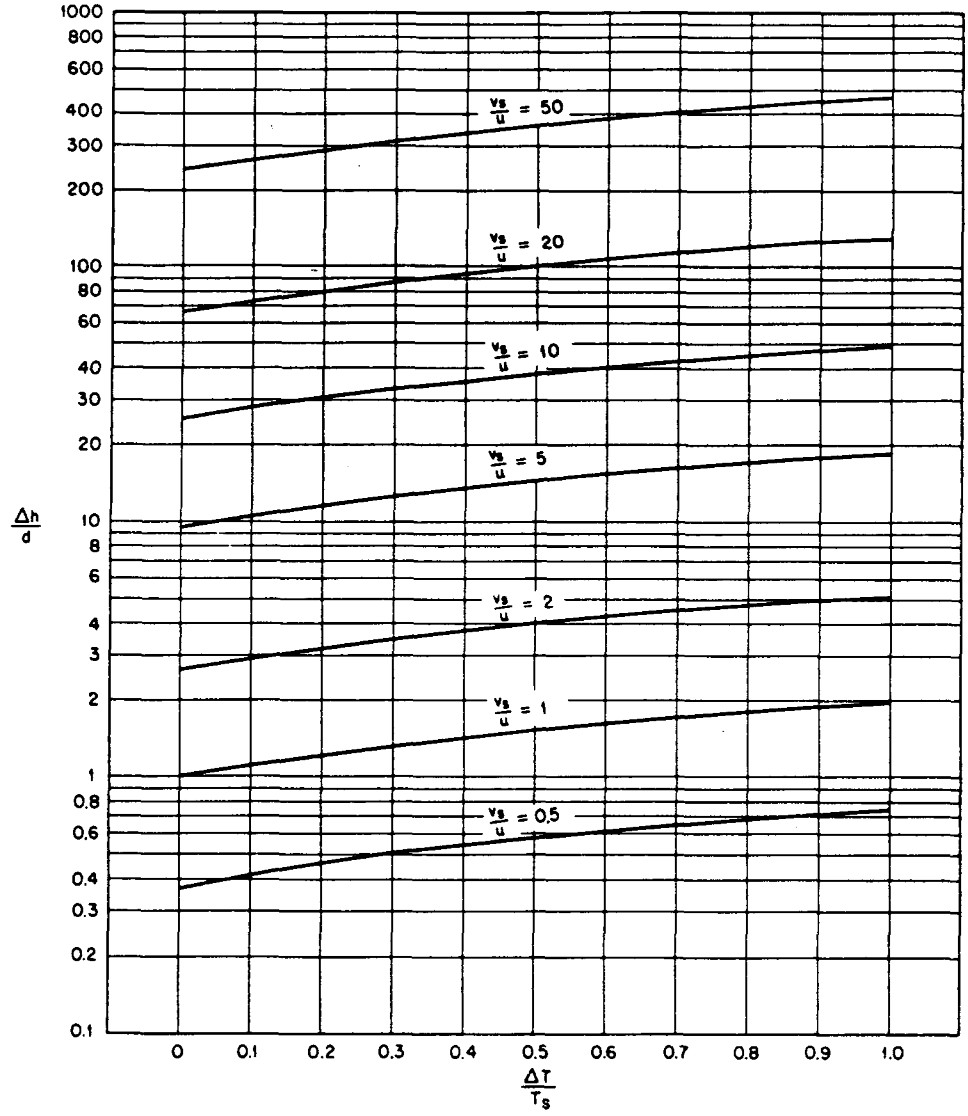

Fig. 5.16—Height that plume rises above stack for various stack diameters, effluent and wind speeds, and temperatures. $\Delta h/d = (v_s/u)^{1.4}[1 + (\Delta T/T_s)]$ (Bryant and Davidson).

rate and stack diameter. Assuming a specific volume (reciprocal of density) of 12.4 cu ft/lb of air at 30 in. Hg (approximately sea level) and 32°F, it can be shown that

$$v_s = \frac{0.962 D T_s}{d^2 P} \approx \frac{D T_s}{d^2 P} \tag{5.8}$$

where D is the discharge rate in pounds per second and P is atmospheric pressure in inches of mercury. This expression is valid when the effluent is mostly (ventilating or cooling) air, as in the case of most atomic energy plants. Figure 5.17 is a graph of Eq. 5.8 that can be used to determine the effluent velocity.

When stack emission is known in terms of cubic feet per minute, stack exit velocity can be computed by

$$v_s = \frac{6.09 \times 10^{-4} \times (\text{cu ft/min})}{d^2} \tag{5.9}$$

where $v_s$ is in meters/sec and d is in meters.

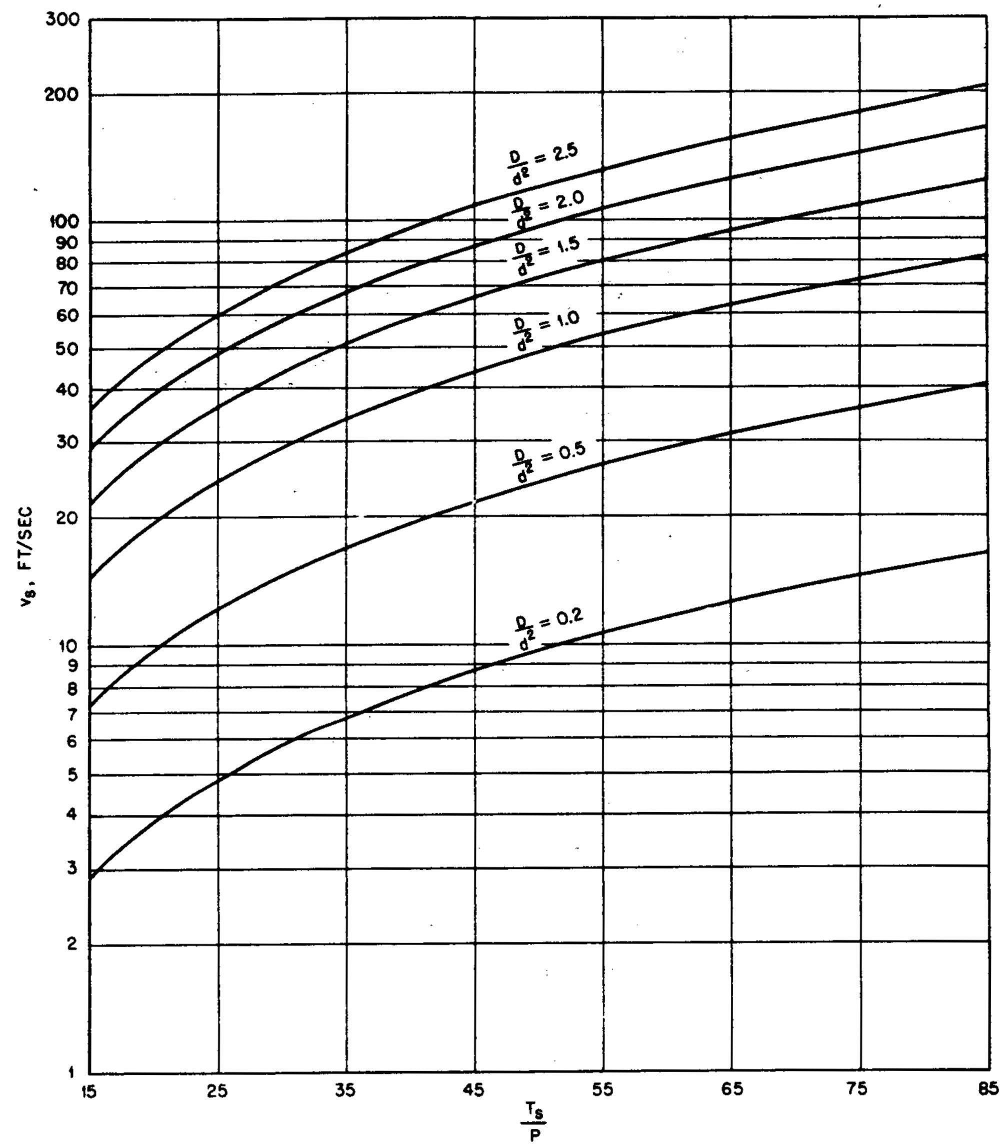

Fig. 5.17—Stack draft velocity for various stack diameters, effluent and wind speeds, and temperatures. $v_s = 0.962DT_s/d^2P$.

## 6. CHOOSING THE PROPER STACK

An example of a possible use of Figs. 5.16 and 5.17 is given below. Other uses will occur to the reader.

It is determined that an effective stack height of 300 ft is needed to maintain tolerable ground concentrations in the environs of a plant near sea level that will discharge 200 lb/sec of effluent at a temperature of 500°F (960° Rankine). The smallest feasible stack diameter† is 10 ft, as determined by limitations of the exhaust fans. During times of plant operation it is expected that the average ambient temperature will be 50°F, average pressure 30 in. Hg, and aver-

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† Substitution of Eq. 5.8 into Eq. 5.6 shows $\Delta h$ to vary inversely as $d^{1.8}$; thus the smallest feasible stack diameter is desirable from the standpoint of effective stack height.

age wind speed 8 mph (about 12 ft/sec). What height stack is required to obtain the necessary effective stack height?

*Solution:* On Fig. 5.17 $T_s/P = 960/30$ intersects $D/d^2 = 200/100 = 2$ at a point where $v_s = 62$ ft/sec. On Fig. 5.16 $\Delta T/T_s = 450/960 = 0.47$ intersects $v_s/u = 62/12 \approx 5$ at a point where $\Delta h/d = 14$. Multiplying by $d = 10$ gives $\Delta h = 140$ ft. The required stack height then is 160 ft.

It should be noted here that a frequency tabulation of inversion heights may show that a large number of inversion conditions may be avoided by choosing a sufficient stack height. At certain locations extension of the stack height might avoid 80 to 90% of the inversions. Only a thorough study of the local lapse rate could verify this.

## 7. DILUTION WITHIN THE STACK

As stated earlier, where exposure to effluent can occur before it has a chance to diffuse appreciably (such as may occur with short stacks or vents), it is common practice to mix sufficient air with the effluent to dilute it to a tolerable concentration prior to release. For tall stacks, however, additional factors must be considered. First of all, the "natural" dilution from tall stacks is so great that, as far as ground concentrations are concerned, the addition of air into the stack for dilution purposes is hardly worth while.

Dilution in the stack is beneficial in instances when the increased draft velocity thus obtainable serves to increase the effective stack height. This would be true if the diluting air and effluent were of about the same temperature or if hot air were being mixed with the effluent to increase its buoyancy. Stack dilution may be actually detrimental where air of ambient temperature is added to hot stack gases since plume buoyancy is sacrificed.

A note of caution must be interjected before leaving the subject of stack gases. The various formulae for plume rise and the methods of estimating plume behavior from meteorological observations are not exact, although they are reasonably good approximations. In particular, these approaches will more nearly represent mean, not instantaneous, conditions; hence short period spot observations may show considerable variation from predicted behavior.

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# 6

# Behavior of Explosion Debris Clouds

In the normal course of events the behavior of debris clouds created by explosions will be of little concern to the atomic energy industry. However, two situations, one of them actual and one postulated, exist where the rise and spread of explosion clouds can affect site operations.

The actual occurrence would, of course, be the detonation of nuclear weapons and the resultant release and transport of radioactive debris across the various atomic energy installations. Although the activity of the diffusing cloud is not of biological concern, it may still be sufficiently above background to play havoc with the normal readings of sensitive monitoring instruments. If it were not known that these anomalous readings resulted from explosion debris, considerable time and expense might be required for on-site testing and tracing. Fortunately it is usually possible, with the use of meteorological data and forecasts, to predict when individual sites will be affected by nuclear weapon debris effects. Later in this section the formation, rise, and diffusion of weapon clouds will be discussed. The explosion of an atomic reactor is the postulated situation. It is common practice in reactor hazard analysis to assume a combination of circumstances which might result in a nuclear incident with a release of material to the atmosphere. It is not within the scope of this report to examine the manifold plausibilities that might lead to an explosion or the possible methods of release (vaporization and violent explosion, slow melting and gradual leakage, etc.) of gaseous and/or particulates from such an occurrence. However, if the formation of a cloud is assumed and some idea of its energy content is obtainable, estimates of the cloud behavior in the atmosphere can be made.

## 1. NUCLEAR WEAPON CLOUDS

When an atomic weapon is detonated, the airborne radioactivity in the cloud will consist of the fission products due to the fast neutron fission of the uranium or plutonium, the remaining uranium or plutonium which does not fission, vaporized metals or other materials which have been subjected to a high neutron flux during the detonation, and usually significant amounts of dust which also has induced activity. Most of the tremendous amounts of energy of atomic explosive devices is evolved in the form of heat, although some is emitted in the form of gamma rays and in the neutrons (which are expelled within a short time) and some remains in the radioactive energy of the fission products.

The initial release of energy results in the formation of an intensely hot fireball which produces the thermal radiation and shock wave that are responsible for the great damage caused by the weapon. For convenience in discussing the debris clouds, it is possible to divide the detonation of nuclear weapons into three classes:

1. Air bursts (fireball does not intersect the surface).
2. Surface burst (fireball intersects the surface).
3. Subsurface burst (underwater or underground).

In an air burst, the fission products are of the most concern. Table 6.1 gives the total gamma activity[63] of these products from the detonation of a nominal bomb (20,000 tons of TNT equivalent, $2 \times 10^{13}$ calories, or fission of 1 kg of $U^{235}$).

After an air burst the solid material in the cloud consists of the remains of the bomb casing and auxiliary equipment, which are vaporized by the explosion and are condensed by cooling. Only relatively small amounts of soil or other surface material are sucked up into the atomic cloud by the violent updrafts created by the explosion.

However, for a surface burst the intersection of the fireball with the ground not only serves to induce activity on a large mass of soil but also to eject the order of tons of debris from the earth into the atomic cloud, as the result of the intense thermal radiation which penetrates into the soil. Another consequence of the injection of large amounts of soil into the fireball is that the soil particles serve as condensation surfaces for vaporized material so that the resulting radioactive particles are much larger than is the case with air bursts.

Table 6.1 — Total Gamma Activity of Fission Products

| Elapsed time since detonation | Activity, curies |
|---|---|
| 1 min | $8.2 \times 10^{11}$ |
| 1 hr | $6.0 \times 10^{9}$ |
| 1 day | $1.3 \times 10^{8}$ |
| 1 week | $1.3 \times 10^{7}$ |
| 1 month | $2.3 \times 10^{6}$ |

Subsurface bursts throw large amounts of soil or water into the atmosphere, much of which is radioactive. However, the resulting cloud is not carried nearly as high into the atmosphere as that from a surface or air burst.

## 2. INITIAL STAGES OF CLOUD DEVELOPMENT

About 1 sec after detonation the fireball from an air or surface burst attains its maximum diameter, and after a short period of "hovering" the buoyant bubble of intensely heated gases begins to accelerate upward, attaining a maximum upward velocity of about 300 ft/sec within a few seconds. The ascent continues until the gases cool, by radiation, entrainment of ambient air, and adiabatic expansion, to the temperature of the environment.[101,140]

During its ascent the cloud evolves into the familiar mushroom shape. The mushroom top consists initially of a vigorous toroidal circulation which gradually decreases as the cloud rises and, for a nominal bomb, has a thickness of about 10,000 ft after the cloud stabilizes. This normally occurs when the cloud enters the base of the stratosphere, about 30,000 to 40,000 ft in temperate latitudes. but may occur at some lower level if less initial energy is available.

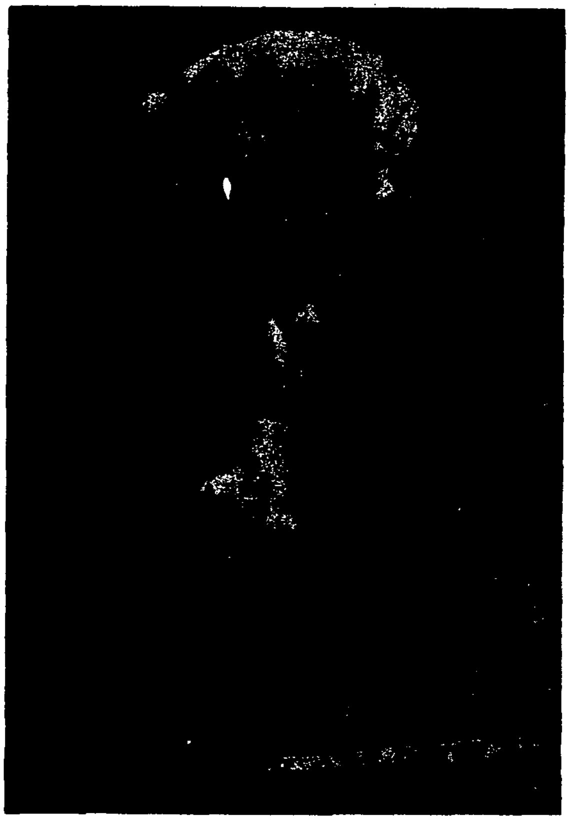

Fig. 6.1 — Cloud from a typical atomic burst near stabilization, Nevada Proving Grounds, Apr. 22, 1952.

The time from detonation to stabilization is of the order of 5 to 15 min.

The character of the trailing portion of the cloud, the stem of the mushroom, is dependent on the type of burst. For a high air burst the stem is practically nonexistent since almost no surface material is brought into the cloud. The visible part of the stem in this case is principally composed of a water cloud which forms in the wake of the ascending bubble, although significant radioactivity is also present. For lower air bursts the shock wave and thermal heating tend to dislodge more soil to be carried in the updrafts. Figure 6.1 shows a typical air burst cloud near stabilization. Note the evidence of the toroidal ring in the mushroom, as shown by the lesser density of the central portion of the cloud. The detachment of the tenuous stem from the top is also typical of air bursts. The lower dust cloud extends to only about one-third the height of the stem; the remainder of the visible portion is principally a water cloud. A surface or tower burst, on the other hand, would have a continuous dark column of falling dirt and debris reaching from the ground to the mushroom top.

The configuration of the mushroom and stem is dependent upon meteorological parameters. Stable layers not sufficient to stop the ascent may result in a more rapid deceleration and broadening of particular parts of the cloud, and, more important, wind shears act to tear apart and in some cases actually detach certain portions of the cloud.

## 3. INTERMEDIATE STAGES OF CLOUD HISTORY

After stabilization the subsequent configuration of the cloud is determined principally by the nature of the wind field which moves and diffuses it and by the size distribution and rate of fall of the particles. In the event precipitation was occurring, large amounts of activity would be scoured from the air by the scavenging action of the precipitation elements.

The action of the winds is to transport the cloud approximately horizontally with the speed and direction of the prevailing wind at each level. Since in the atmosphere wind direction and speed vary from level to level, the resulting wind shears tend to elongate the cloud greatly and often to break it up into several separate segments. Superimposed on the primary movement of the cloud are the small-scale movements due to turbulent eddies that are too small to be measured by conventional techniques. Such eddies serve to diffuse the cloud segments both horizontally and vertically and cause an apparent increase in diameter of the initial column. For the first 4 to 8 hr following detonation, the horizontal rate of growth of the cloud at any one level appears to be about 3 mph. This horizontal growth, coupled with vertical, wind shear, and fall-out, results in a rapid deformation of the original cloud configuration.

The deposition of activity in the immediate vicinity of the burst is largely dependent on the particle size distribution in the cloud. For an air burst, since the ball of fire does not intersect the earth, relatively little extraneous material is sucked into the cloud and the resulting radioactive particles are small, with negligible rates of fall. At Nagasaki, a high air burst, only about 0.02% of the fission products were left on the ground within a radius of some 2000 ft of Ground Zero, and even a few minutes after the explosion, the area did not present a radiation hazard. At Alamogordo, where the detonation was from a tower, dangerous contamination existed for many hours after the burst.

At slightly greater distances (up to approximately 200 miles), the amount of fall-out also depends primarily on particle size, and the location of the fall-out is a function of the wind field through which the particles fall. (A discussion of the fall velocities of the particles will be given later.)

Some idea of the probable location of close-in fall-out from a burst can be obtained by constructing a "fall-out diagram," which graphically integrates the effect of the wind field on the falling particle. A simple fall-out plot can be constructed as follows (see Fig. 6.2):

1. Obtain the upper wind observation or prognosis most representative of conditions at burst time (the complete wind observation is desirable; however, if necessary, the conventional coded PIBAL message can be used).
2. Find the mean wind direction and speed in each 5000-ft layer from the surface to the top of the atomic cloud.
3. Locate the site of the burst on an appropriate map (1 in. = 10 miles is a convenient scale) and label this point O (a transparent overlay may be used).
4. From O, lay off a vector corresponding to a 1-hr movement of the mean wind in the lowest 5000-ft layer. (Since it is often convenient to use layers beginning at multiples of 5000 ft above sea level, the lowest layer may be less than 5000 ft thick. In that event, lay off the appropriate fraction of 1-hr movement, e.g., if the lowest layer is 2000 ft thick, lay off a vector corresponding to two-fifths of the 1-hr movement.) Label the endpoint of this vector A.
5. From A, lay off a vector corresponding to the 1-hr movement of the mean wind in the next higher layer; label the endpoint B. Repeat this process for each succeeding 5000-ft layer to the top of the cloud (or the base of the stratosphere if the cloud height is unknown).
6. Draw lines from O extending through points A, B, C, etc. In Fig. 6.2 the vector OF indicates the direction of the resultant wind acting on a

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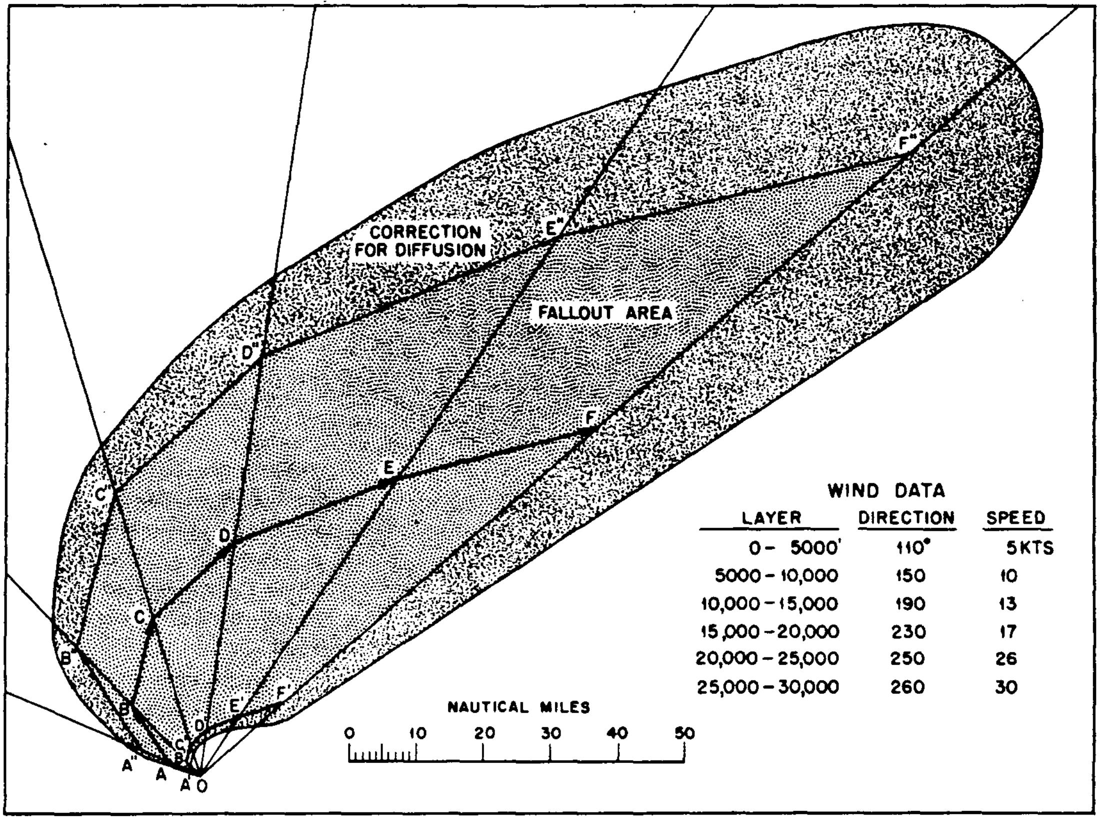

WIND DATA

| LAYER | DIRECTION | SPEED |
|---|---|---|
| 0 - 5000' | 110° | 5KTS |
| 5000 - 10,000 | 150 | 10 |
| 10,000 - 15,000 | 190 | 13 |
| 15,000 - 20,000 | 230 | 17 |
| 20,000 - 25,000 | 250 | 26 |
| 25,000 - 30,000 | 260 | 30 |

Fig. 6.2 — Example of a fall-out plot.

particle which fell at a constant speed from 30,000 ft to the surface. The point F is the surface position of a particle which fell at the rate of 5,000 ft/hr from 30,000 ft. Similarly, the line OAB...F represents the locus of all particles which fell at this rate from various parts of the cloud. The locus of particles which fell at any other rate can be found by taking appropriate fractions or multipliers of the vectors OA, OB, OC, etc. (e.g., the locus of particles which fell at the rate of 10,000 ft/hr can be found by connecting the midpoints of OA, OB, OC, etc.; all particles which fell at rates between 5,000 and 10,000 ft/hr would be between this line and line OABC...F).

7. Determine the particle size range to be considered (a typical density for atomic debris is about 3), and from the right-hand scale of Fig. 6.3 find the proportion of each vector OA, OB, etc., corresponding to the smallest and largest particles considered (50μ and 150μ in the example shown). Lay off this fraction or multiple along each of the vectors and connect points for the largest, OA'B'C', and smallest, OA"B"C", particles. The area enclosed represents the computed fall-out area, uncorrected for diffusion.

8. To make an approximate correction for small-scale diffusion, displace points A'B'C', and A"B"C", so as to make for the maximum increase in the fall-out area, about 1 mile for each 7 miles distance from the burst site.

The fall-out diagram can also be used to indicate where fall-out is likely to occur at specified times following the burst. Each of the lines OA, OB, OC, etc., can be marked off in the number of hours necessary for particles to reach the ground. For example, in Fig. 6.2, particles which fell in 6 hr from 30,000 ft would be at F, particles which fell in 1 hr would be on the line OF at one-sixth of the distance to F, those in 2 hr at two-sixths the distance, etc. Similarly the point E represents the location of particles which fell in 5 hr from 25,000 ft, and one-fifth the distance represents 1 hr of fall. Each of the lines OA, OB, OF, etc., can be treated similarly, and isochrones of fall-out time after burst can be constructed.

Although any fall-out diagram can serve only as a rough guide to where fall-out will occur, it is possible to modify the diagram to take advantage of any additional information which may be available. If the winds are changing with time, a second diagram can be drawn for conditions (observed or forecast) about 6 hr later and the fall-out pattern can be interpolated. If most of the debris is concentrated in the mushroom, greater activity should be expected in the area bounded by the appropriate vectors. For example, in Fig. 6.2, if the activity were confined to the layer from 20,000 to 30,000 ft, then fall-out would be expected in the area bounded by D'DD" and F'F" (plus the appropriate diffusion corrections). Another consequence of the concentration of activity in the upper part of the cloud is the persistence of relatively high activity out to some distance from the burst site, corresponding to fall-out from the mushroom. Such occurrences have been observed following several of the Nevada tests.

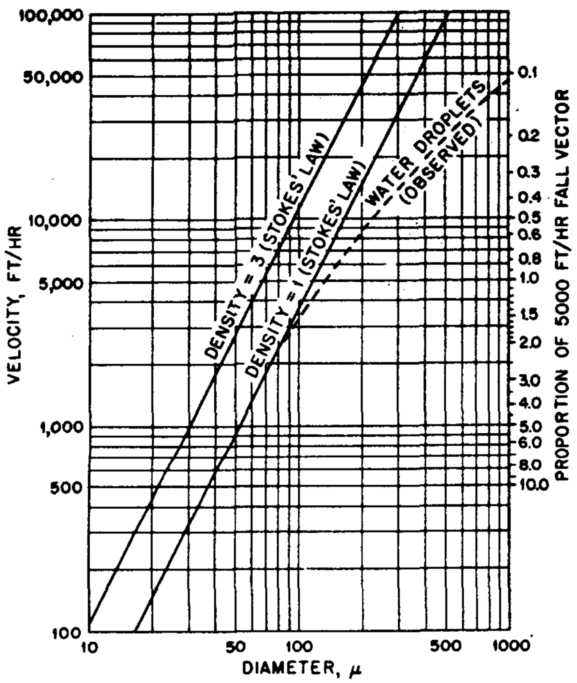

Fig. 6.3—Fall velocity as a function of particle size and density (Stokes' law) (USWB).

If precipitation is occurring at the time of detonation, it may be assumed that a large portion of the activity will be scavenged by the falling precipitation elements. If the drop size of falling rain or drizzle can be ascertained, the area most likely to be affected by fall-out can be computed from the fall-out diagram. In this case the fall velocities appropriate to the droplets should be used, as determined from the dashed curve[68] in Fig. 6.3. As a rough guide, the average diameter of drizzle droplets is 100 to 400 μ, and rain droplets range upward from 400 μ.

## 4. LONG-RANGE CLOUD TRAVEL

As the cloud of atomic debris is carried far away from the burst site, gravitational settling becomes of lesser importance since only the smaller particles remain and these can be considered to be in virtual colloidal suspension in the atmosphere; i.e., the small-scale eddy motions completely dominate the gravitational settling.

The movement of the cloud is governed by the wind field. At any level the trajectory of the primary cloud, that portion of the initial cloud which moves approximately horizontally and is practically unaffected by diffusion or fall-out, can be computed by conventional meteorological techniques from the upper air wind and pressure data. (Examples of computed trajectories are shown in Fig. 3.1.)

The most practical technique for computing trajectories is to assume that the flow pattern shown on any map remains unchanged for a period equal to the interval between maps and centered at map time. In general, it is better to use the actual reported wind data in preference to computing the wind from the pressure field. If it becomes necessary to use the pressure field, then the simple geostrophic approximation† is preferable to more complex techniques since it is difficult to evaluate all the nongeostrophic accelerations.

In the United States, with its relatively dense network of upper-air stations, the average error in the after-the-fact trajectory computations is found to be about 20% of the total length of the trajectory.

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† Obtained from a weather map by means of a convenient transparent scale that is used to estimate wind speeds from isobar spacing.

In addition to the movement of the primary cloud, it is evident that the ever-present turbulent elements of the atmosphere will diffuse the debris both horizontally and vertically at a rate many orders of magnitude greater than ordinary molecular diffusion. The extent of the diffusion depends not only on the characteristics of the turbulent eddies of the atmosphere but also on the time and space scale under consideration.

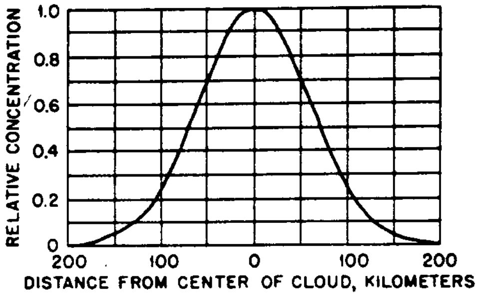

Fig. 6.4—Lateral distribution of debris after two days, assuming an effective diffusion coefficient of $10^8$ cm$^2$/sec.

As the cloud grows, larger and larger eddies become diffusing elements; thus the rate of growth increases.

Horizontal and vertical wind shears coupled with fall-out and diffusion result in a very rapid spreading of the cloud, both in width and, even more markedly, in length. After a few days of cloud growth, the ordinary cyclones and anticyclones of the synoptic map may act as diffusing elements.

At about two days following the burst, it is estimated that a Fickian diffusion coefficient of roughly $10^8$ cm$^2$/sec will serve to describe the spread of debris which is observed at any one level in the atmosphere under average conditions. This spread is due to the combination of several processes and can only be approximated by any simple diffusion laws. Figure 6.4 shows the lateral distribution of debris which might be expected at a given level after two days.

4.1 *Large-scale Effects.* Shear is one of the important factors that reduces ground concentrations of atomic debris at distances hundreds or thousands of miles from the explosion. If, for example, the significant debris from an explosion were initially confined to a cylindrical column 1 mile in diameter and 5000 ft high and if the vector difference in the wind at the top and bottom of the layer were 20 mph, then the projection of the debris on the earth's surface would be 100 miles long after 5 hr. Thus, neglecting diffusion, the concentration of debris that might be scavenged by rain would be only about 1% of that which would be scavenged if the entire column moved along the same path, i.e., if the cloud remained vertical. Meteorological trajectories have indicated that after 24 hr the mushroom tops of atomic clouds have generally been spread out over distances of much more than 100 miles.

4.2 *Small-scale Effects.* Even in the event of a low-power explosion which might leave a contaminant only in the lowest 100 or 500 ft, the shear in such a layer would be important in determining the deposition pattern of the radioactive material. Sometimes large shears are found in the lowest few hundred feet of the atmosphere, especially with thermal stability; whereas at other times there is relatively little shear through such a layer, particularly when there is thermal instability or mechanical mixing induced by strong winds.

## 5. REACTOR DISASTER CLOUDS

For simplicity it would be desirable to deal with debris clouds, puffs, or other instantaneously generated contamination sources in the same manner that was used for stack plumes, but there are several reasons why this is not possible. There are no photographs or observations of such clouds made during various meteorological conditions; in fact no "reactor disaster" clouds have ever occurred. It is tempting to draw conclusions about reactor explosions from experience with atomic weapons. However, the results can hardly be expected to apply to the relatively low-order explosion of a reactor. Chemical warfare experiments also are not of the right scale.

A large variety of behaviors are possible in the case of instantaneous releases. For example, a discrete puff is influenced completely by the eddy structure existing at the point of release. During some meteorological conditions this structure at any location is constantly changing, and the variety of patterns is almost infinite. For a continuous source, such as a stack, individual segments of the plume may behave differently, but still a time-mean pattern can be envisaged. Even during stable meteorological conditions the variety of cloud behavior is increased by such nonmeteorological factors as force or power of explosion, heat released, degree of confinement of the explosion by the building in which it occurs, and cloud composition.

5.1 *Size of Source.* All sources are initially finite volumes rather than points, but, if interest in the dosage or concentration is sufficiently far from the source, in theory there is no difference in the downwind concentrations between point and volume sources. Near the point of release, however, the exposure varies considerably according to the assumption about the initial size of the radioactive cloud.

(a) *Cloud Content.* Any reactor disaster will emit gaseous contaminants, but not all need produce particulate matter. In the case of particulate matter, the problem of removal by deposition and the hazard due to deposited material which remains in the same place (as opposed to the gaseous cloud which will be carried away by the wind) must be considered. A treatment of this subject is given in Chap. 7.

(b) *Cloud Height.* As with the volume source, the influence of the cloud height becomes less important as the distance from the source becomes greater. The range of cloud heights for reactor disasters may be between zero (essentially no rise) and a height somewhat less than atomic bomb clouds.

If a contaminant is released over a period of, say, tens of minutes, it may be described as a "continuous source," in which case the height of rise can be estimated with the formulae given earlier for stack plumes. If all the material is released within a few minutes, the source is best described as an "instantaneous" one, in which case a different approach must be used.

Sutton[140] uses his theory for diffusion from a point source for computation of the diffusion of heat in the cloud as it rises and determines the height at which the cloud is no longer warmer than its environment. The formula is

$$H = \left[\frac{2(3m + 2p)Q}{9C_p\rho\pi^{3/2}C^3a}\right]^{1/[p+(3m/2)]} \qquad (6.9)$$

where m = 2 − n (see Chap. 4 on diffusion theory for a definition of the stability parameter, n), ρ is air density, Q represents the amount of heat released in the explosion, Cp is the specific heat at constant pressure for the gases of the cloud, C is the Sutton generalized coefficient of diffusion, and a and p are defined below. Sutton suggests that C might be about 0.45 $(\text{meters})^{1/8}$ and m about $^7/_4$, values which apply to ordinary atmospheric turbulence for a cloud which moves horizontally. The applicability of the same turbulence factors for a cloud which moves relative to the air is questionable. The numbers a and p are derived from the relation, $\theta = \theta_0 - azp$ where θ stands for potential temperature, z for height, and subscript 0 denotes the potential temperature at the place where z = 0. Figure 6.5 is a graph of Eq. 6.9 for the conditions listed above, and p = 1 and a = $10^{-3}$ °C/meter.

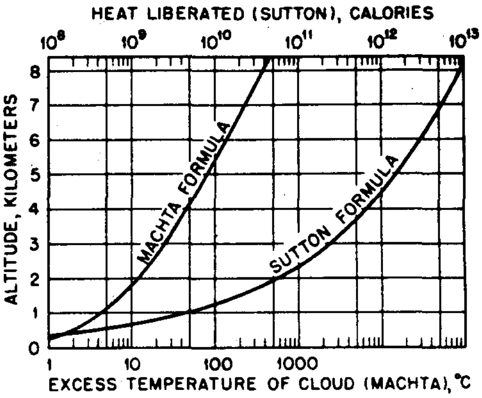

Fig. 6.5—Height of rise of cloud of hot gases.

Machta[101] has developed a formula for the maximum rise of a gaseous cloud based on a constant rate of entrainment of environmental air. It is written

$$H = \frac{1}{\frac{1}{M}\frac{\partial M}{\partial z}} \log_e \left\{ \frac{\frac{1}{M}\frac{\partial M}{\partial z}}{\frac{\partial\theta'}{\partial z}} \left[ (\Delta\theta)_0 + \frac{\frac{\partial\theta'}{\partial z}}{\frac{1}{M}\frac{\partial M}{\partial z}} \right] \right\} \qquad (6.10)$$

where H = maximum height of the cloud
M = mass of the cloud
$(1/M)(\partial M/\partial z)$ = constant percentage rate of entrainment per unit increase in height
$(\Delta\theta)_0$ = initial excess in potential temperature of the cloud over the environment
$\partial\theta'/\partial z$ = lapse rate of potential temperature

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The atmosphere plays a role in two terms: first, in the rate of entrainment (which for cumulus clouds is estimated to be about $0.5 \times 10^{-5}$ cm$^{-1}$ and which is greater with increased turbulence) and, second, in the potential temperature lapse rate of the air. For a standard atmosphere this lapse rate is about 3.5°A/kilometer, and for an isothermal atmosphere it is 10°A/kilometer. Equation 6.10 also is graphed in Fig. 6.5. A standard atmosphere is assumed, and the constant entrainment rate that was given above is used.

Machta's formula gives a rise of several kilometers for cloud temperatures only a few hundred degrees warmer than the environment, and therefore it may be less applicable to clouds from low-order explosions. It is easily seen that cloud size is an important factor. Machta's formula would be more applicable to a very large cloud (say as large as an average cumulus congestus cloud, whose base may be some 3 to 5 miles across) in which a temperature excess of 100°C would represent an enormous amount of heat energy. Also the entrainment rate assumed would be more likely to hold for a large cloud.

One may criticize these formulae as being very crude, but then the initial cloud temperature (or heat release) will not be accurately known in an actual explosion. The formulae may be used to obtain an order of magnitude approximation of cloud rise and perhaps a qualitative notion of the sense and magnitude of the meteorological factors. Both formulae have given good approximation for the rise of atomic bomb clouds.

The two theories are similar in that they deal with a gaseous cloud which rises because of its temperature excess over the environment, and the cloud cools by mixing with the environment air and by adiabatic expansion. In both theories, cooling due to radiation is omitted, a factor which may be highly important in the first few seconds after an explosion. Furthermore, the density of the cloud is undoubtedly affected by the presence of solid matter.

Considering the uncertainties involved, more convenient though less rigorous "height of rise" and cloud volume formulae applicable to reactor incidents may be stated as follows:

To compute $Z_{max}$, the height of cloud rise at night, use the formula

$$Z_{max} = \left(\frac{Q_h}{2c_p\rho\pi^{3/2}C^3\theta_a'}\right)^{0.276} \tag{6.11}$$

where $Q_h$ = heat liberated (calories)
$c_p$ = specific heat at constant pressure (0.25 calorie per gram per degree centigrade)
$\rho$ = air density (grams per cubic meter)
$\theta_a'$ = gradient of potential temperature (degrees centigrade per meter)
$C$ = diffusion coefficient [(meters)$^{1/8}$]; C varies from 0.3 for stable to 0.6 for unstable conditions

To compute volume of cloud at $Z_{max}$ use the formula

$$V_N = \frac{\Delta\theta_1}{\Delta\theta_2} V_G \tag{6.12}$$

where $\Delta\theta_1$ = initial excess temperature above ambient (degrees centigrade)
$\Delta\theta_2$ = $Z_{max}\theta_a'$, decrease in temperature excess (degrees centigrade)
$V_G$ = volume of cloud at the ground (cubic meters); this volume might be that of the reactor room, a building, etc.
$V_N$ = volume of the night cloud at $Z_{max}$

For the daytime cloud the lapse rate of potential temperature in the free air will be near that at which the cloud is assumed to cool; thus the preceding formulae are not applicable. Instead a reasonable height of rise may be selected by assuming that the cloud will reach 300 to 500 meters above the average base of fair weather cumulus clouds. (A height of 1500 meters is assumed at Oak Ridge; in the western mountain areas a stabilization height of 2000 to 3000 meters above the terrain would be more representative.)

After a daytime stabilization height has been chosen, the volume of the cloud at this height may be obtained by (1) computing the temperature excess at stabilization height from

$$\Delta\theta_3 = \Delta\theta_2 \left(\frac{Z_{max}}{Z_s}\right)^{2.62} \tag{6.13}$$

where $\Delta\theta_2 = Z_{max}\theta_a'$ from Eq. 6.11
$Z_{max} = Z_{max}$ from Eq. 6.11
$Z_s$ = assumed stabilization height

and (2) computing the required volume from the relation

$$V_D = \frac{\Delta\theta_2}{\Delta\theta_3} V_N \tag{6.14}$$

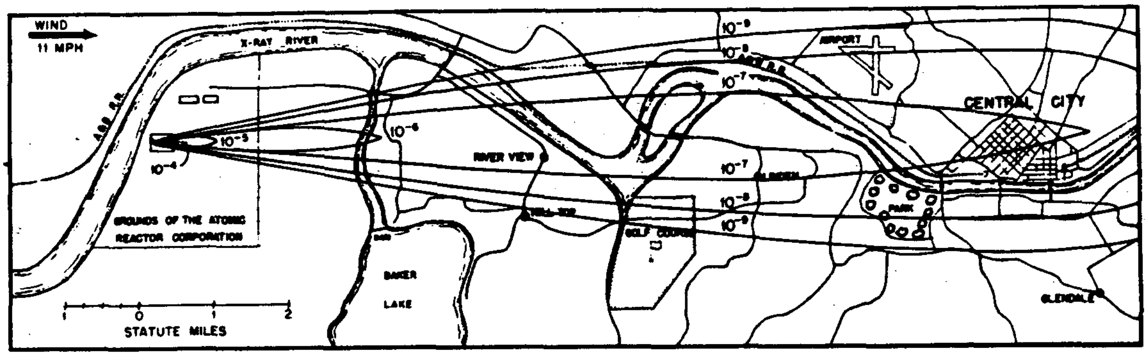

Fig. 6.6—Surface concentrations for release at ground level, average conditions (wind speed, 11 mph; $C^2$, 0.033; n, 0.25). Isolines give units of volume concentration (per cubic meter) per unit source strength (grams per second, curies per second, etc.) for a continuous point source. For instantaneous point source dosages (due to the passage of a unit puff) multiply by the number of time units necessary to make the continuous source equal to the instantaneous source.

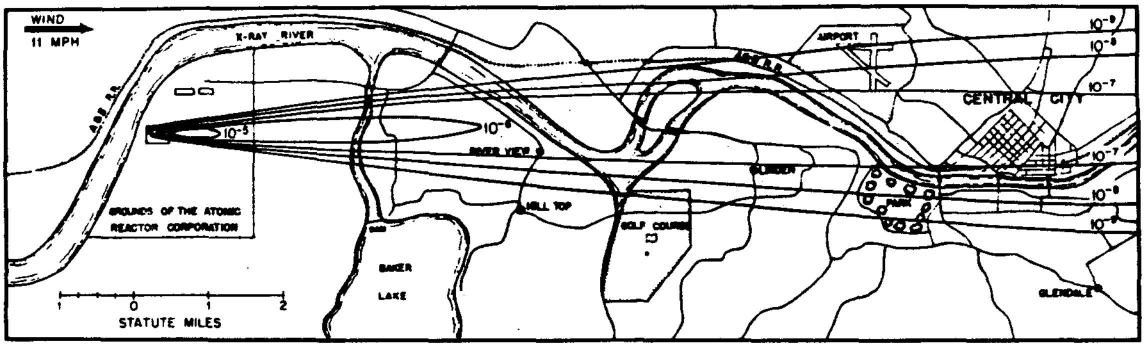

Fig. 6.7—Surface concentrations for release at 50 meters, average conditions (wind speed, 11 mph; $C^2$, 0.02; n, 0.25). Comparison with Fig. 6.6 shows that the increased height of release does not markedly affect concentrations at large distances from the source. Isolines give units of volume concentration (per cubic meter) per unit source strength (grams per second, curies per second, etc.) for a continuous point source. For instantaneous point source dosages (due to the passage of a unit puff) multiply by the number of time units necessary to make the continuous source equal to the instantaneous source.

where $\Delta\theta_2 = Z_{\max}\theta'_a$ from Eq. 6.11
$\Delta\theta_3 = \Delta\theta_3$ from Eq. 6.13
$V_N = V_N$ from Eq. 6.12

Although the preceding method is one of approximation only, when it is used to calculate a hypothetical event, it is probably as accurate as the uncertainties in estimating the amount of heat released, ground volume of the cloud, etc.

Other factors which may influence strongly the height of rise but which also cannot be dealt with mathematically are initial cloud shape, cloud circulation, and the effects of inertia. For example, in a sharp explosion smoke clouds or puffs may be ejected as smoke rings, or toroidal circulations, that may rise higher than if only buoyancy forces were operating.

5.2 *Surface Concentrations or Dosages.* By and large, interest in the cloud from a reactor disaster is limited to the ground concentrations or ground dosages. The gaseous portions of the cloud are brought to the ground levels by air motions (diffusion), whereas particulate portions of the cloud may also be brought to the ground levels by gravitational settling.

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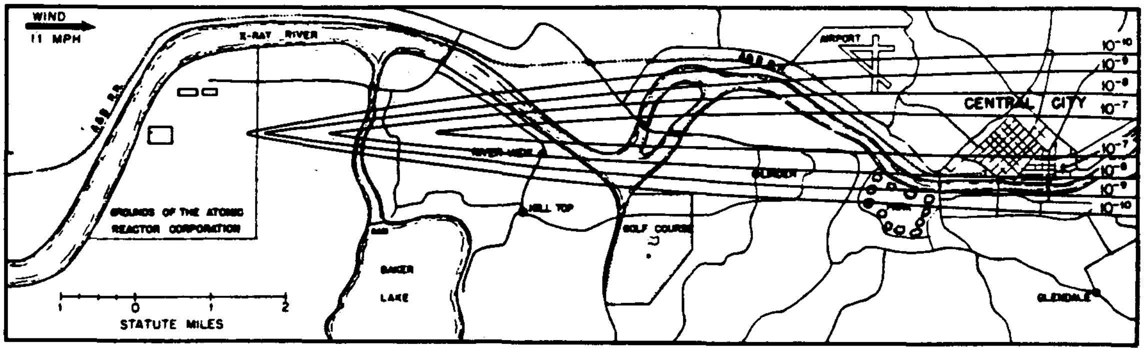

Fig. 6.8—Surface concentrations for release at 300 meters, average conditions (wind speed, 11 mph; $C^2$, 0.01; n, 0.25). In comparison with Figs. 6.6 and 6.7, the greatest effect of the increased source elevation is near point of release. Isolines give units of volume concentration (per cubic meter) per unit source strength (grams per second, curies per second, etc.) for a continuous point source. For instantaneous point source dosages (due to the passage of a unit puff) multiply by the number of time units necessary to make the continuous source equal to the instantaneous source.

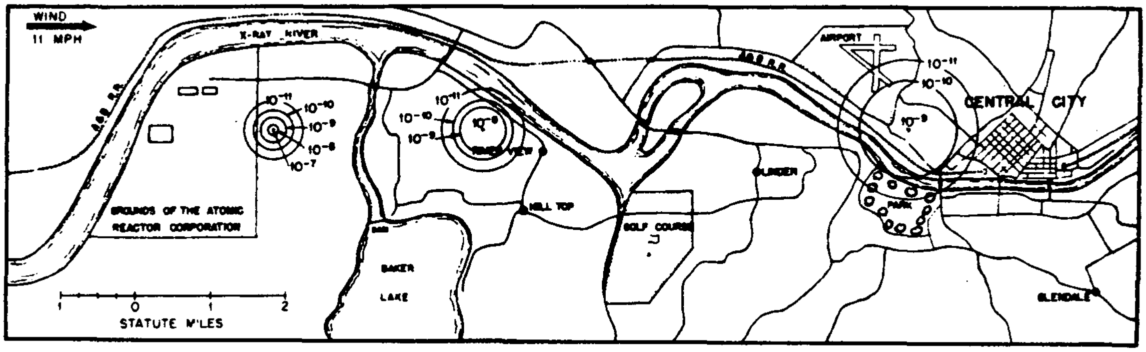

Fig. 6.9—Successive instantaneous surface concentration patterns from a release at 50 meters, average conditions (wind speed, 11 mph; $C^2$, 0.02; n, 0.25). Isolines give instantaneous volume concentrations (per cubic meter) per unit source strength (grams, curies, etc.) at about 8 min, 23 min, and 53 min, respectively, from time of burst or release.

During periods of precipitation, collection by precipitating elements may increase the downward transport. In this section discussion will be limited to the ground concentrations or dosages in nonprecipitating weather, and cloud depletion by deposition on the ground will be neglected.

Chapter 9 gives a nomogram which solves the most commonly used diffusion equations. The application of any diffusion theory in the scale of interest, namely, 1 to 10 miles from the source, probably indicates only orders of magnitude since there has been little or no verification of the formulae in this range of distances. The particular values of the diffusion characteristics will not be discussed here, but rather it is desired to show how the downwind concentrations or dosages vary according to some of the physical features of the initial cloud and weather conditions. Sutton's approach will be used in this presentation.

Sutton's formula yields the instantaneous (3-min average) concentration. The dosage, the concentration multiplied by time, may thus be obtained by integrating the concentration during the time over which the dosage is desired. In particular, the total dosage during the passage of a cloud over an observer is of greatest inter-

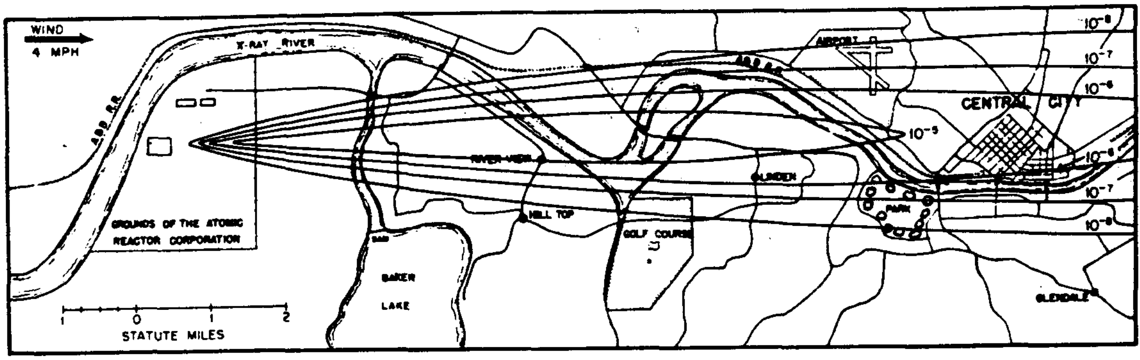

Fig. 6.10—Surface concentrations for release at 50 meters, stable conditions (wind speed, 4 mph; $C^2$, 0.003; n, 0.33). Comparison with Fig. 6.7 shows the much greater concentrations or dosages, except near the release point, that occur in stable conditions. Isolines give units of volume concentration (per cubic meter) per unit source strength (grams per second, curies per second, etc.) for a continuous point source. For instantaneous point source dosages (due to the passage of a unit puff) multiply by the number of time units necessary to make the continuous source equal to the instantaneous source.

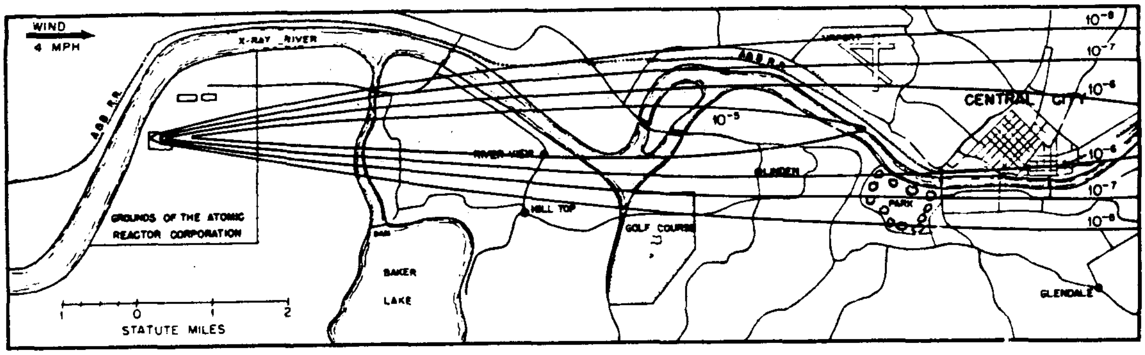

Fig. 6.11—Surface concentrations from volume source at 50 meters, stable conditions (wind speed, 4 mph; $C^2$, 0.003; n, 0.33). Source is initially spherical with a diameter of 30 meters. In comparison with Fig. 6.10, computations based on a finite volume show that the concentrations near the source are appreciably changed but at great distances they differ only slightly. Isolines give units of volume concentration (per cubic meter) per unit source strength (grams per second, curies per second, etc.) for a continuous point source. For instantaneous point source dosages (due to the passage of a unit puff) multiply by the number of time units necessary to make the continuous source equal to the instantaneous source.

est, which in theory means integrating the concentration at the given point from time zero to time infinity. Because of the mode of derivation of Sutton's continuous source formula, as the superimposition of a series of puffs, the integration of the concentration from zero to infinity for the passage of a single puff in order to obtain the dosage is rendered very simple. If the concentration is given for a continuous source at any point downwind, one merely multiplies this concentration by the number of units of time required to make the amount of contaminant from the instantaneous source equal to that from the continuous source.†

---

† Thus, if the instantaneous source emitted 6 g of gaseous matter and if the continuous source concentrations are based on an output at the rate of 2 g/sec, then the dosage from time zero to infinity for the instantaneous source is found by multiplying the continuous source concentrations by 3.

Figures 6.6 to 6.11 illustrate the ground concentrations based on Sutton's formulae for various types of sources under both neutral and stable conditions. The figures provide illustrations of typical ground dosages and concentrations which one may expect from the theory. It is perhaps worth repeating that in actual situations, relatively local areas may detect concentrations at least an order of magnitude greater or less than that predicted from the theory.

In translating these examples to practical problems, the assumptions listed on each example should be noted carefully. Additional assumptions are listed below:

1. No rain-out or fall-out of debris from the cloud (this effect is treated in Chap. 7).
2. No wind shear.
3. Horizontal and vertical diffusion are equal.
4. Wind speed for "average conditions" is 11 mph, and for "stable conditions" (small turbulence) it is 4 mph.

For a continuous source, given Q units of matter (grams per second) or radioactivity (curies per second), then the isolines indicate concentrations near the ground in terms of the source Q in units (grams or curies) per cubic meter. Q is multiplied by the value of the isoline.

For an instantaneous source (puff or explosion), the isolines give dosage values when multiplied by the ratio of the instantaneous source to the continuous source and the source strength, i.e., Q (instantaneous)/Q (continuous) × Q (instantaneous).

# 7

# Fall-out, Wash-out, and Rain-out from Airborne Clouds

Although fall-out, wash-out, and rain-out are features of the behavior of airborne clouds, the treatment of these phenomena requires consideration of factors not common to uninfluenced diffusion. Furthermore, the prolonged and possibly enhanced deleterious effects obtained from the deposition of radioactive material, compared to the relatively temporary effect from the moving airborne cloud, are of sufficient importance to merit a separate treatment.

Deposition of material from an explosion cloud or a stack plume is conveniently divided into dry weather and precipitating weather conditions, with subdivisions for gaseous products and particulate products. Sutton's equation for diffusion can be modified to take into account the effects of deposition during precipitating and nonprecipitating conditions.

Fall-out is used to designate deposition during nonprecipitating weather and includes the effects of both gravitational settling and impaction. Wash-out is used to designate removal of material from the air due to capture by falling precipitation elements.

Rain-out and wash-out have sometimes been used interchangeably in the literature, but in this publication rain-out is defined as removal due to association of the particulate or gaseous matter with the precipitation element prior to its descent. Except for the fact that rain-out significantly increases ground deposition in the case of debris clouds from nuclear weapons, practically nothing is known about the process. Bomb clouds extend above the natural clouds, and they may in part mix with them for a period of time before precipitation occurs. In addition to the effects of turbulent mixing, rain-out may be assisted by condensation of water onto the particle or by absorption of gas into a water droplet.

The wash-out process, which is of greater interest industrially, is applicable to airborne matter entirely below the bases of precipitating clouds. Fortunately, this process is more easily investigated in the laboratory and is a little better understood. However, the wash-out process also is immensely complicated, and only pioneering work has been accomplished to date.

## 1. EFFECTS OF FALL-OUT (NO PRECIPITATION)

1.1 *Particulate Products.* (a) *Gravitational Settling.* The rate of descent of particles in a gravitational field depends upon the balance between the resistance force of the atmosphere and the buoyancy force due to the weight of the particle. If the resulting fall speed is less than 1 cm/sec, then the actual transport of the particles in the atmosphere is largely controlled by the vertical turbulence; i.e., the vertical atmospheric motions are much larger than the rate of descent of the particles.

(1) *Theory.*[31] The resistance force acting on a particle falling through air can be expressed as follows:

$$F = \frac{1}{2} \rho_a v^2 A C_D \qquad (7.1)$$

where $\rho_a$ is the density of the air, v is the velocity of the particle through the air, A is the cross-sectional area of the particle, and $C_D$ is the drag coefficient, which is a function of the Reynolds number

$$Re = \frac{2\rho_a v r}{\mu} \qquad (7.2)$$

where r is the radius of the particle and $\mu$ is the dynamic molecular viscosity coefficient of the air. Combining Eqs. 7.1 and 7.2 gives

$$F = \frac{\mu v A}{r} \frac{Re C_D}{4} \tag{7.3}$$

For a particle falling at terminal velocity, this drag force will be equal and opposite to the gravitational force

$$G = Vg(\rho_p - \rho_a) \tag{7.4}$$

where V is the volume of the particle, g is the acceleration of gravity, and $\rho_p$ is the density of the particle. Eqs. 7.3 and 7.4 can be combined and solved for v

$$v = \frac{4Vg(\rho_p - \rho_a)r}{\mu A(Re C_D)} \tag{7.5}$$

The relation between drag coefficient and Reynolds number has been empirically determined and can be given for the entire range of particle sizes likely to be of interest as follows:

| | |
|---|---|
| Streamline motion ($10^{-4} < Re < 2$) | $C_D = \frac{24}{Re}$ |
| Intermediate motion ($2 < Re < 500$) | $C_D = 0.4 + \frac{40}{Re}$ |
| Turbulent motion ($500 < Re < 10^5$) | $C_D = 0.44$ |

For streamline motion, Eq. 7.5 then reduces to

$$v = \frac{Vg(\rho_p - \rho_a)r}{6\mu A} \tag{7.6}$$

If the particles are spherical, the expressions for V and A can be substituted, and the result is the Stokes' law equation

$$v = \frac{2gr^2(\rho_p - \rho_a)}{9\mu} \tag{7.7}$$

This equation would be applicable to spherical particles smaller than about 400 $\mu$ radius except that for very small particles, or at high altitudes where the air density is very low, the velocity would be increased by Cunningham's correction $1 + K(\lambda/2r)$, where $\lambda$ is the mean free path of the air molecules and K is a constant equal to approximately 0.86 for air.

For turbulent motion, Eq. 7.5 reduces to

$$v = \sqrt{\frac{2Vg(\rho_p - \rho_a)}{\rho_a A C_D}} \tag{7.8}$$

which, for a spherical particle, gives

$$v = \sqrt{\frac{8rg(\rho_p - \rho_a)}{3\rho_a C_D}} \tag{7.9}$$

Substituting numerical values and assuming $\rho_p - \rho_a \simeq \rho_p$ gives

$$v = 77.1\sqrt{\frac{r\rho_p}{\rho_a}} \tag{7.10}$$

This equation would be applicable to particles larger than 400 $\mu$ radius.

For intermediate motion the velocity cannot be expressed as a simple function of the particle radius, as could be done for streamline and turbulent motion, and a different procedure must be used. Solving Eq. 7.2 for velocity

$$v = \frac{\mu Re}{2\rho_a r} \tag{7.11}$$

and assuming a spherical particle, Eqs. 7.5 and 7.11 can be solved for r

$$r = \sqrt[3]{\frac{3\mu^2 Re^2 C_D}{32\rho_a g(\rho_p - \rho_a)}} \tag{7.12}$$

The procedure to use would be to take various values of the Reynolds number, compute $C_D$, solve Eq. 7.12 for r, and substitute this value in Eq. 7.11 to obtain v. A graph of velocity vs. radius can then be drawn to obtain velocities for radii other than those computed.

In all the above general formulae for all rates, there is a term $AC_D/V$ or the reciprocal. If the value of r is chosen such that it would give a sphere of volume V, the cross-sectional area A can be expressed as some factor K times the area of the circle with radius r. Or this factor K can be regarded as a correction to the drag coefficient, $C_D$. For streamline motion (Stokes' law) experimental determinations with crushed quartz and coke show that the factor would be approximately 1.5. Therefore the fall velocity for these irregular particles would be $^2/_3$ the fall velocity for an equivalent sphere. For ellipsoidal bodies in the Stokes' law range, one may refer to Fig.

7.1 for corrections to the fall speed of spherical bodies. For turbulent motion these experimental determinations show that the factor K is about 1.2, and therefore the fall velocity would be reduced to about $^9/_{10}$ that of an equivalent sphere. For intermediate motion the factor K would presumably vary from 1.5 to 1.2 as the Reynolds number increased through this region.

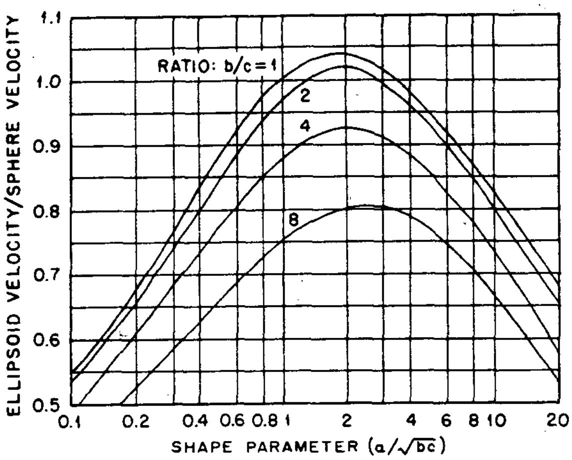

Fig. 7.1—Ratio of terminal velocity of ellipsoid with axes a, b, and c to velocity of a sphere with the same volume and density, Stokes' law (Overbeck). The a axis is vertical.

(2) *Results*. Figure 7.2 shows a graph of fall velocity vs. particle diameter for the four altitudes 10,000, 20,000, 30,000, and 40,000 ft MSL. A particle density of 2.5 g/cm$^3$ has been assumed. The two straight lines show the fall rates calculated according to Stokes' law for temperatures of 0° and −58°C, which are the temperatures used for the 10,000- and 40,000-ft computations, respectively. It can be seen that the fall rates approach Stokes' law fall at the smaller particle sizes. Also, for large particle size, the graphs become straight lines in the region of turbulent motion, where the velocity is proportional to the square root of the particle radius.

Falling water drops generally would descend according to the laws for intermediate or turbulent motion. Calculations of the fall velocity for water drops show excellent agreement with observed velocity (Fig. 6.3) for drop diameters up to about 1000 μ. Above this size there is a flattening of the drops, and therefore the drag coefficient is increased so that the fall velocity lags further and further behind that for an equivalent sphere.

(b) *Impaction on Vertical Surfaces*. Particles which are carried by the wind may strike and adhere to vertical objects which lie in their path, such as human beings, crops, and buildings. However, it is apparent that the air currents must pass around these obstacles; thus they carry at least a fraction of their particulate contaminants with them. The fraction of the particles which are collected by the obstacle relative to the number which would pass through the area occupied by the obstacle if it were not there is called the "collection efficiency." The greater the collection efficiency the greater will be the number of particles which approach the object. The collection efficiency can be found either through direct experimentation or through the use of a theory in which the trajectory of a particle is found and its departure from the air flow is examined in the light of the presence of the obstacle. It must further be assumed that every impaction results in a collection. For the most part, the objects whose collection efficiencies have been determined are very regular, spherical, cylindrical, etc. The results of some of the theoretical studies are given in Figs. 7.3 and 7.4, taken from a paper by Ranz,[122] who has summarized many of the findings to date. Additional calculations of collection efficiencies were made by Glauert[64] and Brun and Mergler.[16]

(c) *Impaction on Horizontal Surfaces*. Since there is no net downward air movement, the above theory for collection efficiency is not applicable for a horizontal surface. However, there is a downward (and upward) deposition of particulate matter due to the vertical turbulent movements of the atmosphere since the departure of the particles from the air flow lines permits deposition on horizontal surfaces. By analogy with the gravitational settling velocity, one may define a "velocity of deposition" as: $v_g$ = (number of particles deposited per unit area per unit time) × (integrated volume concentration over the unit area)$^{-1}$. The velocity of deposition, $v_g$, will equal the fall velocity [redacted] [redacted]

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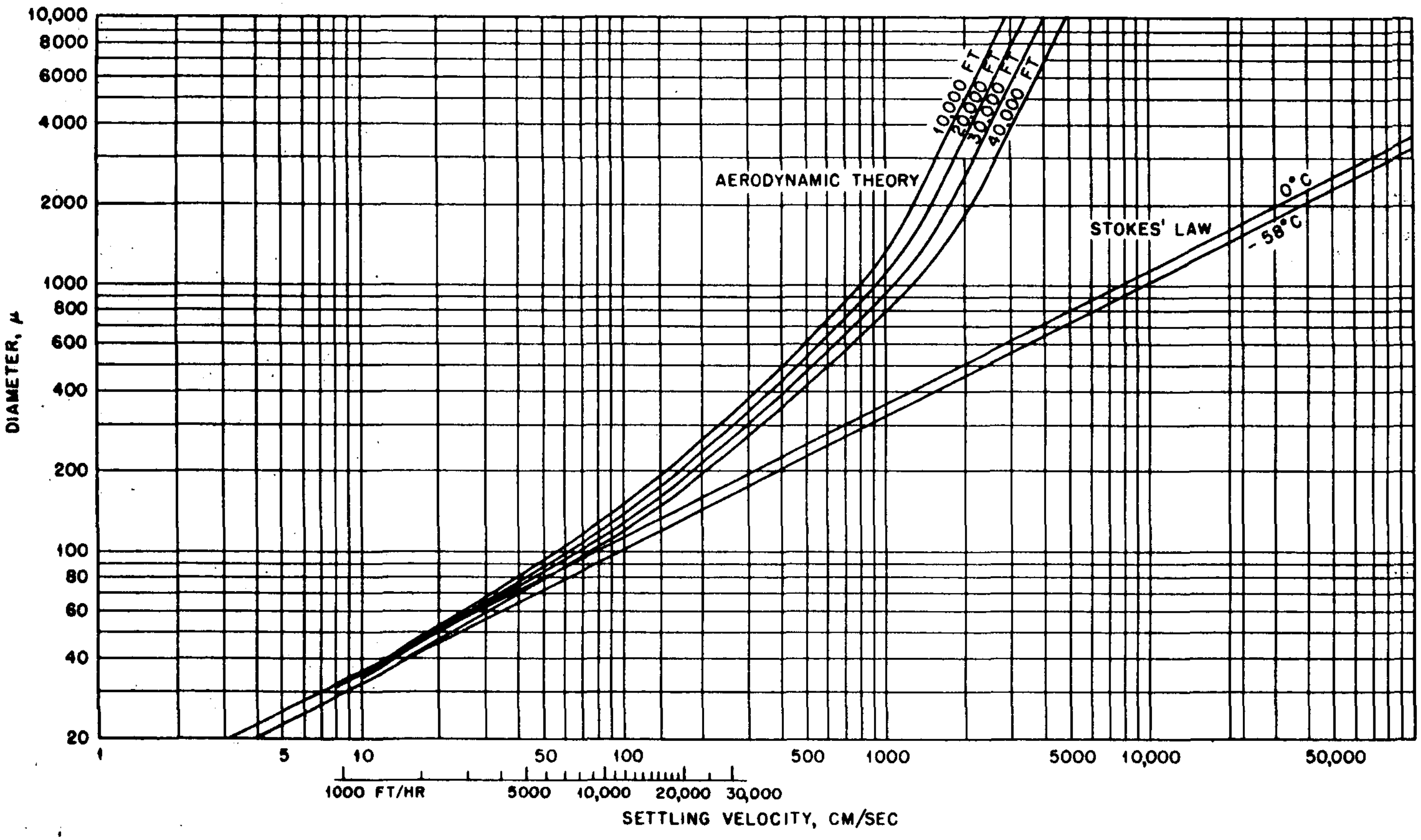

**Fig. 7.2**—Theoretical settling velocity for spherical particles of specific gravity 2.5 according to Stokes' law and aerodynamic theory.

when the latter greatly exceeds the turbulent motions of the atmosphere, but, in general, the two need not be the same. The value of the velocity of deposition should be related to the level at which the concentration is being measured, but, in general, if attention is focused to the lowest few centimeters above the ground, the concentration does not change appreciably with altitude. A few measurements of particles in the 1- to 100-$\mu$ range indicate that the velocity of deposition (1) generally increases with increasing wind speeds (indicating greater turbulence) and (2) is of the order of 1 cm/sec, or equivalent to the settling velocity of a particle having a diameter of about 10 $\mu$. It is established that the velocity of deposition is not always attributable to gravitational settling since deposition is shown to take place on both faces of a horizontal plate.

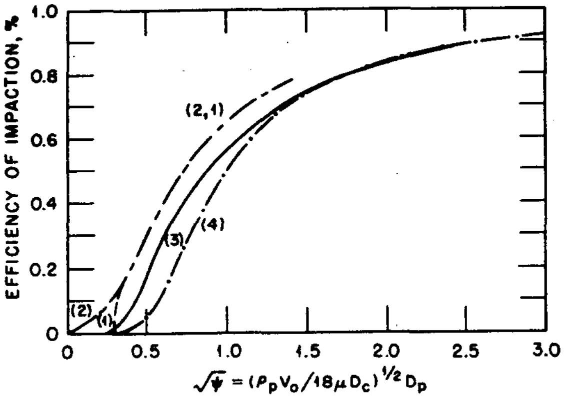

Fig. 7.3—Collection efficiencies for cylindrical collectors. $\rho_p$ = particle density, $V_0$ = speed of particle relative to cylinder, $\mu$ = coefficient of viscosity, $D_c$ = diameter of cylinder, $D_p$ = diameter of particle (Ranz). (1) F. Albrecht, Physik. Z., 32: 48(1931). (2) W. Sell, Forsch. Gebiete Ingenieurw., 2, Forschungsheft 347, August 1931. (3) I. Langmuir and K. B. Blodgett, Report RL-225, General Electric Research Laboratory, Schenectady, N. Y. (1944-45). (4) H. D. Landahl and R. G. Herrmann, J. Colloid Sci., 4: 103(1949).

(d) *Adsorption on Natural Aerosols.* This process occurs and may result in increasing particle size and rate of fall. Investigation and understanding of the processes is still in the fields of chemistry and physics and will not be considered here.

1.2 *Gaseous Products.* (a) *Diffusion onto Surfaces.* This process, in a sense, is the reverse of evaporation of water from a pond; the surface, if it reacts chemically with the gas, is highly soluble for the gas, or absorbs the gas, may act as a sink. The availability of the gas for deposition on the surface depends on the thickness of the laminar boundary layer next to the surface through which there is no atmospheric turbulence.

(b) *Condensation on Grass Surfaces.* This phenomenon might be considered to be analogous to the formation of dew and frost on grass or other surfaces that protrude above the ground. A theoretical treatment by Chamberlain, assuming the vertical diffusion of momentum and the gas to be analogous, yields a velocity of deposition for a typical weather situation of the order of 1 to 10 cm/sec at 2 meters. It is assumed in these calculations that there is a perfect sink on the surface on which the condensation occurs. Chamberlain and Chadwick[22] reported a field experiment which confirmed this order of magnitude of the velocity of deposition.

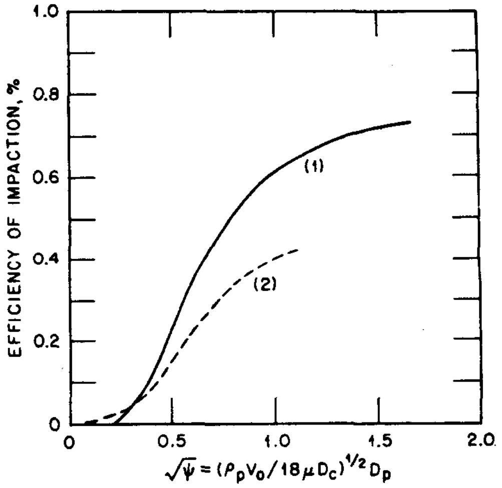

Fig. 7.4—Collection efficiencies for spherical collectors. Same as Fig. 7.3 except $D_c$ = diameter of sphere (Ranz). (1) I. Langmuir and K. B. Blodgett, Report RL-225, General Electric Research Laboratory, Schenectady, N. Y. (1944-45). (2) W. Sell, Forsch. Gebiete Ingenieurw., 2, Forschungsheft 347, August 1931.

1.3 *Modification of Diffusion Formula for Dry Deposition.* Chamberlain[21] has shown that Sutton's formula for a continuous point source originating at height z = 0 may be modified to yield the air concentration χ as follows:

$$\chi_{(x,y,z)} = \frac{2Q_0}{u\pi C_y C_z x^{2-n}} \exp\underline{\underline{\left(-\frac{4v_g x^{n/2}}{nu\pi^{1/2} C_z}\right)}} \times \exp\left(-\frac{y^2}{C_y x^{2-n}}\right) \times \exp\left(-\frac{z^2}{C_z^2 x^{2-n}}\right) \qquad (7.13)$$

The underlined term is the new factor which results from the removal of part of the cloud due to deposition. The quantity $v_g$ is the velocity of deposition, and, provided the settling velocity is much smaller than the horizontal wind, the settling velocity may be used in place of $v_g$. The treatment of cases of appreciable settling velocities by Davies[35] and Baron, Gerhard, and Johnstone[6] is more complicated.

One may also determine the amount of the contaminant which is deposited in the above model per unit time and per unit area as

$$\text{Rate of dep.} = \frac{2Q_0 v_g}{u\pi C_y C_z x^{2-n}} \exp\left(-\frac{4v_g x^{2-n}}{nu\pi^{1/2} C_z}\right) \times \exp\left(-\frac{y^2}{C_y^2 x^{2-n}}\right) \qquad (7.14)$$

Of interest is the settling velocity which will produce the maximum deposition at a given distance x from the source,

$$v_g = \frac{nu\pi^{1/2} C_z x^{-n/2}}{4} \qquad (7.15)$$

and it turns out that for distances of interest (up to perhaps 10 miles) the values of $v_g$ (for maximum deposition at given x), using reasonable values for the diffusion and stability factors, lie within the range suggested by actual experimentation.

A simpler procedure than the one above is to assume that all the diffusing particles are settling uniformly with a velocity v. This velocity might be determined by Stokes' law, by some other suitable formula, or by recourse to observation. The effect of this settling is to tilt the axis of the plume (from a continuous point source) downward so that it intersects the ground at an angle θ, where $v/\bar{u} = \tan\theta$. This angle will be rather small, in general. Thus we may approximate the elevation, z′, of the plume above the ground at each distance x downwind by

$$z' = h - \frac{xv}{\bar{u}}$$

or

$$z' = h - x \tan\theta \simeq h - x\theta \qquad (7.16)$$

Then Sutton's continuous elevated point source formula becomes

$$\chi_{(x,y)} = \frac{Q}{\pi C^2 \bar{u} x^{2-n}} \exp\left[-\frac{y^2 + (z')^2}{C^2 x^{2-n}}\right] \qquad (7.17)$$

The factor of 2 has been dropped since complete deposition is now assumed, rather than reflection. Equation 7.17 gives the ground concentration at any point (x,y). The deposition rate is obtained by multiplying this by v, the settling velocity.

Since maximum deposition, ω, is an item of primary concern, this information can be computed at a distance x downwind by

$$\omega_{\max} = \frac{nQ}{2e\pi^{1/2} C_y x^{2-(n/2)}} \qquad (7.18)$$

where ω is the deposition rate (gram per square meter per second) for a steady source (Q in grams per second) or total deposition (gram per square meter) for an instantaneous source (Q in grams).

## 2. EFFECTS OF WASH-OUT DURING PRECIPITATING WEATHER

**2.1** *Particulate Products.* There are four means by which a precipitation element (raindrop, snowflake, etc.) may act as a collector of particulate matter during its descent:

1. Particle inertia
2. Interception
3. Electrostatic attraction
4. Random molecular motion, or Brownian diffusion

As a further means of precipitation elements sweeping out atmospheric particulate impurities, one may include the possibility of the particles acting as nuclei during the process of formation of the precipitation element. This latter possibility at the present appears to be too remote to warrant further attention. Of the four mechanisms listed above, the inertia effect is probably predominant, the interception is important only when radii of the particles are similar to that of the precipitation element, and little or nothing is known about the electrostatic attraction by induction or charges and the effects of Brownian motion.

Table 7.1—Collection Efficiency E For Drops of Radius S Falling Through a Cloud of Smaller Drops of Radius r (Langmuir)

| S, μ | r, μ<br>2 | 3 | 4 | 6 | 8 | 10 | 15 | 20 |
|---|---|---|---|---|---|---|---|---|
| 15 | | | | | 0.092 | 0.269 | 0.500 | 0.643 |
| 25 | | | | 0.050 | 0.277 | 0.411 | 0.613 | 0.724 |
| 40 | | | | 0.205 | 0.394 | 0.510 | 0.690 | 0.782 |
| 70 | | | 0.035 | 0.340 | 0.500 | 0.608 | 0.750 | 0.834 |
| 100 | | | 0.133 | 0.418 | 0.564 | 0.660 | 0.793 | 0.862 |
| 150 | | 0.010 | 0.245 | 0.498 | 0.631 | 0.713 | 0.829 | 0.887 |
| 200 | | 0.085 | 0.326 | 0.564 | 0.684 | 0.756 | 0.859 | 0.908 |
| 300 | | 0.213 | 0.425 | 0.643 | 0.749 | 0.810 | 0.892 | 0.929 |
| 400 | 0.040 | 0.303 | 0.500 | 0.698 | 0.793 | 0.849 | 0.919 | 0.950 |
| 600 | 0.121 | 0.355 | 0.530 | 0.731 | 0.827 | 0.876 | 0.939 | 0.963 |
| 1,000 | 0.140 | 0.358 | 0.535 | 0.738 | 0.834 | 0.886 | 0.944 | 0.966 |
| 1,400 | 0.168 | 0.360 | 0.534 | 0.735 | 0.840 | 0.890 | 0.950 | 0.970 |
| 1,800 | 0.117 | 0.288 | 0.456 | 0.680 | 0.800 | 0.865 | 0.935 | 0.965 |
| 2,400 | 0.075 | 0.220 | 0.372 | 0.606 | 0.743 | 0.823 | 0.920 | 0.950 |
| 3,000 | 0.050 | 0.170 | 0.306 | 0.546 | 0.690 | 0.785 | 0.900 | 0.940 |

(a) *Particle Inertia.* The collection efficiency of precipitation elements by the departure of the particle trajectories from the air flow lines has been largely determined by theory, although there has been some experimental verification by Gunn and Hitschfeld.[67] Table 7.1 is taken from Langmuir's paper,[90] in which he attempts to span the transition from aerodynamic flow around the precipitation (spherical) element for large droplet Reynolds number (>1500) to viscous flow for small Reynolds number (< 1). This table represents a useful first approximation. Later work by McCully[109] indicates that additional factors must be considered for precise calculations. In general, for rain, the larger the drop size the more intense the rain; thus on the small end of the raindrop scale one might be dealing with fogs or drizzles and on the other end with cloudbursts. An ordinary rain might involve raindrops of the diameter of 1 mm.

Recent investigations into the mechanism of coalescence of water droplets[147] has shown that the flow field around a falling drop results in other drops of equal mass being drawn in radially behind the leading drop and then falling down the wake and coalescing with the leading drop. It is stated that this mechanism can operate for a distance of 40 diameters behind any given drop and for as much as 10 diameters radially. Thus such a drop has a very high collection efficiency. Although this investigation was limited to drop sizes very near 150 μ, it is reasonable to assume the same mechanism will markedly increase the collection efficiency for other drop sizes.

The collection efficiency of snowflakes is not known. From the structure of the flake and from the findings of radioactive snow following atomic tests, it is probable that the efficiency is at least as high as that of typical raindrops. Hitschfeld and Gunn conclude that, although there may be a question as to whether impaction between particles and raindrops results in collection, their experimental evidence supporting Langmuir's collection efficiency appears to indicate that collection does occur.

(b) *Particle Interception.* This means of precipitation elements collecting aerosol particles depends upon the fact that the center of gravity of the aerosol may follow the streamline around the falling raindrop (that is, be inertialess), but the edges of the two bodies intersect and collection is achieved. Figure 7.5 shows the collection efficiency as a function of the precipitation rate and particle size. It should be noted that the collection efficiency due to interception becomes significant only when the particle size is of the same order of magnitude as the precipitation element; thus in this case the fall velocity of the particle is significant, and deposition may not be greatly augmented by the precipitation process unless the precipitation element subsequently grows.

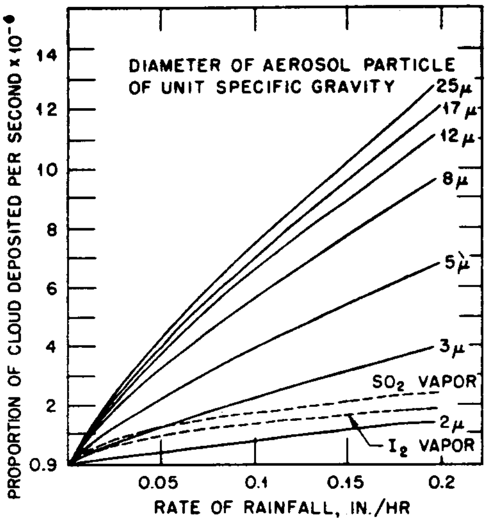

Fig. 7.5—Percentage of removal of particles in a cloud according to particle size and rate of rainfall. For $SO_2$ and $I_2$ the removal process is due to absorption onto the droplets since the vapors are water-soluble (Chamberlain).

Two ingredients are necessary to determine the fraction of the particles which are scavenged by falling precipitation elements: first, the collection efficiency and, second, the distribution of precipitation element sizes as a function of the intensity of precipitation falling on the ground. Data for the first of these are available from Table 7.1, and for the latter they are available from the work of Best[11] or Marshall.[104] From simple geometrical considerations and elaborate computations, one is able to prepare a chart, such as Fig. 7.6, which uses only the Langmuir collection efficiencies and Best's size distribution. The ordinate of this figure provides the percentage number of particles per second removed by falling spherical precipitation elements. Collection efficiencies greater than 1.0 are obtained by considering the total cross section of the collector rather than only the mid-point.

2.2 *Gaseous Products.* Gaseous products may be washed out of the atmosphere by diffusion of the gas to raindrops in which they are soluble (in a sense, the reverse of the evaporation of raindrops). The problem of computing the fraction of the gas which is washed out in a unit of time depends on two factors: first, the flux of the gas onto a raindrop of a given size (which depends on the rate of diffusion of the gas into water, the fall velocity of the raindrop, and the kinematic viscosity of air, as well as the concentration of the gas) and, second, the distribution of raindrops for a given rate of precipitation. Results of such computations for two gases, $SO_2$ and $I_2$, are included in Fig. 7.5, which shows that the rate of removal lies in the range computed for particles of unit specific volume and radii of 2 and 3 μ.

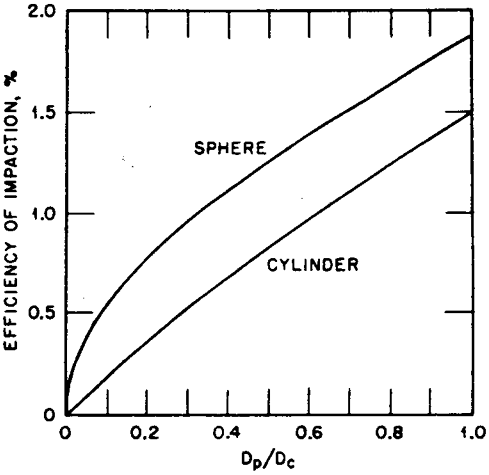

Fig. 7.6—Efficiency of collection or impaction. $D_p$ and $D_c$ are diameter of particle and sphere or cylinder, respectively.

2.3 *Modification of Diffusion Formula for Scavenging.* Chamberlain[21] has shown that Sutton's formula for a continuous point source originating at z = 0 may be modified to yield the air concentration χ as follows:

$$\chi_{(x,y,z)} = \frac{2Q_0}{u\pi C_y C_z x^{2-n}} \underline{\underline{\exp\left(-\frac{\Lambda x}{u}\right)}} \times \exp\left(-\frac{y^2}{C_y^2 x^{2-n}}\right) \exp\left(-\frac{z^2}{C_z^2 x^{2-n}}\right) \quad (7.19)$$

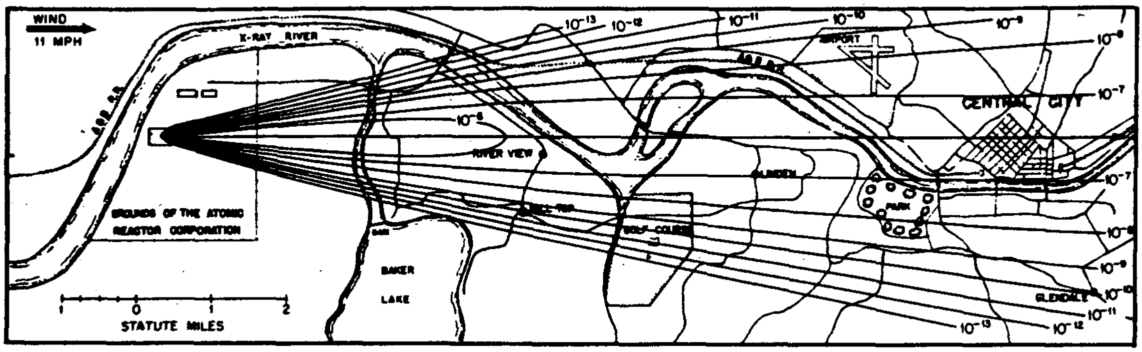

Fig. 7.7—Surface air concentration, no fall-out or wash-out, using Sutton's formula and assuming: release at ground level; wind speed, 11 mph; $C_y$, 0.21(meters)$^{1/8}$; $C_z$, 0.12(meters)$^{1/8}$; n, 0.25; no fall-out or precipitation scavenging. Isolines give units of volume concentration (per cubic meter) per unit source strength (grams/sec, curies/sec, etc.) for a continuous point source. For instantaneous point source dosages (due to passage of a unit puff) multiply isoline values by the number of time units necessary to make continuous source equal to instantaneous source.

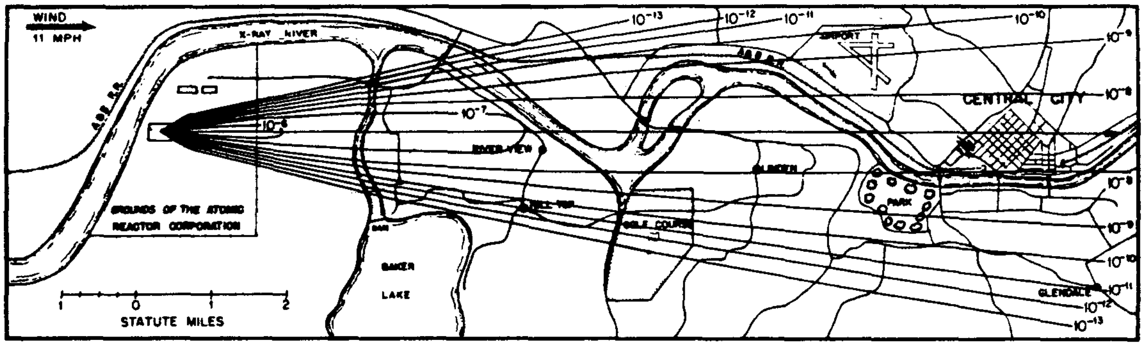

Fig. 7.8—Surface air concentrations modified by dry fall-out, using Sutton's formula and assuming: release at ground level; wind speed, 11 mph; $C_y$, 0.21(meters)$^{1/8}$; $C_z$, 0.12(meters)$^{1/8}$; n, 0.25; deposition velocity, 4 cm/sec. Comparison with Fig. 7.7 shows a decrease in concentration near the center of the cloud of about one order of magnitude due to dry fall-out. Isolines give units of volume concentration (per cubic meter) per unit source strength (grams/sec, curies/sec, etc.) for a continuous point source. For instantaneous point source dosages (due to passage of a unit puff) multiply isoline values by the number of time units necessary to make continuous source equal to instantaneous source.

The underlined term is the new factor which results from the removal of part of the cloud by scavenging. $\Lambda$, proportion of cloud removed per second, is the ordinate of Fig. 7.6 and depends on the particle characteristics and on the rate of precipitation as described above. The effect of scavenging by precipitation, although superficially similar to deposition by fall-out, is different in that the removal of matter from the cloud is derived from the entire depth of the cloud as opposed to only the ground level for dry deposition by fall-out.

One may also determine the amount of the contaminant which is deposited in the above model per unit time and per unit area as

$$\text{Rate of dep.} = \frac{\Lambda Q_0 e^{-\Lambda x/u}}{u\pi^{1/2} C_y x^{(2-n)/2}} \times \exp\left(-\frac{y^2}{C_y^2 x^{2-n}}\right) \quad (7.20)$$

Of interest is the scavenging rate (fraction of the cloud removed per unit time) which will

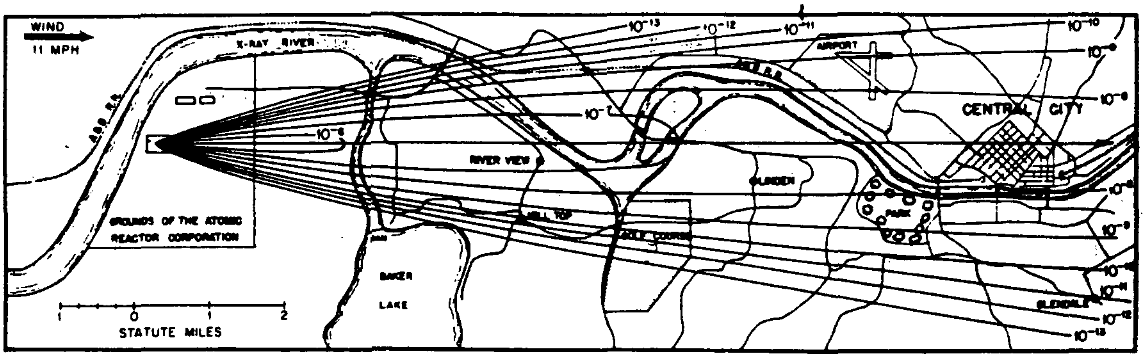

Fig. 7.9—Surface air concentrations modified by precipitation wash-out, using Sutton's formula and assuming: release at ground level; wind speed, 11 mph; $C_y$, 0.21(meters)$^{1.8}$; $C_z$, 0.12(meters)$^{1.8}$; n, 0.25; percentage rate of removal by precipitation, $6 \times 10^{-4}$ sec$^{-1}$. Comparison with Fig. 7.7 shows a decrease in concentration near the center of the cloud of about one order of magnitude due to scavenging action of precipitation. Isolines give units of volume concentration (per cubic meter) per unit source strength (grams/sec, curies/sec, etc.) for a continuous point source. For instantaneous point source dosages (due to passage of a unit puff) multiply isoline values by the number of time units necessary to make continuous source equal to instantaneous source.

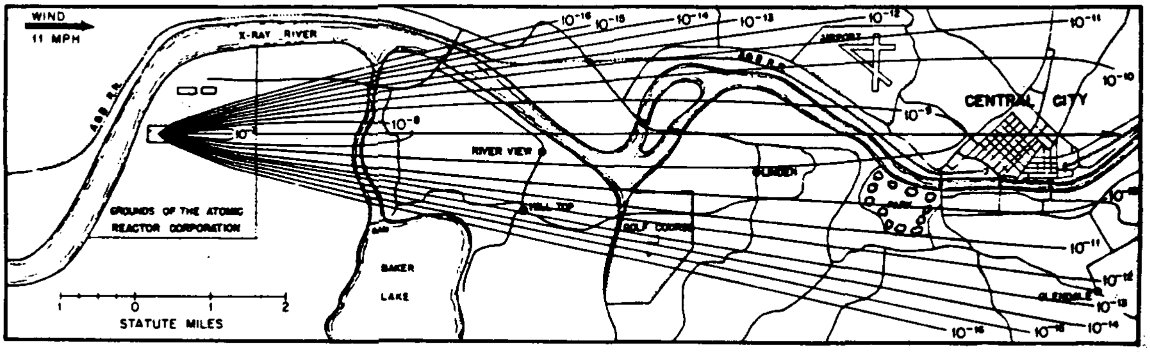

Fig. 7.10—Ground deposition due to dry fall-out, using Sutton's formula and assuming: release at ground level; wind speed, 11 mph; $C_y$, 0.21(meters)$^{1.8}$; $C_z$, 0.12(meters)$^{1.8}$; n, 0.25; deposition velocity, 4 cm/sec. Comparison with Fig. 7.8 indicates that the area deposition is about one order of magnitude smaller than the surface air concentration. Isolines give ground deposition per unit time in units of area deposition (per square meter) per unit source strength (grams/sec, curies/sec, etc.) for a continuous point source. For instantaneous point source deposition (total deposition due to the passage of a unit puff) multiply by the number of time units necessary to make the continuous source equal to the instantaneous source.

produce the maximum deposition at a given distance x from the source, which is

$$\Lambda = \frac{u}{x} \cdot$$

and again for the distances from 1 to 10 miles and for reasonable wind speeds (say 10 mph), the maximum value for Λ is readily obtained from particles about 5 μ and over with reasonable rates of rainfall.

Here, too, the maximum deposition due to wash-out is of concern. This value can be computed by

$$\omega_{\text{rain max}} = \frac{Q}{e\pi^{1/2} C_y x^{2-(n/2)}} \tag{7.21}$$

where ω is the deposition rate (gram per square meter per second) for a steady source (Q in grams per second) or total deposition (gram

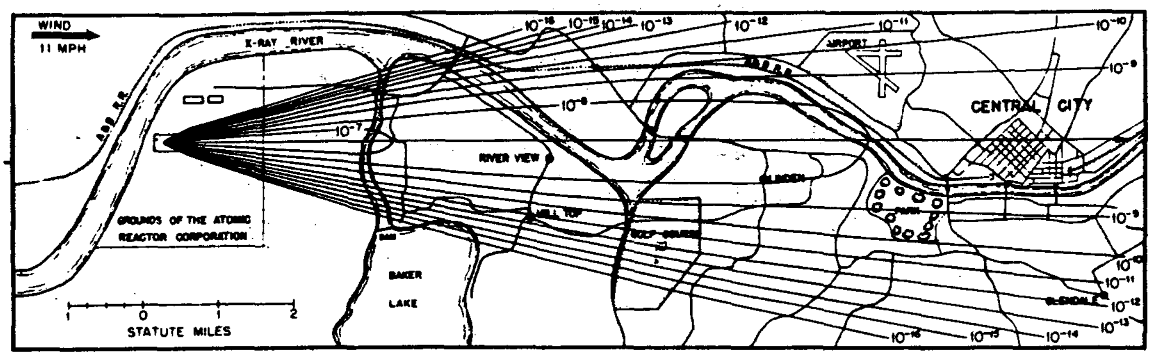

Fig. 7.11—Ground deposition due to wash-out by precipitation, using Sutton's formula and assuming: *release at ground level*; wind speed, 11 mph; $C_y$, 0.21(meters)$^{1.8}$; $C_z$, 0.12(meters)$^{1.8}$; n, 0.25; percentage rate of removal by precipitation, $6 \times 10^{-4}$ sec$^{-1}$. Comparison with Fig. 7.10 shows that wash-out deposition is about an order of magnitude greater than the dry fall-out deposition. Isolines give ground deposition per unit time in units of area deposition (per square meter) per unit source strength (grams/sec, curies/sec, etc.) for a continuous point source. For instantaneous point source deposition (total deposition due to the passage of a unit puff) multiply by the number of time units necessary to make the continuous source equal to the instantaneous source.

per square meter) for an instantaneous source (Q in grams).

2.4 *Total Instantaneous Wash-out.* For the limiting case of instantaneous deposition of an entire cloud or plume of airborne material, such as might occur in a sudden heavy rain shower, Holland[81] gives these formulae based upon Sutton's equations.

*Instantaneous point source:*

$$\text{Deposition} = \frac{Q}{\pi C^2 (\bar{u}t)^{2-n}} \tag{7.22}$$

*Continuous point source:*

$$\text{Deposition} = \frac{Q}{(2\pi)^{1/2} C_y \bar{u} x^{(2-n)/2}} \tag{7.23}$$

Thus, using the equations appropriate to the assumed (or actual) conditions, estimates can be obtained of the hazard due to deposited material and/or the depletion of the airborne cloud resulting from the removal of this material. It is interesting to note that, aside from the hazard due to inhalation of airborne radioactivity having a strong biological affinity, Eqs. 7.19 and 7.21 can represent for long-lived gamma emitters the conditions of greatest hazard for locations at large distances from the source. For this reason the total wash-out over some selected area is often a consideration of the "maximum plausible accident" in a reactor hazard analysis.

A nomogram for the ready computation of maximum fall-out and maximum wash-out is contained in Chap. 9. It may be appropriate, however, to conclude this section with illustrations showing the effects of these phenomena. Figures 7.7 to 7.9 show the changes in the surface concentrations (or dosages) from the moving airborne cloud caused by fall-out and wash-out. Figures 7.10 and 7.11 are examples of ground concentrations due to fall-out and wash-out, respectively. It can be seen that the deposition of appreciable amounts of long-lived activity could present a serious contamination problem.

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# 8

# Radioactive Cloud Dosage Calculations

A cloud of radioactive material released instantaneously into the atmosphere, spreading under the action of turbulent eddies and possibly subject to settling or to wash-out by precipitation, could irradiate people downwind in the following ways:

Externally: (1) during passage of the airborne cloud and (2) after deposition of material on the ground or skin.

Internally: (1) by inhalation of airborne material and (2) by ingestion of deposited material.

Alpha, beta, or gamma radiation might be involved in each case. However, most routine process wastes or accidentally released fission products would be primarily beta or gamma emitters. Furthermore the range of influence of alpha emitters is in general so small and their half lives are so long that they can be treated in nearly all respects by the same computation methods as would be applied to nonradioactive toxic agents. Therefore the present discussion will be limited to beta and gamma emitters.

External beta radiation is received only from emitters located within a few meters of the receptor owing to the short range of beta particles in air. In clouds of the dimensions of several meters or greater, therefore, the external beta dose rate is proportional to the local concentration of beta emitting atoms within the accuracy of the prediction, or measurement, of the concentration. Gamma radiation on the other hand has a mean free path in air of the order of 100 meters. In order to calculate the gamma dose rate, it is therefore necessary to integrate the radiation from a volume which may be comparable to, or greater than, the dimensions of the cloud. In both cases the total dosage is calculated by integrating the dose rate with respect to time.

External radiation exposure from an accidental release would be influenced by a number of factors, the knowledge of which would be very meager, at least for the first few critical hours following the incident. The amount and composition of the radioactivity, physical state of the released material, initial temperature and volume of the cloud, and existing meteorological conditions all would be unknown or difficult to determine. In addition, knowledge would be lacking on the location and movement of people in the path of the cloud and the shielding effects of clothing, buildings, etc. Given an estimate of the radiation dosage, there are further uncertainties of the degree of injury or damage implied.

Internal exposure resulting from inhalation involves additional biological parameters, such as breathing rate and retention and uptake of specific radioisotopes by various organs. Internal dosage due to ingestion of deposited material from the passing airborne cloud involves most of the preceding uncertainties plus factors concerning treatment of water supplies, uptake and reconcentration by plants and animals, relocation by wind, etc.

In general, the errors introduced by imperfect knowledge of diffusion laws and parameters are not likely to be large in relation to the other uncertainties of the problem. Presently available methods of computing airborne concentration which have been outlined in previous chapters should suffice to indicate the range of possible dosages for given source conditions. The upper limits of surface deposition density and total external gamma dosage can be obtained with the least uncertainty since the space and time integrations in these two cases render the results least sensitive to assumptions regarding height of rise or diffusion. On the other hand, external beta and inhalation dosages can vary by many orders of magnitude with relatively minor changes in the height of rise of the cloud, particularly at distances, from the origin, less than about 10 times the height of rise of the cloud.

## 1. EXTERNAL BETA DOSAGE FROM AIRBORNE CLOUDS

On the assumption that the cloud concentration is essentially uniform over the range of beta radiation (roughly 1 to 10 meters for beta energies of 0.5 to 2 Mev), the energy absorbed in a volume of air is equal to that emitted from the same volume. A human body would serve as a nearly perfect absorber; therefore the total energy flux per unit area at the surface of the skin would be one-half that in air. The presence of the earth's surface introduces a further reduction with respect to the free air radiation flux. This factor varies from ½ at the ground to 1 at heights greater than the range of the beta radiation and has been computed by Taylor[146] to average 0.64 for a man 1.8 meters tall. The beta radiation dosage received at the surface of the body from a cloud of radioactive material released into the atmosphere is then

$$D_B = (0.5)(0.64)\frac{1\ \text{r}}{6.8 \times 10^{10}\,\text{Mev/m}^3} \times \frac{\rho_0}{\rho}\int_0^{\infty} \chi_B \, dt \qquad (8.1)$$

where $D_B$ = beta dosage in roentgens per second
$\chi_B$ = concentration, at the receptor, of beta energy in million electron volts per second per cubic meter
$\rho$ = atmospheric density
$\rho_0$ = atmospheric density at sea level
$t$ = time measured from the release

If $\chi_B$ is given by Sutton's formula and sea level atmospheric density is assumed, this leads to the "Total Integrated Dosage" (TID) formulae of Chap. 4

$$D_B = \frac{0.64 Q_B \exp\left(-\dfrac{h^2}{C_z^2 d^{2-n}}\right)}{\pi \bar{u} C_y C_z d^{2-n}\,(6.8 \times 10^{10}\,\text{Mev/m}^3/\text{r})} \qquad (8.2)$$

where $Q_B$ = total beta source strength corrected for decay en route in million electron volts per second
$d$ = distance of the receptor directly downwind from the point of release in meters

The dosage would approach zero in the interior of the body.

Equation 8.2 describes the total dosage during the passage of a cloud resulting from an instantaneous point source. If the "virtual origin" (Chap. 4) is used to approximate a finite initial volume, the decay must be computed from the actual (not virtual) origin. Diffusion and decay during the cloud passage over the receptor are neglected in this formula; i.e., the dose rate has been integrated with respect to $x/\bar{u}$, rather than $t$, from $-\infty$ to $\infty$, whereas $t$ has been held constant at $d/\bar{u}$. This amounts to an assumption that the travel time of all particles is the same and equal to $d/\bar{u}$ during passage over the receptor. The error introduced by this assumption is small compared to other uncertainties in the diffusion theory.

If $Q_B$ in Eq. 8.2 is replaced by $\partial Q_B/\partial t$ (Mev/sec²), the rate of release from a continuous source, $D_B$, is replaced by the corresponding continuous dose rate $\partial D_B/\partial t$ (r/sec) at a distance d downwind.

For the special case of a reactor runaway, the beta source strength of the fission products is approximately[146]

$$Q_B = 4.8 \times 10^{16}\, E_r (t/t_1)^{-1.21}\ (\text{Mev/sec})$$

where $E_r$ = nuclear energy release in megawatt-seconds (1 Mw-sec equals $10^6$ joules)
$t_1$ = 1 sec (this dimensional parameter will be understood in subsequent formulae)

Thus

$$D_B(\text{r/Mw-sec}) = \left[(4.8 \times 10^{16}\,\text{Mev/sec})(\text{Mw-sec}) \times (0.64) E_r \bar{u}^{(0.21)} \exp\left(\frac{-h^2}{C_z^2 d^{2-n}}\right)\right] \times \left[(6.8 \times 10^{10}\,\text{Mev/m}^3/\text{r}) \times \pi C_y C_z d^{(2-n)+(1.21)}\right]^{-1} \qquad (8.3)$$

## 2. EXTERNAL GAMMA DOSAGE FROM AIRBORNE CLOUDS

This problem, although straightforward in principle, is perhaps the most involved mathematically of the various cloud dosage problems. Instructive approximate solutions have been obtained by previous investigators under various assumptions. Luckow, Widdoes, and Mesler[98] assumed uniform concentration in a cloud whose dimensions were determined by Sutton's formula, completely neglecting absorption. Taylor[146] carried out the space integration of the dose rate from the Sutton cloud, assuming simple exponential absorption, then multiplied by a time of passage determined from Sutton's formula and the wind speed, holding the decay constant at the central value. Fitzgerald, Hurwitz, and Tonks[46] carried out the space and time integrations for a cloud passing without change, as in the present solution, but without considering multiple-scattering build-up or decay during passage. All three of the above solutions were obtained only for a cloud release at the ground. Waterfield[151] carried out the complete space-time integration for elevated as well as surface clouds, still, however, assuming exponential absorption and holding the decay constant during passage. He also presented a decay-integral correction factor for the case $f(t) = t^{-1.21}$ which tends to improve the accuracy at intermediate, but not at small (< 300 meters), distances. None of the above workers has retained the decay function in the time integral, nor has any considered multiple-scattering build-up.

In the present treatment all particles of the cloud have been assumed to pass the receptor with the mean wind velocity, and only isotropic turbulence has been considered, but otherwise no simplifying assumptions have been made.

The gamma energy absorbed per unit mass in the body exposed to a radioactive cloud would be approximately the same as that absorbed in air. This is the product of the time integral of the total energy flux, $\phi$ (Mev/m$^2$/sec), and the mass absorption coefficient, $\mu_m$(m$^2$/g). The dosage is then

$$D_G(\text{Mev/g}) = \mu_m \int_0^\infty \phi \, dt$$

Assuming sea level air density and converting to roentgens

$$D_G(r) = \mu_a \frac{1\ r}{6.8 \times 10^{13}\ \text{Mev/m}^3} \int_0^\infty \phi \, dt$$

where $\mu_a$ = linear absorption coefficient for gamma radiation in air at sea level (meter$^{-1}$).

The flux from each infinitesimal volume element, dV, of the cloud would be, in the absence of an intervening absorbing medium,

$$d\phi = \frac{\chi_G \, dV}{4\pi r^2}$$

where $\chi_G$ = rate of gamma energy emission per unit volume in million electron volts per cubic meter per second

r = distance between volume element and receptor in meters

In an absorbing but nonscattering medium, the flux would be

$$d\phi_2 = \frac{[\chi_G \exp(\mu_a r)] \, dV}{4\pi r^2}$$

In an absorbing and scattering medium, the flux due to the direct ray alone would be further attenuated by scattering

$$d\phi_3 = \frac{\{\chi_G \exp[-(\mu_a + \mu_s)r]\} \, dV}{4\pi r^2}$$

where $\mu_s$ is the linear scattering coefficient (meter$^{-1}$). When the scattered radiation from the volume element, dV, arriving at the receptor from all directions is added, the flux finally becomes

$$d\phi = \frac{[B_r \chi_G \exp(-\mu r)] \, dV}{4\pi r^2}$$

where $B_r$ = multiple-scattering build-up factor, a complicated dimensionless function of $\mu r$ and the gamma energy. $\mu$ = total absorption-scattering coefficient $\mu_a + \mu_s$ (meter$^{-1}$). $\mu$ is about 0.01 meter$^{-1}$ in air for gamma energies of the order of 0.5 to 1 Mev. $1/\mu$, the mean free path, is therefore about 100 meters in the present application. $B_r$ has been tabulated by Goldstein and Wilkins.[65] In the range of interest for meteorological problems, it can be represented approximately by the formula

$$B_r = 1 + \mu r + \frac{(\mu r)^2}{7E^{2.4}}$$

The "attenuation factor" will be denoted in the following discussion by

$$G(r) = \frac{B_r \exp(-\mu r)}{r^2}$$

where $r^2 = (d - \bar{u}t + x)^2 + y^2 + z^2$ in the coordinate system with x and y the downwind and cross wind distances, respectively, of the receptor from the center of the cloud; d is the distance of the receptor from the origin of the release; and $\bar{u}$ and t have their usual meaning. Then the gamma dosage becomes

$$D_G = \frac{\mu_a}{4\pi \times 6.8 \times 10^{10} \mathrm{Mev/m^3/r}}$$

$$\times \int_0^{\infty} \int_0^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \chi_G(x,y,z,t)$$

$$\times G(r)\, dx\, dy\, dz\, dt$$

Assuming isotropic diffusion, the "concentration factor" $\chi_G$ would be

$$\chi_G(\mathrm{Mev/m^3/sec}) = \left[ Q_G \left\{ \exp\left[ -\frac{(z-h)^2}{\sigma^2} \right] \right.\right.$$

$$\left. + \exp\left[ -\frac{(z+h)^2}{\sigma^2} \right] \right\}$$

$$\left. \times \exp\left( -\frac{x^2 + y^2}{\sigma^2} \right) \right] \left( \pi^{3/2} \sigma^3 \right)^{-1}$$

where $Q_G$ = gamma source strength in million electron volts per second, corrected for decay

z = height above ground in meters

$\sigma = C(\bar{u}t)^{(2-n)/2}$, a length, in meters, proportional to the cloud radius, according to Sutton's formula

Then after some manipulation (the complete derivation will be included in a paper by J. Z. Holland to be published elsewhere),

$$D_G = A \int_0^{\infty} [J_0(\alpha) \exp(-\beta)]$$

$$\times \left[ \int_0^{\infty} G(r)\, f(t)\, dt \right] s\, ds \qquad (8.4)$$

where $A = \dfrac{\mu_a Q_0}{2\pi\sigma^2 (6.8 \times 10^{10} \mathrm{Mev/m^3/r})}$

$J_0(\alpha)$ = zero order Bessel function of $\alpha$

$\beta = (s^2 + h^2)/\sigma^2$

$r^2 = (d - \bar{u}t)^2 + s^2$

$S = \sqrt{y^2 + z^2}$

f(t) = the decay function

$Q_0$ = initial source strength in million electron volts per second

Thus the problem is essentially reduced to the following:

1. Integrating the dosage with respect to time for each particle of the cloud, resulting in a point source dosage which is a function of the distance of passage s and the wind speed for each distance of the receptor downwind of the origin.
2. Determining the distribution of particles as a function of s for each h and $\sigma$.
3. Integrating the product of the point source dosage and the source distribution function with respect to s.

## 3. GAMMA DOSAGE NOMOGRAMS

3.1 *Power Excursion.* A short-lived nuclear reactor power excursion of 1 Mw-sec would result in the production of radioactive fission products which would emit approximately $4.8 \times 10^{16}\ t^{-1.21}$ Mev/sec of gamma energy with an average energy of 0.7 Mev/dis,[146] where t is in seconds. This formula overestimates the source strength for $t < 10$ sec; however, the time integral of the actual source strength from 0 to 10 sec is very nearly equal to the integral of the formula from 1 to 10 sec. Since integrated dosages are desired and since the concomitant variation of the attenuation factor between $t = 0$ and $t = 1$ sec can generally be neglected in the ranges of distances and wind speeds of meteorological interest, the lower time limit will be taken as 1 sec. Thus

$$Q_0 = 4.8 \times 10^{16}\ Q_E$$

where $Q_E$ = nuclear energy release in megawatt-seconds and $f(t) = t^{-1.21}$

A nomogram for computing integrated cloud gamma dosages in the case of expulsion to the atmosphere of the fission products resulting from a reactor power excursion has been developed by the following steps:

1. Performing the time integration of the attenuation-decay factor for a selection of values of s, d, and $\bar{u}$ sufficient to permit graphical integration to two place accuracy. It was found that for $d > 2000$ meters the ratio of this integral to $s\ G(s)\ d^{-1.21} \bar{u}^{0.21}$ is independent of d and $\bar{u}$.
2. Preparing curves from which the distribution factor could be computed to better than two

significant figures as a function of $(s - h)^2/\sigma^2$ and $2sh/\sigma^2$.

3. Integrating the product with respect to s and computing dosages for $Q_E$ = 1 Mw-sec and for a selection of values of d, h, $\sigma$, and $\bar{u}$ corresponding to "average" meteorological conditions. These conditions and the resulting dosages are summarized in Table 8.1.

**Table 8.1—Cloud Gamma Dosage, Power Excursion Products, and Average Conditions**

| h, meters | n | C, (meters)$^{n/2}$ | $\bar{u}$, meters/sec | d, meters | $\sigma$, meters | $D_G$, r/Mw-sec |
|---|---|---|---|---|---|---|
| 0 | 0.25 | 0.20 | 3 | 30 | 3.9 | 6.4 |
| | | | | 300 | 22 | $5.1 \times 10^{-2}$ |
| | | | | 3,000 | 221 | $2.35 \times 10^{-4}$ |
| | | | | 30,000 | 1,654 | $3.52 \times 10^{-7}$ |
| 50 | 0.25 | 0.15 | 5 | 300 | 22 | $1.96 \times 10^{-2}$ |
| | | | | 563 | 38 | $1.07 \times 10^{-2}$ |
| | | | | 3,000 | 166 | $3.88 \times 10^{-4}$ |
| | | | | 30,000 | 1,240 | $7.45 \times 10^{-7}$ |
| 200 | 0.25 | 0.10 | 7 | 300 | 15 | $2.74 \times 10^{-3}$ |
| | | | | 3,000 | 110 | $1.43 \times 10^{-4}$ |
| | | | | 4,380 | 154 | $1.31 \times 10^{-4}$ |
| | | | | 30,000 | 827 | $1.73 \times 10^{-6}$ |
| 500 | 0.25 | 0.08 | 9 | 300 | 12 | $1.57 \times 10^{-4}$ |
| | | | | 3,000 | 88 | $5.56 \times 10^{-6}$ |
| | | | | 16,000 | 382 | $4.05 \times 10^{-6}$ |
| | | | | 30,000 | 661 | $1.73 \times 10^{-6}$ |

4. Dosages were computed for a point source of radiation passing at a large selection of heights by substituting h for s in the integrated attenuation-decay function and multiplying by appropriate conversion factors. These point source dosages were plotted as a function of h, d, and $\bar{u}$.

5. The height of a nondiffusing point source of strength $Q_G$ giving the same total gamma dosage as that computed for the cloud was determined graphically, and this "equivalent point source height" h′ was graphed as a function of $\sigma$ and h.

6. The h′ coordinate of the equivalent point source height graph was aligned with the h coordinate of the point source dosage graph.

7. With the assumption that h′ is a function of h and $\sigma$ only, alignment nomograms for computing $\sigma$ from either Sutton diffusion parameters or Fickian (e.g., Roberts) parameters were attached to the $\sigma$ scale of the h′ graph to permit computation of the dosage under arbitrary meteorological conditions.

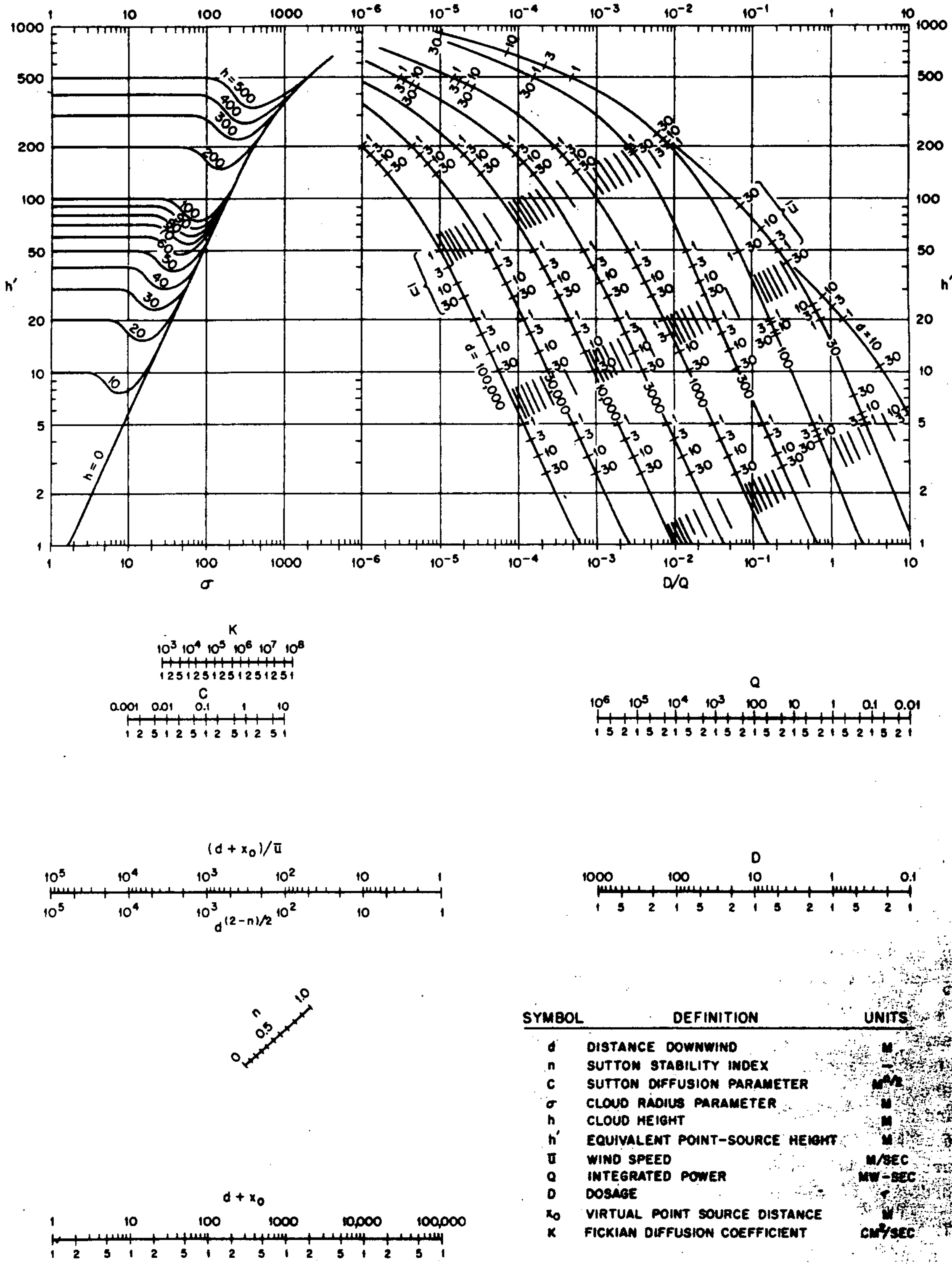
8. An alignment chart for multiplying the resultant unit emission dosage by the actual source released in megawatt-seconds of integrated fission energy was attached to the dosage scale of the point source dosage graph to permit a completely graphical computation of the final dosage.

The resulting nomogram is shown in Fig. 8.1. It is designed to give dosage estimates accurate to about ±20%.

(a) *Nomogram Instructions, Power Excursion.* To calculate the dosage resulting from the release of all fission products of a power excursion of integrated energy of $Q_E$(Mw-sec), at a distance d (meters) from the origin, given the height of rise h (meters), the wind speed $\bar{u}$, (meters/sec), and the Sutton diffusion parameters C[(meters)$^{n/2}$] and n, the procedure is as follows:

1. Place a straightedge through d on the $d + x_0$ scale and n. Mark the point of intersection on the $d^{(2-n)/2}$ scale.

2. Place the straightedge through this point on the $d^{(2-n)/2}$ scale and C. Mark the intersection on the $\sigma$ scale.



| SYMBOL | DEFINITION | UNITS |
|---|---|---|
| $d$ | DISTANCE DOWNWIND | M |
| $n$ | SUTTON STABILITY INDEX | — |
| $C$ | SUTTON DIFFUSION PARAMETER | $M^{n/2}$ |
| $\sigma$ | CLOUD RADIUS PARAMETER | M |
| $h$ | CLOUD HEIGHT | M |
| $h'$ | EQUIVALENT POINT-SOURCE HEIGHT | M |
| $\bar{u}$ | WIND SPEED | M/SEC |
| $Q$ | INTEGRATED POWER | MW-SEC |
| $D$ | DOSAGE | r |
| $x_0$ | VIRTUAL POINT SOURCE DISTANCE | M |
| $K$ | FICKIAN DIFFUSION COEFFICIENT | $CM^2/SEC$ |

Fig. 8.1—Cloud gamma dosage, power excursion products (Holland).

3. Align the straightedge parallel to the vertical axis through this point on the σ scale. Mark the intersection with the curve representing h (or a suitably interpolated point). The ordinate is h′.

4. Align the straightedge horizontally through this h′ value. Mark the intersection with the curve representing d or a suitably interpolated point. (The abscissa is the dosage for a 1 Mw-sec source and a 1 meter/sec wind speed.)

Table 8.2—Meteorological Parameters for Sample Cases

| | | C, meters$^{n/2}$ | | | | $\bar{u}$, meters/sec | | | |
|---|---|---|---|---|---|---|---|---|---|
| Case | n | h = 0 | 50 | 200 | 500 | h = 0 | 50 | 200 | 500 |
| Average conditions | 0.25 | 0.20 | 0.15 | 0.10 | 0.08 | 3 | 5 | 7 | 9 |
| Stable conditions | 0.50 | 0.05 | 0.03 | 0.02 | 0.01 | 1 | 3 | 6 | 9 |
| Unstable conditions | 0.20 | 0.50 | 0.20 | 0.15 | 0.10 | 7 | 10 | 12 | 13 |
| Strong wind conditions | 0.25 | 0.20 | 0.15 | 0.10 | 0.08 | 15 | 22 | 30 | 35 |
| Trapping | | | (σ = 0.75h) | | | | 5 | 7 | 9 |

5. Displace the point found in step 4 along the lines of constant d, a distance equal to the distance between the 1 meter/sec mark and that representing the wind speed $\bar{u}$. (It will be noted that there are several differing wind speed correction scales for each d curve. The wind correction nearest to the point found in step 4 should be used, interpolating if necessary.) Lay the straightedge parallel to the vertical axis through this point to obtain $D/Q_E$.

6. Lay the straightedge through $D/Q_E$ from step 5 and $Q_E$ on the Q scale; the intersection on the D scale is the gamma dosage in roentgens. Note that these dosages are computed on the basis of releasing 100% of the fission products to the air. These values may be adjusted to conform with the postulated release by multiplying by the percentage of fission products assumed to escape.

If the Fickian diffusion coefficient K is given, the procedure is the same except for steps 1 and 2. In this case substitute step 1a, below, for 1 and 2.

1a. Lay the straightedge through the travel time $d/\bar{u}$ on the $(d + x_0)/\bar{u}$ scale and K to determine σ.

(b) *Nomogram Application, Virtual Source.* Since about 90% of the cloud is contained within a sphere of diameter 4.3 σ, $x_0$, the virtual source correction (see Chap. 4) can readily be determined. Lay the straightedge through the point on the σ scale representing ¼ the initial cloud diameter (see Eq. 6.12 for one method of obtaining cloud size) and follow steps 1 and 2 or 1a, in reverse, to find $x_0$ on the $d + x_0$ scale, or $x_0/\bar{u}$ on the $(d + x_0)/\bar{u}$ scale, respectively. The value of $x_0$ thus determined can then be added to the values of d for which dosages are desired. This addition is made only at step 1 or 1a. The value of d used in step 4, representing the decay attenuation distance, must be measured from the actual origin.

(c) *Power Excursion Cloud Dosage Variability.* If σ exceeds 2000 meters, it is possible to compute dosages, on the assumption of approximate radiative equilibrium at each point of the cloud, by dividing the TID obtained from Eq. 4.72 by $1.36 \times 10^{10}$ Mev/m$^3$/r using $4.8 \times 10^{16}\ Q_E\ (\bar{u}/d)^{1.21}$ as the source strength. It will be noted that this dosage, received by a person at the surface, is ½ that which would be received in the absence of the ground.

However, in this case, as well as that of h > 500 meters, it can be seen by inspection of the nomogram that a power excursion of at least 2000 Mw-sec would be required to produce a cloud gamma dosage as large as 1 r at any distance even if all the fission products were released.

The dosage reaches a maximum at a distance from the origin depending on the height of rise of the cloud and the wind speed. The dosages for distances less than those given by the outer curves in the upper right of Fig. 8.1 (d = 10, 30, 100 meters) are smaller than those given by these curves owing to the short exposure time during the approach of the cloud at these small distances.

It can be seen that elevated clouds behave essentially as point sources when σ is less

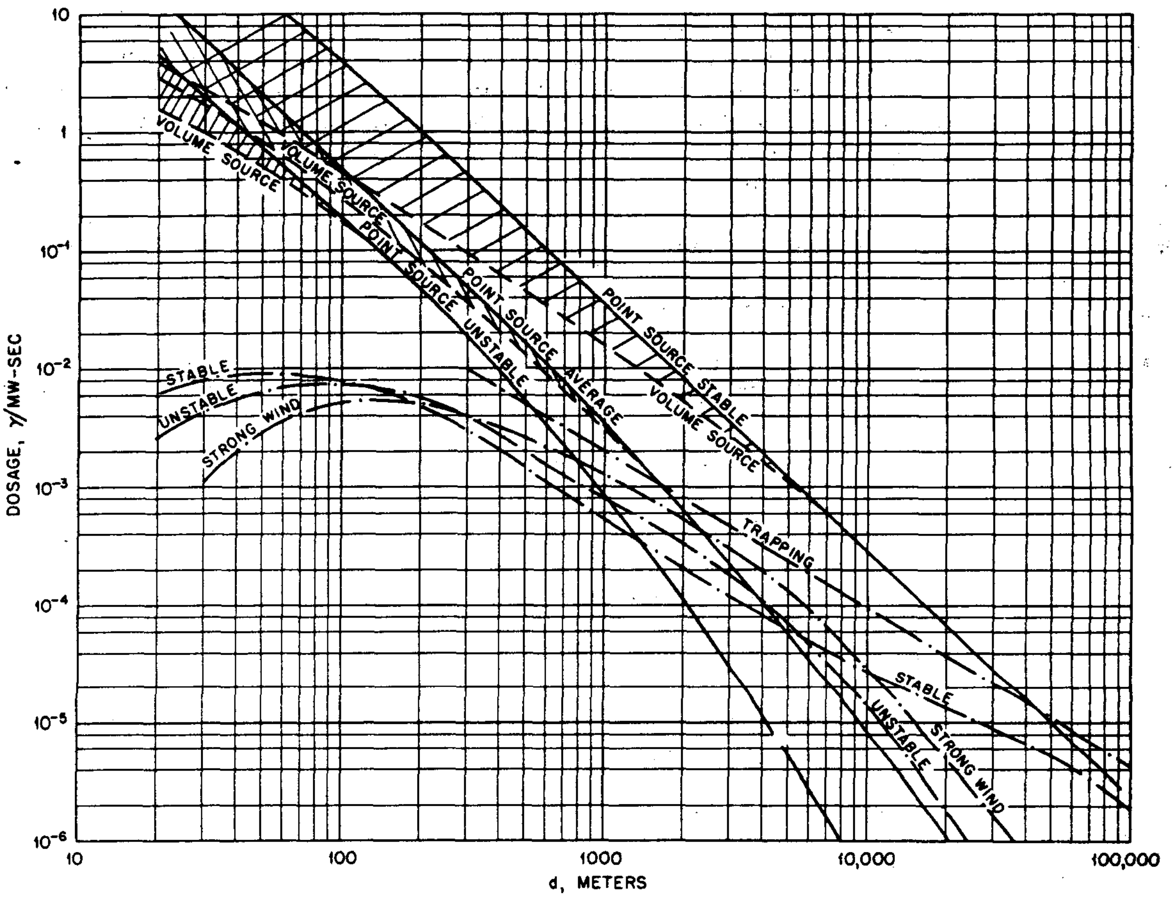


Fig. 8.2—Gamma dosage variability, power excursion. ——, h = 0 (point source). —·—, h = 200 meters (point source).

than about h/5. The maximum dosage (or minimum equivalent point source height) for a cloud of given strength and elevation occurs when $\sigma$ is 3h/4, i.e., when the cloud width is 3h. When $\sigma$ increases beyond about 2h (cloud diameter = 8h), cloud elevation has no further effect on the dosage, given equal diffusion parameters.

An idea of the values to be expected under a plausible variety of meteorological conditions can be obtained from Fig. 8.2. These values were obtained from the nomogram of Fig. 8.1, using the meteorological parameters in Table 8.2.

Except in the "trapping" case, computations were made for both a point source and an initial volume source for which the value of $\sigma$ at the origin was taken as $\sigma$ = 10 meters + 0.3h. The factor 0.3h corresponds roughly to the rate of cloud spread, with rise, given by Sutton's hot puff formula (Eq. 6.9) with C = 0.6. The trapping case was designed to approximate a situation in which diffusion is confined to downward motion, and the horizontal spread is also limited (as by a valley). In this case $\sigma$ was held to 3h/4 to maximize the dosage, and computed dosages were doubled to take into account downward reflection.

It will be noted (Fig. 8.2) that when h = 0, increasing the volume of the initial source significantly decreases the dosage at small distances, the reduction reaching a factor of about 12 at d = 30 meters in the stable case. The effect of a finite volume decreases at larger distances, and the point and volume source dosages become essentially the same at about 100 meters for the unstable case, 1000 meters in the average case, and 3000 meters for the stable case.

Increasing atmospheric stability results in larger dosages at all distances, ranging from a factor of about 2 at 30 meters (for an initial volume source) to about $10^4$ at 30 km.

For the elevated sources ($h > 0$) the dosages change less with variations in the meteorological parameters. Trapping of course always gives the highest dosage. Of the others, the stable case results in the highest dosages at great distances; the strong wind case is the worst at intermediate heights and distances; and at greater heights the unstable cases with the resulting rapid spread of the cloud results in the highest dosages at small and intermediate distances.

3.2 *Steady Power Fission Products.* In the case of a sudden dispersion into the atmosphere of the contents of a nuclear reactor which has been operating at a steady power level, the gamma source strength in million electron volts per second is

$$Q_G = 2.3 \times 10^{14}\, P[t^{-0.21} - (t_0 + t)^{-0.21}] \qquad (8.5)$$

where P = previous steady power of the reactor in kilowatts
t = time after shutdown in seconds
$t_0$ = duration of steady operation in seconds

If $t_0$ is greater than a few months, this can be approximated by

$$Q_G = 2.3 \times 10^{14} P t^{-0.21} \qquad (8.6)$$

without serious error. In view of the slow decay rate it is justifiable, for the purpose of estimating hazards, to neglect decay during cloud passage in the space-time integration of the radiation flux from the cloud. A nomogram for this purpose was developed as follows:

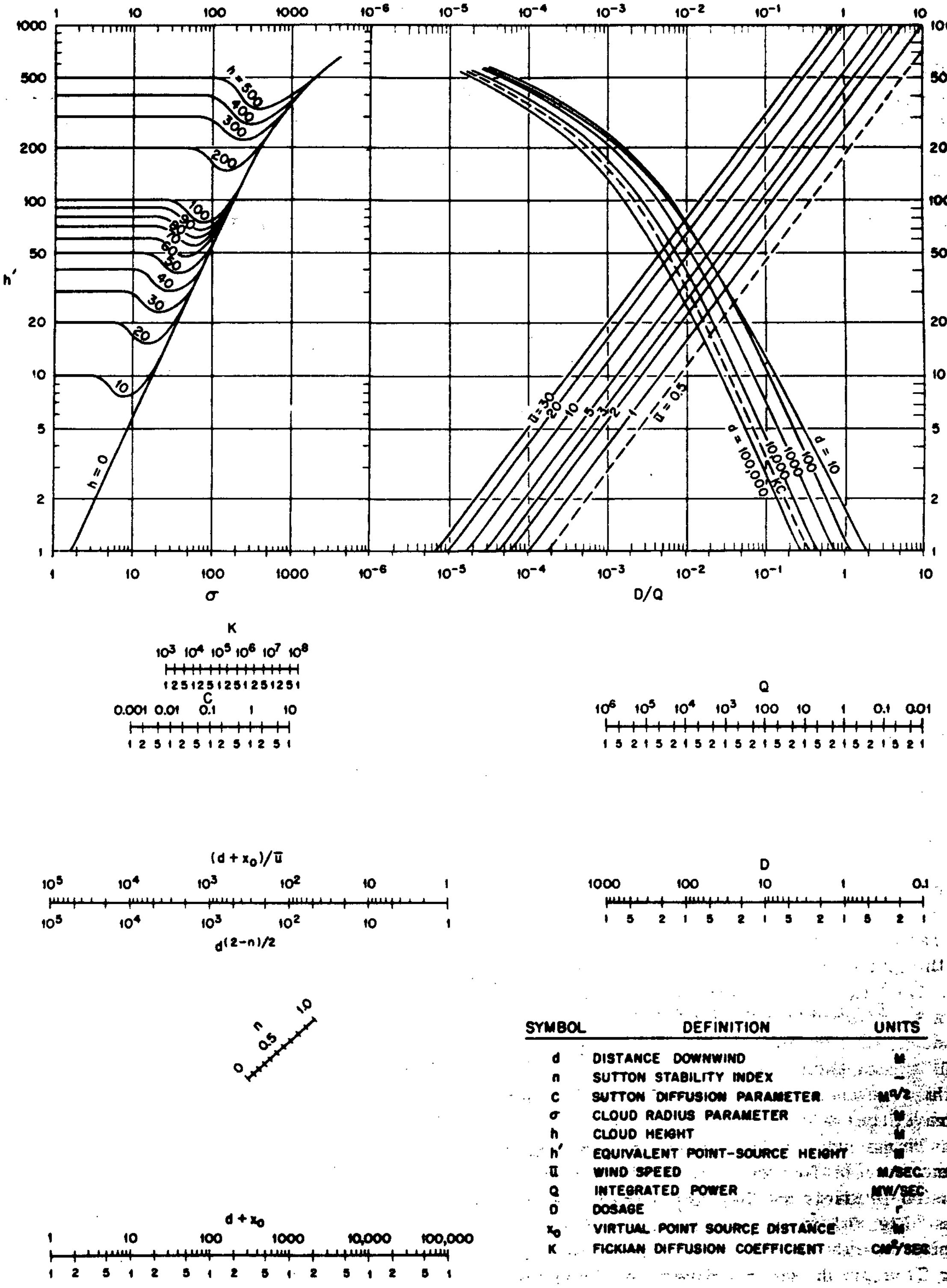
1. The point source dosages were computed for a selection of values of $d/\bar{u}$ and h, replacing the decay function in the integrand by a constant $(d/\bar{u})^{-0.21}$ for each integration but taking account of the shortened approach path at small values of travel time $d/\bar{u}$.
2. This point source dosage was graphed as a function of d and h for unit wind speed.
3. The wind speed correction factor $(\bar{u})^{-0.79}$ was incorporated in the graph as a set of sloping straight lines.
4. This graph was substituted for the upper right graph of Fig. 8.1, and the resulting nomogram for steady-power computations is shown in Fig. 8.3

(a) *Nomogram Instructions, Steady Power.* To compute the gamma dosage for the steady power case from Fig. 8.3, where the previous steady power is expressed in kilowatts, for a distance d (meters) from the origin, given the height of rise h (meters), the wind speed $\bar{u}$ (meters/sec), and the Sutton diffusion parameters $C[(\text{meters})^{n/2}]$ and n, the procedure is as follows:

1. Place a straightedge through d on the $d + x_0$ scale and n; mark the intersection on the $d^{(2-n)/2}$ scale.
2. Place the straightedge through this point on the $d^{(2-n)/2}$ scale and C; mark the intersection on the $\sigma$ scale.
3. Align the straightedge parallel to the vertical axis through this point on the $\sigma$ scale; mark the intersection with the curve representing h (or a suitably interpolated point). The ordinate is h′.
4. Align the straightedge horizontally through this h′ value; mark the intersection with the curve representing d (or a suitably interpolated value). (*The abscissa is the dosage for a* 1-kw previous steady power and 1 meter/sec wind speed.)
5. The wind speed adjustment is as follows: Lay the straightedge parallel to the vertical axis through the point on the d scale (step 4), and mark the intersection with the 1 meter/sec wind speed line.
6. Lay the straightedge horizontally through this point and mark the intersection with the line representing the wind speed $\bar{u}$.
7. Lay the straightedge vertically through this point and mark the intersection with the D/Q axis.
8. Lay the straightedge through D/Q from step 7 and Q; the intersection on the D scale is the gamma dosage in roentgens. Note that these dosages are computed on the basis of releasing 100% of the fission products to the air. These values may be adjusted to conform to the postulated release by multiplying by the percentage of fission products assumed to escape.

As with Fig. 8.1 scales are included to permit the use of Fickian diffusion coefficients or the computation of virtual source corrections $x_0$. Instructions for these computations are given in Sec. 3.1a, step 1a, and Sec. 3.1b.

(b) *Steady Power Cloud Dosage Variability.* The slower decay with distance results in a



| SYMBOL | DEFINITION | UNITS |
|---|---|---|
| d | DISTANCE DOWNWIND | M |
| n | SUTTON STABILITY INDEX | — |
| C | SUTTON DIFFUSION PARAMETER | $M^{n/2}$ |
| σ | CLOUD RADIUS PARAMETER | M |
| h | CLOUD HEIGHT | M |
| h' | EQUIVALENT POINT-SOURCE HEIGHT | M |
| ū | WIND SPEED | M/SEC |
| Q | INTEGRATED POWER | MW/SEC |
| D | DOSAGE | r |
| $x_0$ | VIRTUAL POINT SOURCE DISTANCE | M |
| K | FICKIAN DIFFUSION COEFFICIENT | $CM^2/SEC$ |

Fig. 8.3—Cloud gamma dosage, steady power products (Holland).

maximum dosage at the distance of the maximum ground concentrations. The wind speed variation, now acting in the same sense as the stability variation, increases the spread of dosages between the stable and unstable cases (as defined in Table 8.2). In stable conditions dosages exceeding $3 \times 10^{-3}$ r/kw can occur as far as 20 km from the point of release or with an initial cloud rise of as much as 50 meters. Dosages greater than 1 r/kw are found only at distances less than 100 meters with a small initial cloud diameter and no height rise. Maximum gamma dosages anywhere at the ground for the elevated clouds are about $6 \times 10^{-3}$ r/kw for $h = 50$ meters; $6 \times 10^{-4}$ for $h = 200$ meters; and $3 \times 10^{-5}$ for $h = 500$ meters.

(c) *Dosages for Specific Radioisotopes.* The dashed curve marked "KC" in Fig. 8.3 is included to permit computation of the gamma dosage of a cloud of any specific radioisotope whose gamma energy is of the order of 0.5 to 1 Mev and whose half life is large compared to the cloud passage time (e.g., 1 hr or more). In this case follow the same procedure as that for the steady power case up to step 4, then use the dashed curve marked KC to obtain the dosage per kilocurie for $E = 0.7$ Mev and $\bar{u} = 1$ meter/sec. To obtain the gamma dosage in roentgens, this should be multiplied by

$$\frac{Q_i\, E \exp\left(\frac{-0.693\, d}{\bar{u}\, T}\right)}{0.7\bar{u}} \qquad (8.7)$$

where $Q_i$ = initial source strength in kilocuries
$E$ = gamma ray energy in million electron volts
$T$ = half life in seconds
$d$ = distance of the receptor in meters
$\bar{u}$ = mean wind speed in meters per second

(d) *Continuous Release of Fission Products.* The KC curve of Fig. 8.3 may also be used in this same manner for continuous source problems (except for the continuous emission of fission products as they are formed, in which case Fig. 8.1 is applicable); substitution of the emission rate $dQ_i/dt$, in kilocuries per hour, for $Q_i$ yields the gamma dose rate, in roentgens per hour. $dQ_i/dt$ may require a further correction for decay if there is an appreciable holdup time prior to release to the air.

(e) *Dosage Contours.* If it is desired to compute dosages for locations other than directly under the axis of the cloud ($y = 0$), these values can be obtained for any distance $y$ from the $x$ axis by substituting $\sqrt{y^2 + h^2}$ for $h$ on the nomogram. Computation of a sufficient number of these values for various distances will permit the ready construction of isodose lines.

## 4. EXTERNAL GAMMA DOSAGE DUE TO SURFACE DEPOSITION

The dose rate 1 meter above an infinite, horizontally uniform deposit of 1 curie/m² of fission products giving off 0.7 Mev of gamma radiation is approximately 10 r/hr.[63] This relation can be used with the deposition equations, Eqs. 7.3, 7.6, or 7.7, to obtain an estimate of the dose rate near the ground. The resulting value is an upper limit to the dosage since it does not take into account either the finite size and inhomogeneity of the area of deposition or the probable shielding by surface irregularities.

In order to obtain the total dosage, the dose rate must be integrated over a period of time

$$D_d = 3 \times 10^{-3} \frac{\text{r m}^2}{\text{sec curie}} \int_{t_1}^{t_2} \chi_d\, dt$$

where $\chi_d$ is the surface deposition in curies per square meter. $\chi_d$ can be represented as $\chi_0\, f(t)$, where $\chi_0$ is the deposition factor, a function only of the initial source strength and deposition parameters, and $f(t)$ is the decay factor. Then

$$\int_{t_1}^{t_2} \chi_d\, dt = \chi_0 \int_{t_1}^{t_2} f(t)\, dt$$

where $t_1$ is ordinarily the travel time preceding deposition $d/\bar{u}$ and $t_2$ may be chosen according to the specific problem under consideration. Thus for $f(t) = t^{-1.21}$, as in the case of the products of a short-lived nuclear energy excursion, $t_2$ may be taken as infinity:

$$\int_{d/\bar{u}}^{\infty} f(t)\, dt = \frac{1}{0.21}\left(\frac{d}{\bar{u}}\right)^{-0.21} \qquad (8.8)$$

On the other hand, for $f(t) = t^{-0.21}$, as in the case of the fission products of a reactor operating at a steady power for a long time,

$$\int_{d/\bar{u}}^{t_2} f(t)\,dt = \frac{1}{0.79}\left[t_2^{0.79} - \left(\frac{d}{\bar{u}}\right)^{0.79}\right] \qquad (8.9)$$

which increases without bound with increasing values of the upper limit $t_2$.

For exponential decay $f(t) = e^{-\lambda t}$ and

$$\int_{d/\bar{u}}^{t_2} f(t)\,dt = \frac{1}{\lambda}\left(e^{-\lambda d/\bar{u}} - e^{-\lambda t_2}\right)$$

or

$$\frac{T}{0.693}\left(e^{-0.693d/\bar{u}T} - e^{-0.693t_2/T}\right) \qquad (8.10)$$

where T is the half life of the radioactivity. This always has a finite value for $t_2 = \infty$, but if T is of the same order of magnitude as (or larger than) the expected exposure time of individuals, a finite upper limit should be used.

## 5. INHALATION OR INGESTION DOSAGES

The TID formula (Eq. 4.72) can be used to obtain estimates of the inhalation hazard. For specific isotopes, dosages calculated by this formula can be compared with maximum permissible concentrations[105] given in the National Bureau of Standards Handbook 52 for appropriate exposure times. As a rough rule it has been estimated by various writers that the inhalation dosage of 10 curie sec/m$^3$ of mixed fission products would result in an internal radiation dosage equivalent to about 25 r. The major portion of the dosage is contributed by a selection of biologically active radioisotopes comprising about 10% of the total mixed fission products.

Estimates of the probable hazard of ingesting contaminated food, etc., must be made by calculating the deposition density due to fall-out or wash-out, postulating some sequence of events leading to ingestion, and comparing the resulting consumption of radioactivity with the permissible limits given in the NBS Handbook 52.

## 6. BETA DOSE FROM SKIN DEPOSITION

It has been estimated by Healy[70] that approximately $3 \times 10^{-7}$ curies/m$^2$ of mixed fission products from a nuclear power excursion deposited on the skin would produce a beta dose rate in the skin of 1 r/hr at 1 hr after the incident. This can be compared with calculations of fall-out to estimate the skin beta dosage.

# 9

# Graphical Solutions to Atmospheric Diffusion Problems

Because of the values that the variables and parameters assume, numerical evaluations of diffusion equations are fairly tedious. Furthermore, since in most cases the use of tables of logarithms cannot be avoided, direct numerical calculations will ordinarily produce a degree of accuracy far greater than that warranted by the diffusion theories themselves. Graphical aids would seem, consequently, to be particularly desirable in diffusion calculations.

Graphs for the evaluation of functions of the basic form of those derived from the Gaussian law (Chap. 4) have been given by Frenkiel[50] and Jahnke and Emde.[86] Davidson[32] gives a very useful set of nomograms covering some of Calder's results; and some nomographic presentations of Bosanquet and Pearson's continuous point source formula can be found in Falk et al.[45] Sutton[138] refers to a slide rule invented by Davies which solves the Sutton equation for certain discrete combinations of the meteorological parameters. The pages to follow not only give solutions to basic diffusion equations but also treat many useful modifications. A wide range of variables and parameters is allowable.

The parameters of Sutton's theory, n (stability) and C (diffusion coefficient), may be solved for on the basis of measurements by meteorological instruments, or they may be chosen as estimates from suggestions given in Chap. 4 on diffusion theory. Applicability and limitations of the various theoretical treatments are also given in Chap. 4, and use of the graphical solutions is not advisable unless the user has knowledge of the limitations presented.

Gifford[57,58] has given an alignment chart that is most useful in the numerical evaluation of any diffusion formula of Sutton's type, and this graph is reproduced here as Fig. 9.1. Furthermore, formulae like those of Frenkiel and Roberts can also be evaluated using suitable substitutions.

## 1. THE SUTTON TYPE EQUATION

The use of Fig. 9.1 is illustrated by the following problem:

*Problem:* Find the relative dilution, $\chi/Q$, at a point at the ground beneath the axis of a plume, 1000 meters downwind from a continuously emitting stack which is 100 meters high. The parameters have the values $n = 0.5$, $C^2 = 0.2$, and $\bar{u} = 2$ m/sec.

*Solution on Fig. 9.1:* 1. Align (most conveniently with a transparent straightedge) $x = 1000$ meters, scale I, with n, scale II, locating a point on the reference scale, $R_1$.

2. Align this point with $C^2$, scale III, locating a value of f, scale IV.

3. Align the stack height h, scale V, with the value of f obtained in step 2, on scale VIII (C.P.S. = continuous point source), locating a point on the reference scale, $R_2$.

4. Align this point with $\bar{u}$, scale X, and find that $\chi/Q = 1 \times 10^{-6}$, scale XII.

The light guide lines (a), (b), (c), and (d) on Fig. 9.1 illustrate this problem. If the lateral ground concentration at a given distance y from the point below the cloud axis had been required, the steps would be the same, except that instead of using h, scale V, the value $r^2 = y^2 + h^2$ on scale VI would be used.

To calculate the maximum concentration, $\chi_{max}$, find a line through h, scale V, tangent to scale VIII, locating a point on $R_2$. Then align this point and $\bar{u}$, scale X, and read $\chi_{max}/Q$ from scale XII. The product of this and the

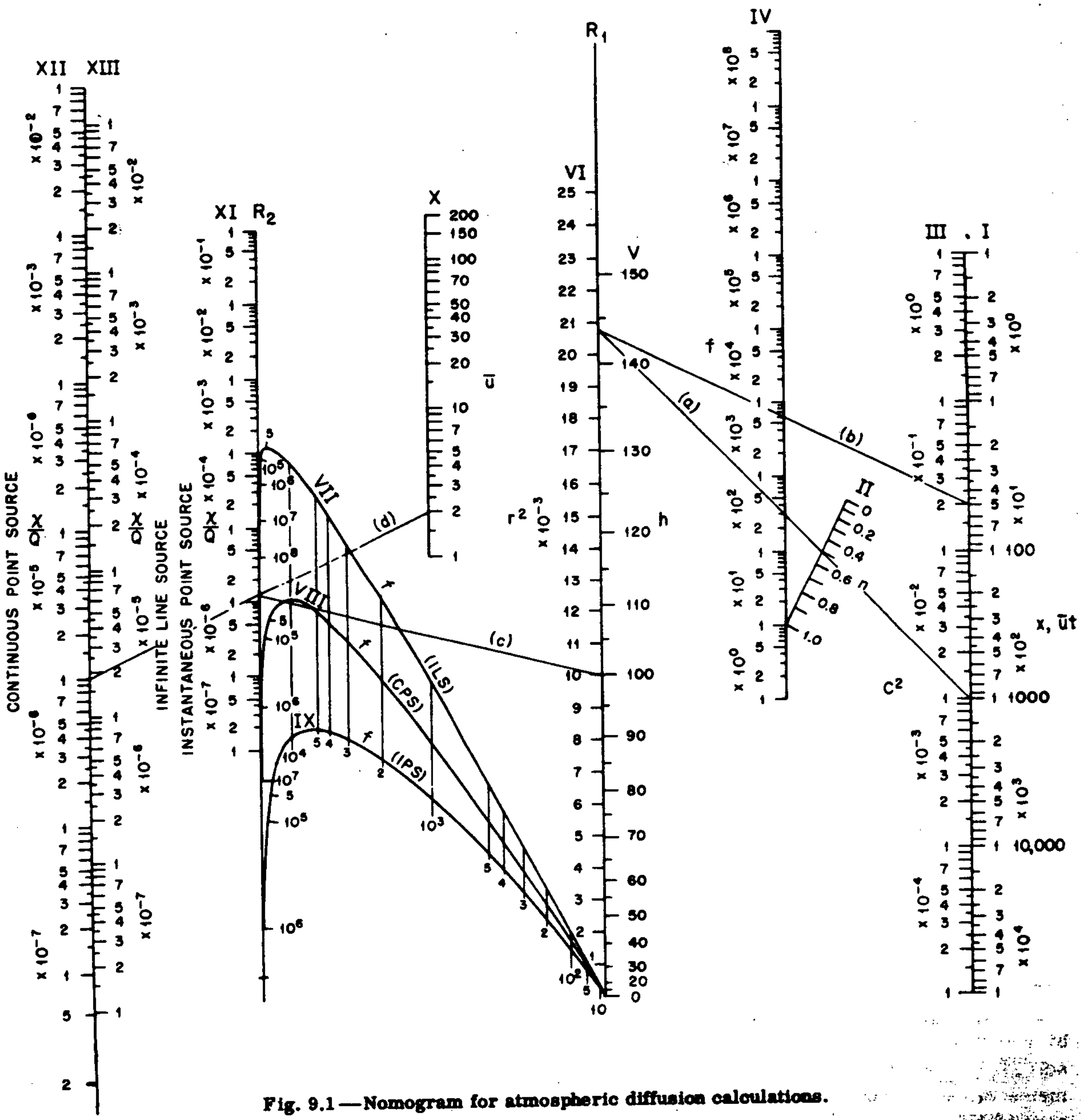


Fig. 9.1—Nomogram for atmospheric diffusion calculations.

emission rate is the desired maximum ground concentration. Table 9.1 lists the alignments, in their proper order, by means of which the most commonly occurring diffusion problems may be solved. Points on three scales are aligned at each step; two of which are known, either from the conditions of the problem or from a previous step. The unknown quantity in the final step is in each case the quantity desired. The mathematical considerations in the construction of the nomogram appear in the original paper.[57]

1.1 *Short-period Peak Concentration.* Only a slight rearrangement of the procedure outlined in the sample problem above is needed to find the eddy peak concentration (for looping conditions) as defined in Chap. 5. Obtain the value of f, scale IV, in the same way (steps 1 and 2), but use $(x^2 + h^2)^{1/2}$ instead of x if these

Table 9.1 — Program for Solving Meteorological Diffusion Problems on Fig. 9.1†

| Source type | Equation | Quantity sought | Symbol | Necessary alignments (symbols refer to corresponding scales, Fig. 9.1) | Remarks |
|---|---|---|---|---|---|
| Instantaneous point source at the ground | 4.36‡ | Ground concentration | $\chi_{(x,y)}$ | $R_1$ – II – I; $R_1$ – IV – III; XI – IX – VI | Use $r^2 = x^2 + y^2$, scale VI;(†) |
| | 4.36‡ | Concentration at a height h | $\chi_{(x,y)}$ | $R_1$ – II – I; $R_1$ – IV – III; XI – IX – VI | Use $r^2 = x^2 + y^2 + h^2$, scale VI;(†) |
| Instantaneous elevated point source at a height h | 4.36‡ | Ground concentration | $\chi_{(x,y)}$ | $R_1$ – II – I; $R_1$ – IV – III; XI – IX – VI | Use $r^2 = x^2 + y^2 + h^2$, scale VI;(†) |
| | 4.63 | Distance of the max. ground concentration | $d_{max}$ | $R_2$ – (t)IX – V; $R_1$ – IV – III; $R_1$ – II – I | § |
| | 4.64 | Max. ground concentration | $\chi_{max}$ | XI – (t)IX – V | § |
| | 4.50 | Integrated ground concentration | | $R_1$ – II – I; $R_1$ – IV – III; $R_2$ – VIII – VI; XII – $R_2$ – X | Cf. text |
| Continuous point source at the ground | 4.50 | Downwind concentration at height h | $\chi(x,0)$ | $R_1$ – II – I; $R_1$ – IV – III; $R_2$ – VIII – V; XII – $R_2$ – X | † |
| | 4.50 | Ground concentration at lateral distance y from cloud axis | $\chi(x,y)$ | $R_1$ – II – I; $R_1$ – IV – III; $R_2$ – VIII – V; XII – $R_2$ – X | Use h = y, scale V; (†) |
| | 4.50 | Concentration at height h and lateral distance y | $\chi(x,y)$ | $R_1$ – II – I; $R_1$ – IV – III; $R_2$ – VIII – VI; XII – $R_2$ – X | Use $r^2 = y^2 + h^2$, scale VI; (†) |
| Continuous elevated point source at a height h | 4.50 | Downwind ground concentration | $\chi(x,0)$ | $R_1$ – II – I; $R_1$ – IV – III; $R_2$ – VIII – V; XII – $R_2$ – X | †,¶ |
| | 4.66 | Ground concentration at lateral distance y from cloud axis | $\chi(x,y)$ | $R_1$ – II – I; $R_1$ – IV – III; $R_2$ – VIII – VI; XII – $R_2$ – X | Use $r^2 = y^2 + h^2$, scale VI; (†) |
| | 4.65 | Max. ground concentration | $\chi_{max}$ | $R_2$ – (t)VIII – V; XII – $R_2$ – X | § |
| | 4.50 | Distance of the max. concentration | $d_{max}$ | $R_2$ – (t)VIII – V; $R_1$ – IV – III; $R_1$ – II – I | § |
| | 4.50 | Distance downwind a given concentration will occur | x | XII – $R_2$ – X; $R_2$ – VIII – V; $R_1$ – IV – III; $R_1$ – II – I | Two values of f are defined by the 2nd alignment, which leads to two values of x |
| | 4.50 | Distance from cloud axis y a given concentration will occur | y | $R_1$ – II – I; $R_1$ – IV – III; XII – $R_2$ – X; $R_2$ – VIII – VI | Use $y^2 = r^2 - h^2$ to find y |
| | 4.50 | n, given the downwind concentration | n | XII – $R_2$ – X; $R_2$ – VIII – V; $R_1$ – IV – III; $R_1$ – II – I | |
| | 4.50 | n, given the concentration at a lateral distance y from cloud axis | n | XII – $R_2$ – X; $R_2$ – VIII – VI; $R_1$ – IV – III; $R_1$ – II – I | |
| | 4.50 | $C^2$, given the downwind concentration | $C^2$ | XII – $R_2$ – X; $R_2$ – VIII – V $R_1$ – II – I; $R_1$ – IV – III | |
| | 4.50 | $C^2$, given the concentration at a lateral distance y from cloud axis | $C^2$ | XII – $R_2$ – X; $R_2$ – VIII – VI; $R_1$ – II – I; $R_1$ – IV – III | |
| Continuous infinite crosswind line source at the ground | 4.53 | Downwind concentration at height h | $\chi_{(x)}$ | $R_1$ – II – I; $R_1$ – IV – III; $R_2$ – VII – V; XIII – $R_2$ – X | † |
| Continuous infinite crosswind elevated line source at a height h | 4.53 | Downwind ground concentration | $\chi_{(x)}$ | $R_1$ – II – I; $R_1$ – IV – III; $R_2$ – VII – V; XIII – $R_2$ – X | † |
| | 4.68 | Max. ground concentration | $\chi_{max}$ | $R_2$ – (t)VII – V; XIII – $R_2$ – X | § |
| | 4.67 | Distance of the max. concentration | $d_{max}$ | $R_2$ – (t)VII – V; $R_1$ – IV – III; $R_1$ – II – I | § |
| | 4.53 | Distances downwind a given concentration will occur | x | XIII – $R_2$ – X; $R_2$ – VII – V; $R_1$ – IV – III; $R_1$ – II – I | Two values of f are defined by the second alignment, which leads to two values of x |
| | 4.53 | n, given the downwind concentration | n | XIII – $R_2$ – X; $R_2$ – VII – V; $R_1$ – IV – III; $R_1$ – II – I | |
| | 4.53 | $C^2$, given the downwind concentration | $C^2$ | XIII – $R_2$ – X; $R_2$ – VII – V; $R_1$ – II – I; $R_1$ – IV – III | |

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† Many other problems can be solved, the listed ones being the most common. It will be evident from the examples in this table how to solve problems not appearing specifically in it. In particular, the source strength, Q, can obviously be found by the same alignments for the problems marked with the symbol †, given an observed $\chi$ and a calculated $\chi/Q$.

‡ With right-hand side multiplied by 2 to account for reflection by the ground.

§ The symbol (t) means "find a tangent to."

¶ A problem of this type is given as a text example.

differ appreciably. Then follow steps 3 and 4, but use the value of h, scale V, equal to zero.

1.2 *Instantaneous Volume Source.* To solve the volume source formula, Eq. 4.58, follow the same alignments as for the instantaneous point source, but use $(\bar{u}t + x_0)$ instead of $\bar{u}t$.

1.3 *Evaluation of Other Equations.* Certain of the remaining diffusion equations that have appeared in the text may also be evaluated on Fig. 9.1. Since Sutton's equations are related to Robert's, if n = 1 and

$$C^2x^{2-n} = \frac{4Kx}{\bar{u}} = 4Kt$$

where $C^2x^{2-n} = f$ in Fig. 9.1, Eqs. 4.5 and 4.47 are readily evaluated by the alignment schemes of Table 9.1. It is necessary to use n = 1 on scale II and for $C^2$ to substitute $(4K/\bar{u})$ on scale III.

Certain of the nonisotropic equations may also be evaluated. For example, if one considers the downwind concentration (y = 0), Sutton's continuous point source equation (Eq. 4.51) becomes

$$\chi = \frac{2Q}{\pi C_y C_z \bar{u} x^{2-n}} \exp\left(-\frac{z^2}{C_z^2 x^{2-n}}\right)$$

Thus it is only necessary to obtain the solution to Eq. 4.50, using $C^2 = C_yC_z$, and then to correct the result by multiplying by $(C_z/C_y)$. By this method Eqs. 4.48 and 4.51 both can be evaluated.

The deposition formula, Eq. 7.6, can likewise be evaluated since it is of the same form as Eq. 4.50. Note also that Eqs. 4.72 to 4.74 are like Eqs. 4.50, 4.66, and 4.65. The user will undoubtedly discover further occasions for employing Fig. 9.1 with little difficulty. For example, the maximum deposition equation (Eq. 7.7) is easily brought to the form of Eq. 4.53 by the use of the factor (n/4e), although a more convenient graph for this specific purpose has been included in this chapter as Fig. 9.7.

1.4 *Maximum Concentrations from Continuous Point Source.* Figure 9.2 is an alignment chart for finding $\chi_{max}$ from a continuous point source which is more convenient for this purpose than Fig. 9.1. The precedure is as follows:

$$\chi_{max} = \frac{2Q}{\pi e \bar{u} h^2} \frac{C_z}{C_y}$$

1. Align $\bar{u}$, scale I, with h, scale II.
2. Find a perpendicular to this line through Q (units per second), scale IV. If isotropic diffusion is assumed, the value of $\chi'_{max}$ which this locates on scale III is the required one.
3. If nonisotropic diffusion is assumed or if the Brookhaven wind trace types are used (see Chap. 5), align the point found on scale III with $C_z/C_y$, or $a_m$, scale V, and read $\chi_{max}$, scale VI.

The Brookhaven standard values for $a_m$ for type A, B, C, and D wind traces have been indicated on scale V for convenience.

## 2. PLUME SPREAD

Figure 9.3 is an alignment chart for solving for the width and height of a plume at a given distance from the source. The procedure is as follows:

1. Align x, scale I, with n, scale II, locating a point on R.
2. Align this point with C or $C^2$, scale III.
3. Find a perpendicular to this (conveniently by sliding an ordinary drafting triangle along the straightedge) passing through P (percentage of central plume concentration), scale IV, and read $2y_0$ or $z_0$ on scale V or scale VI. In the problem illustrated by the guide lines, x = 500 meters, n = 0.5, $C^2 = 0.1$, P = 10, and $2y_0$ = 100 meters.

## 3. EXTENSION OF SUTTON'S PARAMETERS

Barad and Hilst[5] extended the diffusion coefficients given by Sutton for "average" conditions to cover a greater range of conditions. Figure 9.4 is a nomogram from which these extended values may be obtained.

For h = 100 meters, n = 0.25, and $\bar{u}$ = 10 m/sec, C = 0.094.

## 4. INSTRUMENTALLY DETERMINED DIFFUSION PARAMETERS

4.1 *Stability Parameters.* The stability parameter, n, can be solved by Fig. 9.5, given

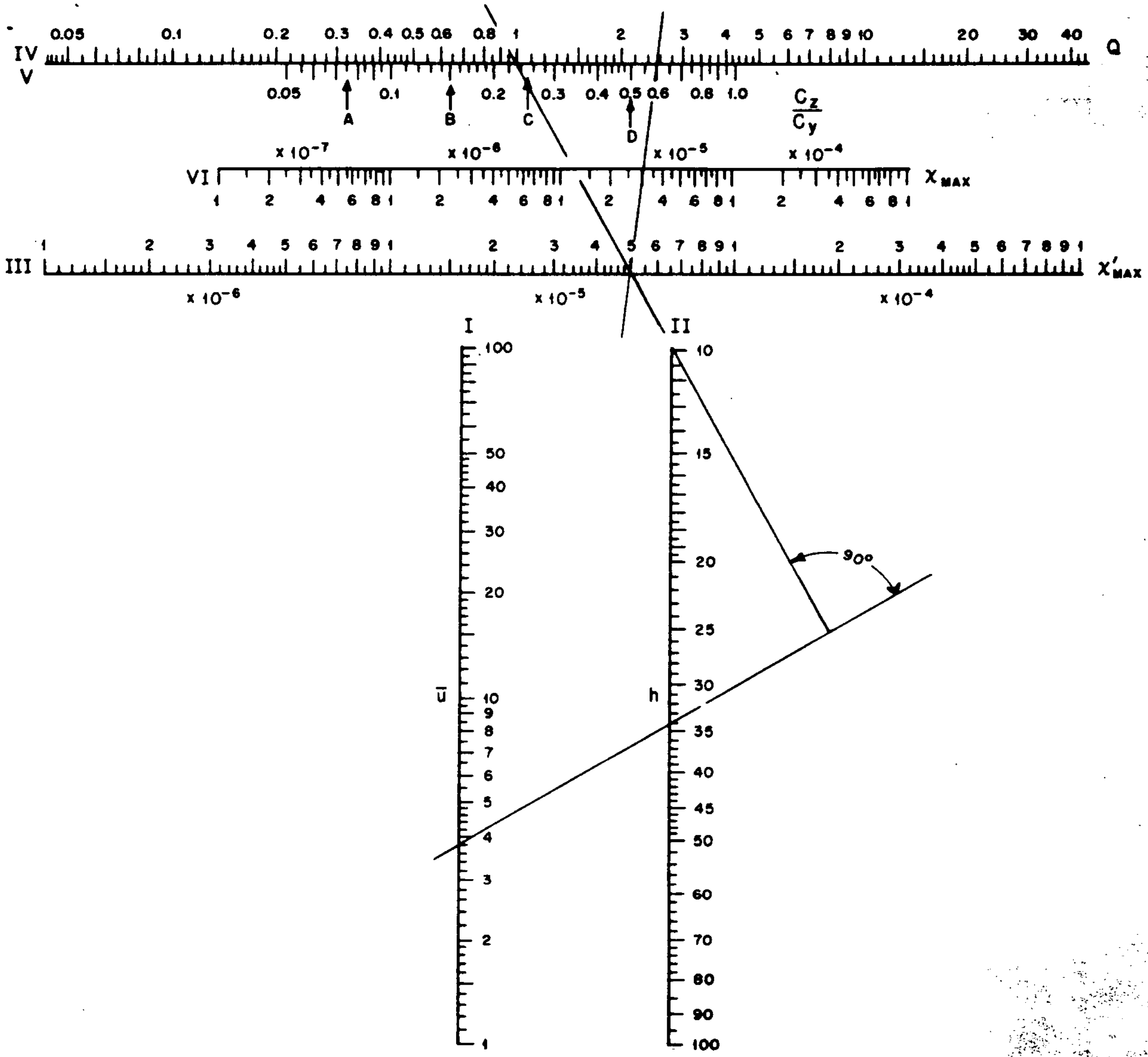


Fig. 9.2—Nomogram for solving Sutton's maximum concentration equation.

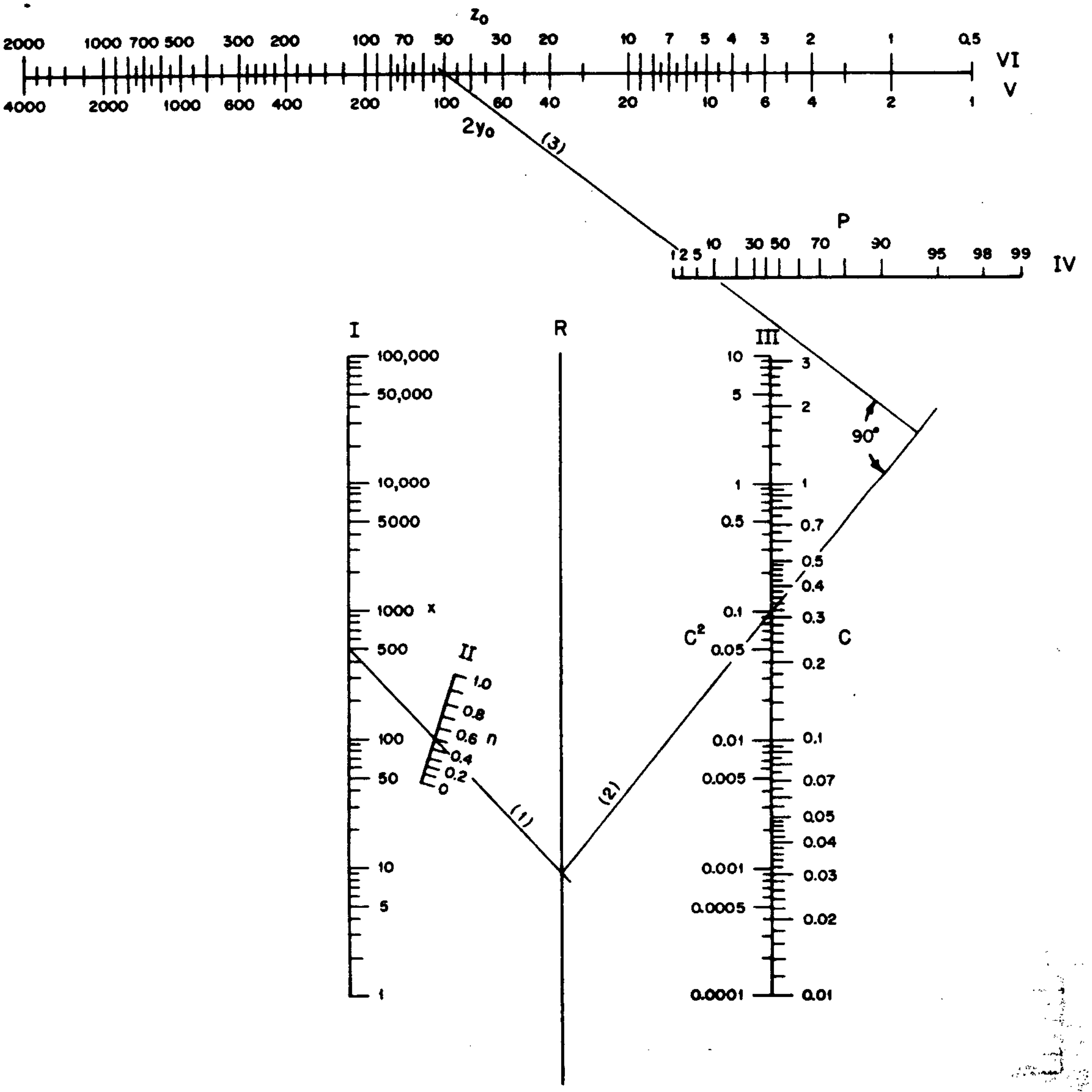


Fig. 9.3—Nomogram for solving Sutton's cloud height and width equations.

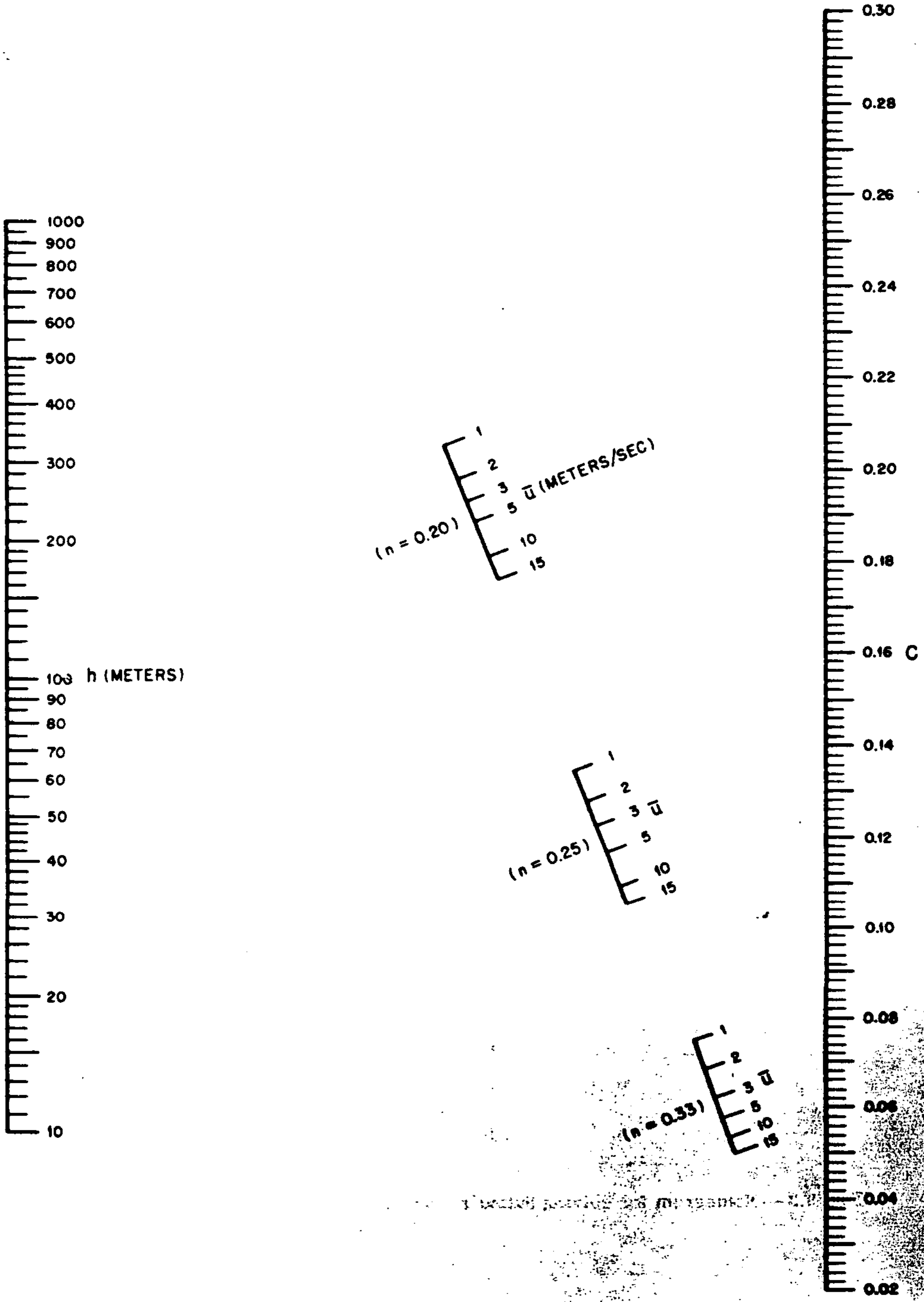


Fig. 9.4—Sutton's coefficient of diffusion (C) as a function of source elevation (h), stability (n), and wind speed (ū).

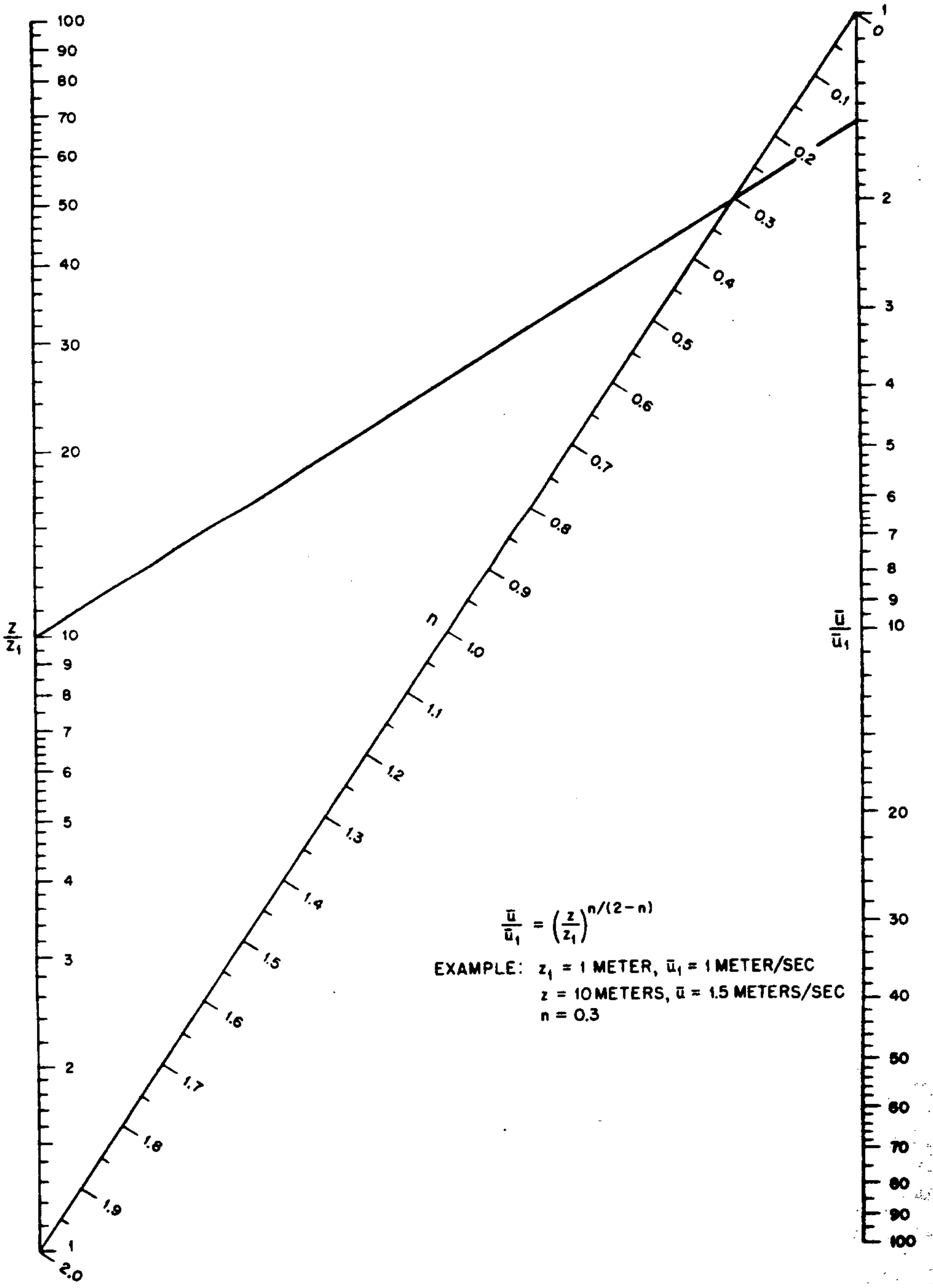
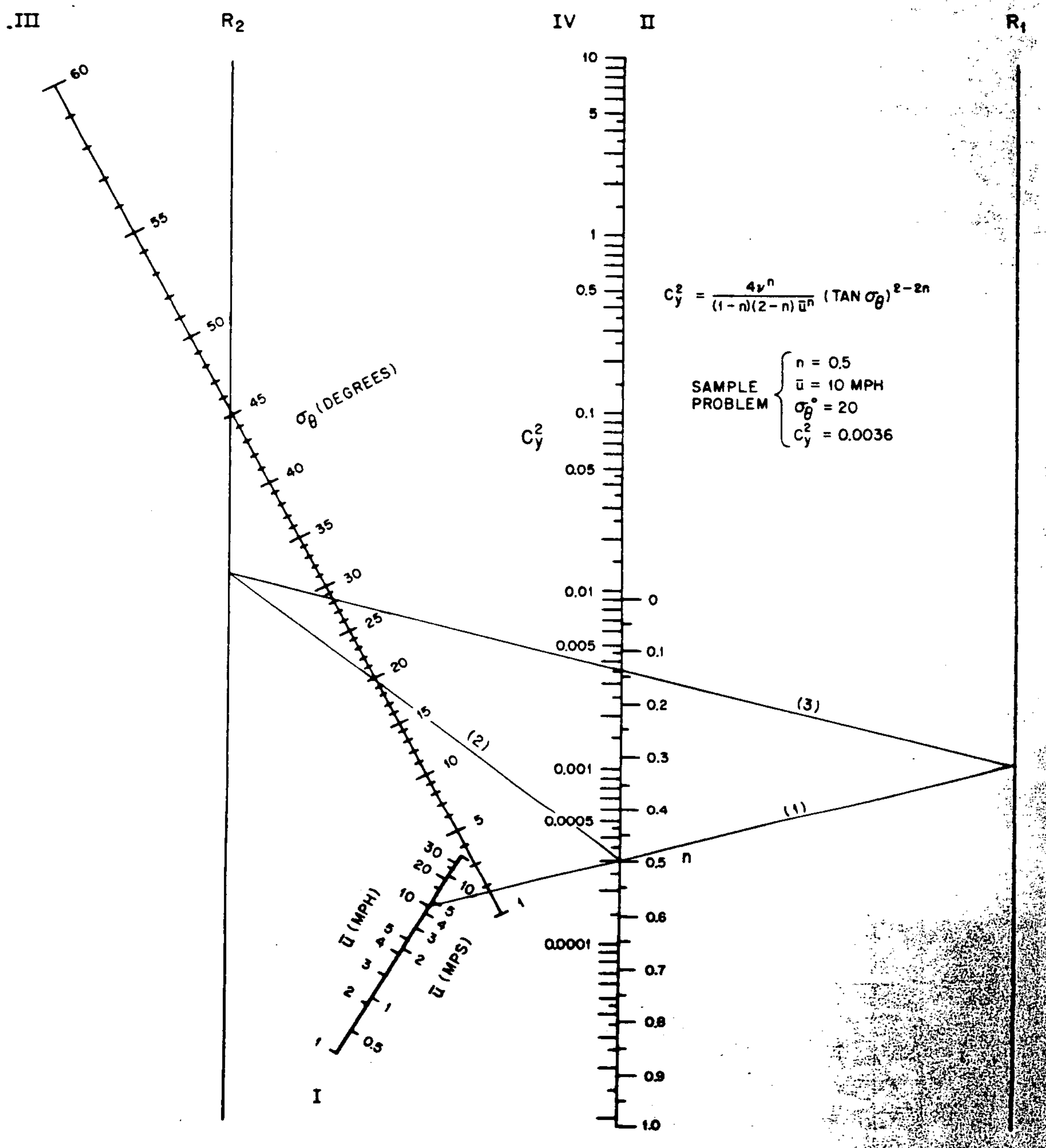


Fig. 9.5—Nomogram for solving Sutton's stability parameter (n) equation.



$C_y^2 = \frac{4\nu^n}{(1-n)(2-n)\bar{u}^n}(\tan\sigma_\theta)^{2-2n}$

SAMPLE PROBLEM
$n = 0.5$
$\bar{u} = 10$ MPH
$\sigma_\theta^\circ = 20$
$C_y^2 = 0.0036$

Fig. 9.6—Nomogram for solving Sutton's $C_y^2$ equation.

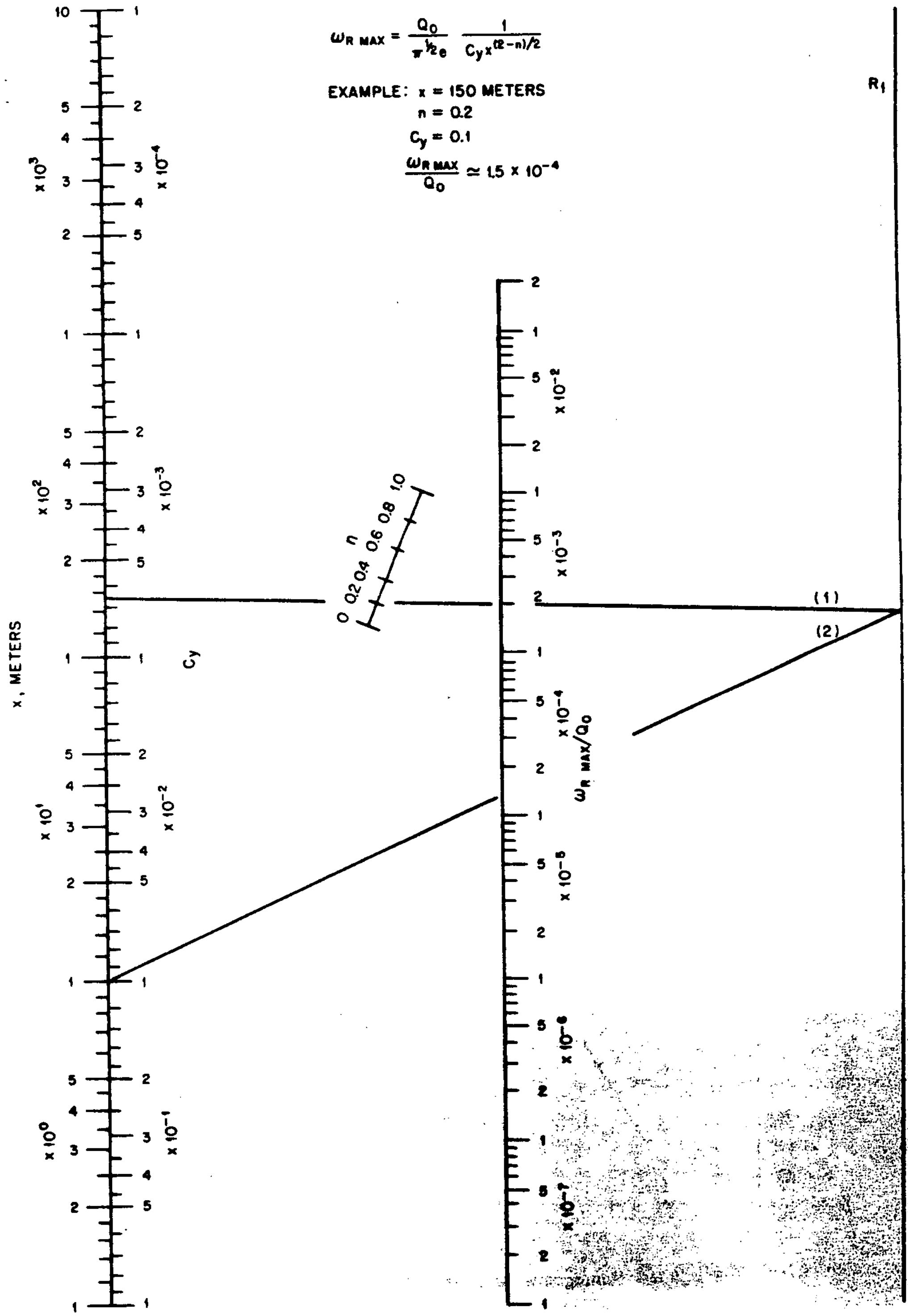


Fig. 9.7—Nomogram for computing maximum deposition.

measured wind speeds at two levels above the ground, provided that they fit a power law wind speed profile. Align the ratio of the wind speeds on the right-hand scale with the ratio of the corresponding heights on the left. The required value of n is read from the center scale.

4.2 *Diffusion Coefficients.* Figure 9.6 is an alignment chart for evaluating Eq. 4.79, from which diffusion coefficients can be determined from the oscillations of a wind vane. The procedure is as follows:

1. Align $\bar{u}$, scale I, with n, scale II, locating a point on $R_1$.
2. Align n, scale II, with $\sigma_\theta$ (standard deviation of vane oscillations) scale III, locating a point on $R_2$.
3. Join $R_1$ and $R_2$, and read $C_y^2$ on scale IV.

(There is at present not much agreement between meteorologists as to the applicability of these instrumentally determined coefficients for substitution into the diffusion equation.)

## 5. DEPOSITION

Of considerable interest is the maximum deposition that will occur at a given distance x, for a constant rate of fall-out or wash-out. For dry deposition the equation is

$$\omega_{\text{dry max}} = \frac{Q_0 n}{2\pi^{1/2} e} \, \frac{1}{C_y x^{(2-n)/2}}$$

and for wash-out deposition

$$\omega_{\text{rain max}} = \frac{Q_0}{\pi^{1/2} e} \, \frac{1}{C_y x^{(2-n)/2}}$$

Note that, although a different rate of deposition is required for each distance x to obtain the maximum deposition, this rate is constant over the interval 0 to x.

Figure 9.7 can be used to solve the above equations by the following steps:

1. Aligning x and n and marking a point on $R_1$.
2. Aligning the point on R with $C_y$, and reading the resulting value of $\omega_{R\ \max}$. To obtain the dry deposition maxima, compute $\omega_{R\ \max}$ and multiply by n/2.

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# 10

# Reactor Hazard Analyses

The Atomic Energy Act of 1954 states that the Atomic Energy Commission is authorized to "prescribe such regulations or orders as it may deem necessary... (3) to govern any activity authorized pursuant to this Act, including standards and restrictions governing the design, location, and operation of facilities used in the conduct of such activity, in order to protect health and to minimize danger to life or property." In the July 1950 semi-annual report "Control of Radiation Hazards in the Atomic Energy Program" it was stated: "The atomic energy industry employs forces that are as yet imperfectly understood; it is being developed at an unprecedented rate without benefit of the years of experience gained in other large industries; ... and it promises to be vitally important in the future of mankind. All these reasons justify a resolute effort to keep it a safe industry for its workers and its neighbors."

As one step toward ensuring reasonable safety precautions, the AEC requires an analysis of possible accidents (or sabotage) that might occur to all new reactors contemplated by any group in the United States. These analyses mainly consider the reactor technology and the nuclear aspects of such incidents; however, meteorology is considered (1) to determine the degree of effort required to ensure adequate containment, by examination of the hazard produced by the release of fission products to the atmosphere, and (2) evaluation of hazards resulting from planned routine release of radioactive material to the air.

Many reports of this type have been prepared in the last few years for review by members of the AEC and the Advisory Committee on Reactor Safeguards (formerly the Reactor Safeguard Committee). Meteorological material has been included in most of these reports, but for each one it has been included in a slightly different manner. It is impossible to set down a standard format which could be used for all, but included in this chapter is a listing of items pertinent to a release of airborne radioactivity which should be considered for possible inclusion in a complete reactor hazard analysis. Not all reactor hazard analyses would, or should, contain all the elements listed below. The type of reactor, its design power level, the site locations, etc., must be considered in fixing the scope of a hazard analysis. Only a first presentation of a very high power reactor would require consideration and treatment of all items. Analyses for reactors at a site for which previous reports have been prepared may well refer to these reports for climatology, site description, etc., and deal only with items or hazards unique to the device under consideration. Standard computational techniques (see Chap. 8 for one such technique) for radiation estimates can eliminate repetition of derivations and basic meteorological data.

The items listed in the outline should not be considered separately but rather should be integrated to whatever extent is necessary into the entire hazard analysis. Obviously, a health physicist and a reactor engineer will have to provide much of the required information.

Maps showing population centers and vulnerable installations, such as water reservoirs, on which are given probable ground concentrations, dosages, or amounts of deposition, may be used to advantage.

The worst possible diffusion situation, although not necessarily the maximum hazard, results from a ground release of contaminant within a stable (temperature inversion) layer. The eddy diffusion rate for these conditions is very small. Wind speeds may be assumed to be very light, probably less than 5 mph, and vertical wind shear may be quite pronounced. Also, under inversion conditions especially, a debris cloud could remain within a valley or follow the contours of a hill. If inversion conditions occur at a reactor site, it is realistic to consider such conditions in the disaster analysis. Wind trajectory analyses, superimposed on maps of the area of interest, are most helpful in dealing with cloud behavior under inversion conditions. In some cases it may be shown that inversion conditions will produce potentially very dangerous situations; but in others it may be shown that under these conditions a cloud is likely to be channeled into a safe direction or, because of low wind speeds, the decay and slow movement may prevent serious damage.

The greater the amount of energy released the higher the debris cloud will rise in the atmosphere, regardless of meteorological conditions. Obviously, the worst disaster may not occur with the greatest explosion. One way to maximize the reactor cloud hazard would be to assume only the minimum amount of heat required to liberate all the fission products to the air.

In dealing with a real reactor problem, it may not be feasible to determine the worst possible meteorological condition. The many variables which represent conditions that could actually occur might render the determination of a "maximum hazard" impossible. For example, at a given location it might be impossible to determine the one combination of wind speed, rainfall, diffusion conditions, and radioactive decay which would produce harmful dosages to the largest number of persons. In this connection it may be necessary to consider and compare hazards from external gamma and beta radiation to the problems of ingestion and inhalation of radioactive products. Perhaps the practical approach is to take several possible cases that are representative but pessimistic and discuss them with candor.

The choice of diffusion parameters for solving specific problems should be consistent with the meteorological conditions under consideration. For example, sometimes the worst situation may be thought to be one in which a debris cloud drifts over a reservoir or a center of dense population and a sudden thundershower washes down all the radioactive material. It should be remembered that a combination of poor diffusion and shower conditions rarely occurs. Similarly, the combination of poor diffusion and strong winds, which might quickly transport the cloud to an important area before there is much radioactive decay, is rare.

Simplifying assumptions with regard to the release of material, the shape of the cloud, and initial concentrations within the cloud are usually necessary, but for the sake of additional safety it is desirable that the assumptions err on the pessimistic side.

Reports may be prepared which have to serve as a site and reactor proposal as well as a reactor hazard analysis. In this case more meteorological data will have to be included.

The inclusion of a large volume of tabular meteorological data in the actual reactor report is not usually necessary or desirable. It will ordinarily suffice to describe the location of the meteorological station(s), the instrumentation, and the types of data collected. The pertinent portions of the summarized and correlated data can then be introduced pictorially as visual presentations (wind roses, frequency graphs, etc.), or as tables. It will often be found that averages of the various elements mask important anomalous conditions (e.g., persistent inversion conditions). These can be treated separately when they relate to the problem under consideration.

The basis of the meteorological estimates, the tabular data, should be kept available for review and use. Experience has shown that a routine program of analyzing and summarizing the meteorological records as they become available will permit the easy and rapid inclusion of additional data in later analyses. It should be noted that it is desirable to extend the length of the meteorological record with all available data to obtain values as reliable as possible.

## CHECK LIST OF METEOROLOGICAL CONSIDERATIONS PERTINENT TO REACTOR HAZARD ANALYSES

For safety the most pessimistic accident is given most attention.

1. What will be the nature of the radioactive cloud before the diffusion begins?

a. From where will the cloud enter the atmosphere?
   (1) A stack?
   (2) Building openings or outlets?
   (3) A demolished building or enclosure?
b. What will be the type of source?
   (1) Instantaneous?
   (2) Continuous?
c. What (and how much) radioactivity may be released? (If the source is not instantaneous, give rate of emission.)
   (1) Fission products (mainly short or long-lived)?
   (2) Irradiated material?
d. What will be the physical composition of the cloud, especially with regard to particulates which will fall out of it?
e. What will be the temperature of the cloud initially?
f. What will be the initial volume of the cloud when it reaches ambient pressure and temperature?
g. What will be the approximate shape of the cloud just after the disaster? How will its shape change with time? What is the initial shape assumed for the purpose of making diffusion estimates?
h. What distribution of material is assumed in the cloud prior to diffusion (uniform, Gaussian, etc.)?
i. How high will the cloud rise in the atmosphere? (What is the "effective height" at which diffusion is asumed to begin?)

2. What are the meteorological conditions chosen for estimating the effects of diffusion?
   a. Wind speeds?
   b. Diffusion parameters?
3. How will the cloud diffuse in the atmosphere?
   a. In the case of the instantaneous source.
      (1) What will be the approximate dimensions of the cloud at various distances? What will be the changes in concentrations near the ground as it moves outward from the source?
      (2) Assuming no radioactive decay, what will be the maximum ground concentrations along the line traversed by the center of the cloud?
      (3) Considering wind speed, how will radioactive decay affect dosages at the ground?
   b. In the case of the continuous point source. (The treatment may be similar to the instantaneous point source except that exposure might be figured on the basis of the duration of the emission rather than on the time required for cloud passage.)
4. How significant is fall-out and the scavenging action of precipitation?
   a. What will be the hazard from particulates at various distances as the radioactive cloud passes?
   b. How will fall-out affect concentrations and dosages near the ground?
   c. How will the scavenging action of precipitation affect concentrations and dosages near the ground?
   d. What will be the ground deposition?
      (1) Due to fall-out?
      (2) Due to the scavenging action of precipitation?
5. How representative are available meteorological data?
   a. What is the period of record? (At least 5 years of data should be considered, if available.)
   b. If the observing station is not on the site, how does its location differ from that of the site?
   c. What significant differences, if any, exist between meteorological conditions at the observing station and the site?
6. What are the significant meteorological conditions?
   a. Wind.
      (1) What is the surface wind direction and speed distribution annually (annual wind rose)?
      (2) What are the significant diurnal differences? (Are there local winds, such as sea breezes, mountain winds, etc.?)
      (3) What are the significant seasonal differences?
      (4) What is the speed and direction distribution during precipitation?
      (5) What is the speed and direction distribution during stable and unstable conditions?
      (6) What are the significant differences between surface winds and those at the height a radioactive cloud may occur?

(7) Will a trajectory away from the site rise, descend, curve, or follow a straight line because of topography?

b. Stability.

(1) What is the frequency of unstable and stable conditions?
  (a) Annually?
  (b) Seasonally?

(2) How is stability affected by local conditions (i.e., valley effects, West Coast subsidence inversion)?

(3) What is the average and maximum duration of inversion conditions?

(4) What significant facts are known about the depth and intensity of inversions?

c. Precipitation.

(1) What are the normal monthly and annual totals, and what extremes have occurred?

(2) Are there significant variations?
  (a) Seasonally?
  (b) Diurnally?

(3) What is the monthly and annual snowfall?

(4) What are the greatest amounts of precipitation recorded for various time intervals, such as 1 hr, 1 day, etc.?

(5) What is the average duration of precipitation?

(6) What is average duration of the intervals between occurrences of precipitation?

d. Severe weather.

(1) What are the possibilities of floods?

(2) What are the possibilities of wind storms (i.e., severe thunderstorms, gusts, tornadoes, and hurricanes)?

e. Miscellaneous (where significant for special designs).

(1) What natural atmospheric dustiness conditions prevail?

(2) Do rapid temperature changes occur which might make automatic control difficult?

7. Are meteorological conditions taken into consideration in the scheduling of operations? Are adverse meteorological conditions being avoided by scheduling with respect to seasonal condition, time of day, etc? Will scheduling be done on the basis of climatology, forecasts, or the actual weather conditions as observed at the time of the operation?

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# 11

# Meteorological Equipment and Records

The meteorological equipment and techniques of particular interest in connection with atomic energy are those necessary to obtain data pertinent to atmospheric diffusion. A more detailed representation of the three dimensional structure of the atmosphere is required for this purpose than is needed for ordinary engineering purposes.

Special equipment found at the larger atomic energy sites includes micro-net stations for additional surface observations of wind temperature and rainfall, meteorological tower facilities for continuous temperature and wind gradient information up to at least as high as the top of the plant stacks, and temperature and wind sounding equipment for periodically reaching levels above the top of the towers. At sites where meteorological research is conducted (as at Brookhaven, Hanford, and Argonne), special instruments for studying atmospheric turbulence are also in use.

Special meteorological records and methods of data tabulation are also necessary at sites where diffusion estimates are required. Many of the necessary parameters (wind direction deviation, temperature gradient, etc.) are not now commonly measured at the usual meteorological installation. The multiplicity of parameters and the necessity for several meteorological stations at a single site can lead to an amazing amount of raw data. Only by orderly tabulation and proper summarization can this information be reduced to a meaningful and digestible form. A sound analysis program is required if one is not to be faced with thousands of feet of wind record and reams of temperature values, all comparatively meaningless until condensed into the appropriate averages, frequencies, or correlations.

Included in this chapter are some of the special meteorological record forms and summaries which have proved useful in the preparation of diffusion climatologies.

## 1. EQUIPMENT

In the early stages of the development, both of the atomic energy industry and the application of meteorology to this field, meteorological instruments and techniques for evaluating diffusion parameters were not readily available from commercial sources. Early workers in the field were forced to utilize standard equipment or to devise and hand-make instruments for special needs. The situation is quite changed as of this writing, and very sensitive wind and temperature measuring equipment is readily available. However, the early necessity of using rugged heavy-duty weather instruments was perhaps fortunate since methods were devised to interpret these records in terms of diffusion and this type of equipment is better adapted to the required continuous, all-weather, field use.

Special types of measurements, and particularly meteorological research in diffusion, continue to require much special equipment.

The following description of instruments and installations is not exhaustive; the basic requirements of meteorological instrumentation are well known, and only the more unusual techniques will be described here. The equipment described has been utilized successfully at several of the larger AEC sites and thus represents field-tested techniques. The mention, by manufacturer's name, of certain instruments is for illustration only since in almost every instance other sources of supply of equal performance are available.

1.1 *Micro-Net Stations.* The term "micro-net" evolved as a time saver from the full

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title of "micrometeorological network" and is here used to refer to automatically operated weather stations strategically placed throughout a plant site. These stations usually measure the surface values of wind, temperature, and precipitation. Typical micro-net stations are shown in Figs. 11.1 and 11.2.

The white louvered shelter such as shown is likely to house a hygrothermograph and liquid-in-glass thermometers. Generally there is a maximum and minimum thermometer and often standard wet and dry bulb thermometers with a hand operated aspirating fan. The shelter at Oak Ridge, shown in Fig. 11.2, also contains wind recording equipment.

A completely electrical wind system is more easily installed and maintained, but suitable power lines are not always available at micro-net station locations. The wind system shown in Fig. 11.1 uses a spring-wound recorder of the Esterline-Angus type and a mechanical linkage to the direction recorder. Most wind systems do not require an outside power source for wind speed. A spinning propeller or a set of cups is used to turn a generator. This provides a voltage proportional to wind speed, which is recorded on a recording voltmeter.

Some wind systems used for micro-net purposes use battery power.[3,81] Another type called the Aerolog (Friez Instrument Division Bendix Aviation Corp.) produces pulses of air with a bellows to activate recording pens.

Precipitation is measured at micro-net stations by standard weighing rain gauges.

When spring-driven clocks are used, it is customary to visit the micro-net stations twice weekly. On one visit, instrument clocks are wound, new charts installed, pens inked, etc. On the second, instruments are checked.

The number of micro-net stations is determined by the size of the area of interest, the irregularity of terrain, the accessibility of locations, and the amount of meteorological information available from other sources. In some instances air flow has been studied by means of stations on hill sides, in narrow valleys, or in among trees and other vegetation.

Micro-net stations are by no means permanent. A micro-net station may be taken out of service when conditions at the location are satisfactorily understood in terms of conditions at the central weather station, or it may be allowed to remain because of its usefulness in connection with a radioactivity monitoring program. Frequently micro-net stations have radioactivity monitoring instruments installed and the maintenance of the station is a joint responsibility of the health physics and meteorology offices.

With or without micro-net stations, any atomic energy area with a meteorological program requires a centrally located, permanent meteorological station with excellent exposure for instruments. This station serves as the control point for the micro-network and will provide the long series of records needed for rigorous climatic studies.

## 2. METEOROLOGICAL TOWERS

For the continuous observations of the vertical gradient of temperature and wind that are necessary for diffusion estimates, a tower or pole is required for supporting the instruments. The first meteorological tower for the atomic energy industry was erected at the Hanford Works in 1944 and has operated continuously since that time. This tower, 400 ft high, was designed entirely for meteorological purposes. The later Brookhaven tower was modeled after this facility. Since such special installations are quite costly, an attempt is usually made to adapt existing structures to dual purposes or to provide acceptable but less expensive installations. Figures 11.3 and 11.4 show the radio tower used for meteorological purposes at NRTS and a high pole used as a tower at Oak Ridge.

The NRTS tower is conveniently located with respect to the weather station in which are housed the recording devices. Its height is 250 ft, the identical height above ground as the tops of the tallest stacks. For most industrial sites, this type of tower, which is basically a commercially available, prefabricated radio tower, will be most economical.

The wind instrument at the top of the tower is an unmodified Aerovane combined wind direction and speed transmitter (Fig. 11.5). The conducting cable for the instrument goes down the tower and underground to the weather station. The recorders for this wind transmitter are mounted above a similar pair of recorders for surface wind data in the instrument cabinet containing other meteorological recording instruments (Fig. 11.6). Surface wind data are not obtained from the tower but from the top of a 20-ft mast which is located away from buildings and other obstructions.

The temperature data from this tower are obtained from two levels where aspirated elec-

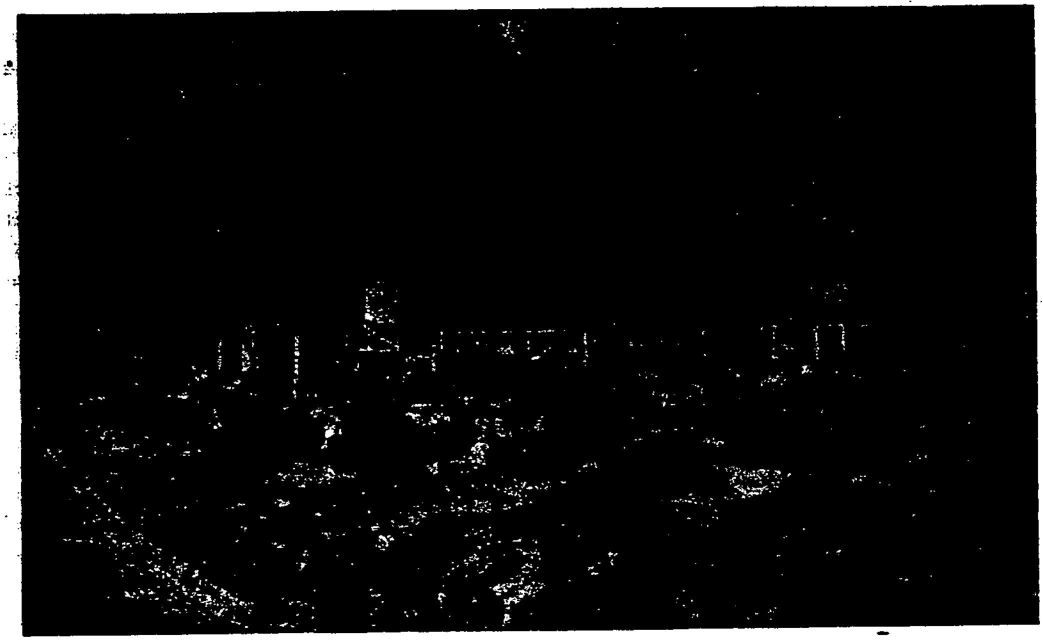


Fig. 11.1—Typical micro-net station at NRTS with wind, temperature, and precipitation measuring instruments.

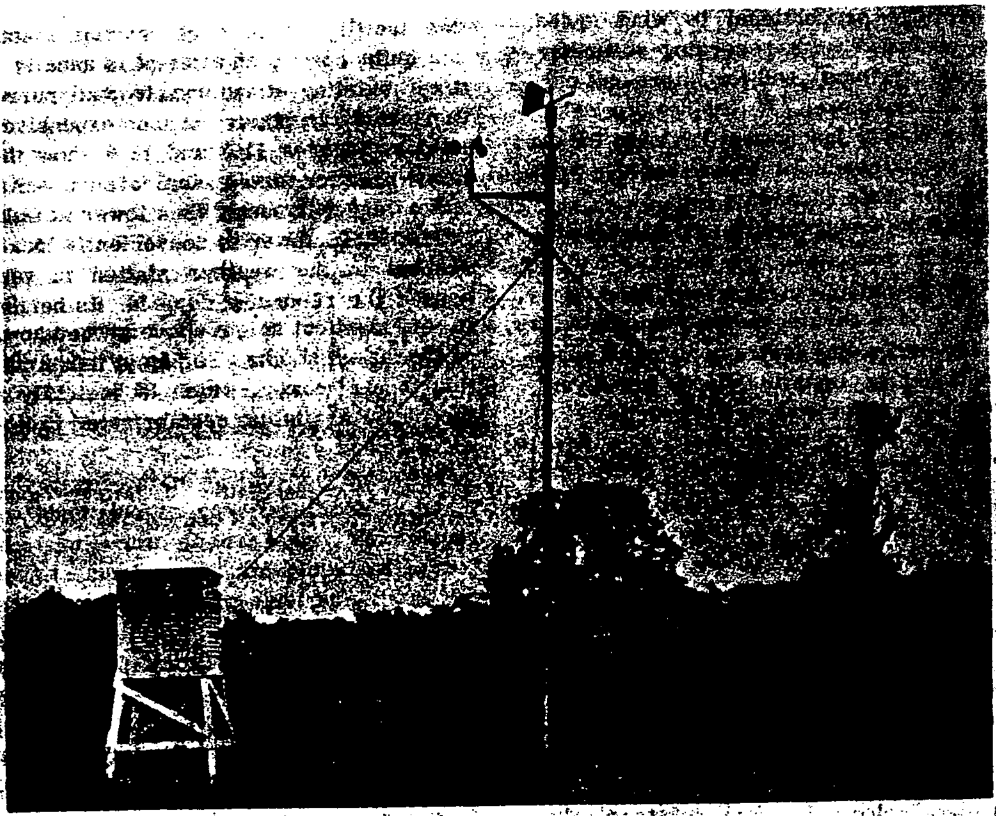


Fig. 11.2—A micro-net station at Oak Ridge, Tenn. (ORNL).

Fig. 11.3—Meteorological instruments installed on a radio tower at NRTS. Arrows indicate thermohm housings.

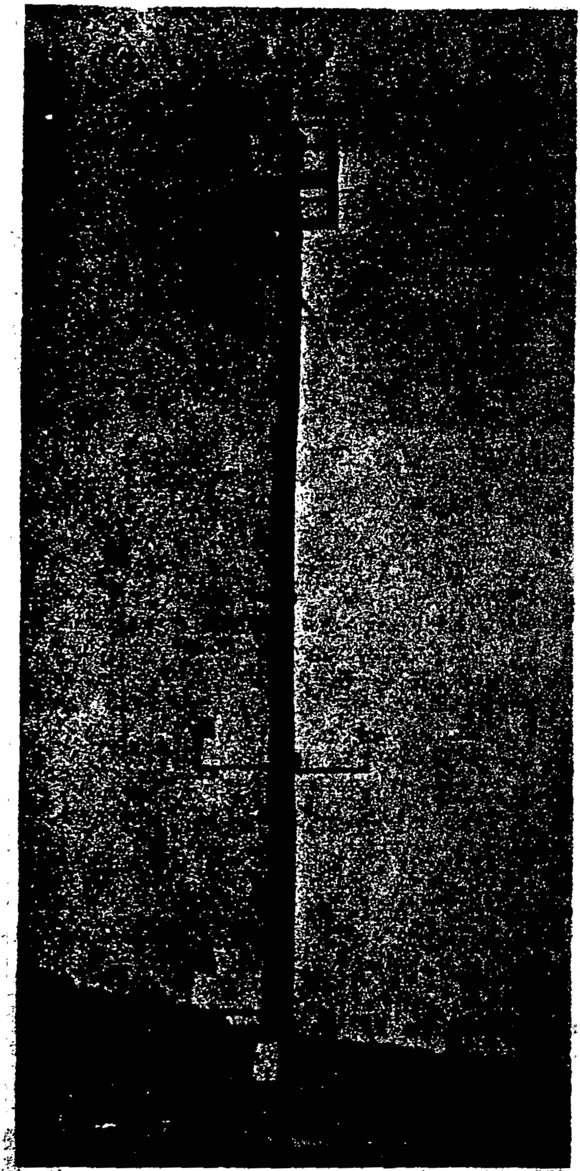


Fig. 11.4—Pole installation of meteorological instruments at Oak Ridge, Tenn. (ORNL).

trical resistance thermometer assemblies (Fig. 11.7) are used. Each assembly resembles a white cylindrical wooden cage and is aspirated with a small motor and fan to minimize direct solar radiation on the temperature sensing elements. An entire set of assemblies can easily be built in a small workshop.

Several meteorological towers, outstandingly the towers at Hanford,[16] Brookhaven,[20] and the University of Washington,[24,25] have used central aspirated systems. There is a powerful blower at the base of the tower and a duct which leads to the individual electrical resistance thermometers (Leeds and Northrup "thermohms") at various levels. The temperature sensing elements are enclosed in aluminum cylinders within cylinders, with the lower side covered so that radiation from the ground will not pene-

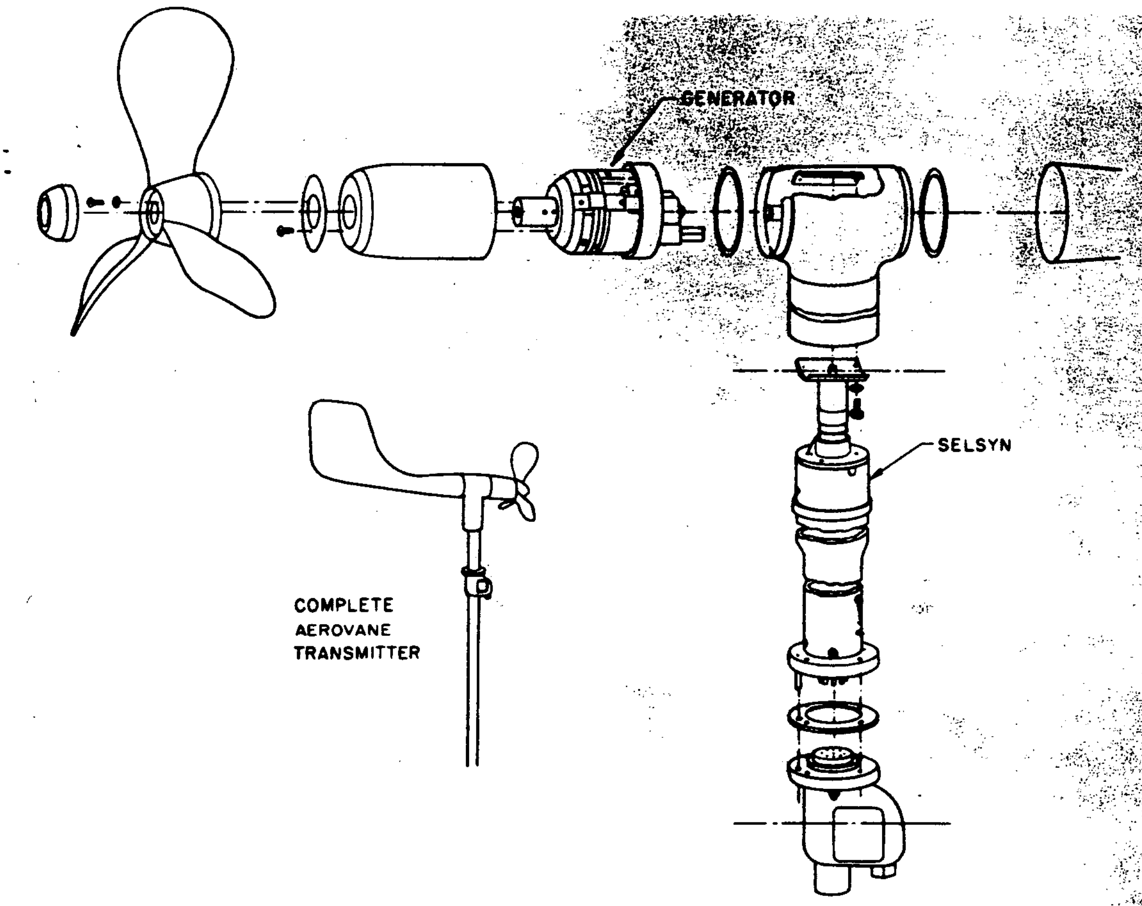


Fig. 11.5—The Aerovane, Bendix-Friez Company.

trate. A close-up of such shields extending down from the ends of booms on the Brookhaven tower is shown in Fig. 11.8.

A tower installation for research such as at Brookhaven (see Fig. 11.9) is far more elaborate than that required for an industrial installation. Nevertheless it is worth while to note some of the Brookhaven tower facilities. The towers are equipped with two-men elevators as well as ladder systems.

The instrument panel at Brookhaven is shown in Fig. 11.10. [From right to left on this panel are two temperature recorders, two temperature difference recorders, the timing mechanism which permits the charts to be operated at the normal speed or high speed, and 14 twin Esterline-Angus wind recorders. Next to the panel board is a wind vertical gradient recorder developed especially for Brookhaven and constructed by Bendix Friez. Adjacent to it is a small panel with the pyrheliometer (top) and the recorder which gives the temperatures at four different levels in the 355-ft smoke stack on the tower.]

## 3. UPPER WIND SOUNDING EQUIPMENT

Pilot balloons (as a rule the 30-g size) observed through a meteorological theodolite are used where necessary to obtain wind direction and velocity at levels above the top of a tower. Usually four routine soundings a day are made at 6-hr intervals during a 24-hr period. Figure 11.11 shows a pilot-balloon theodolite station at NRTS. In some instances two theodolites and a double-triangulation method have been used to obtain the position of the balloon more accurately. Gifford[55] has developed a nomogram which simplifies the double theodolite compu-

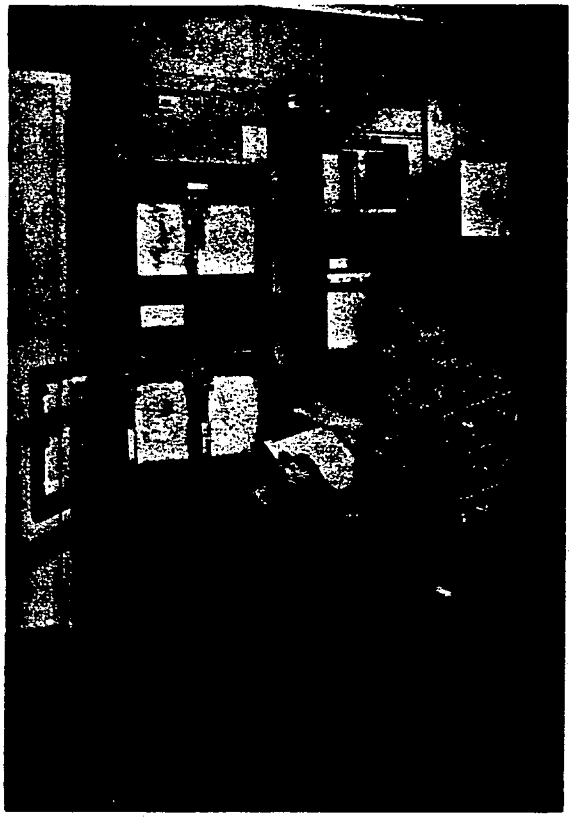


Fig. 11.6—Instrument panel at NRTS central weather station, showing two wind recorders, microbarograph, and the electronic temperature recorder.

tation. (Ordinarily, with a single theodolite the balloon is assumed to rise at a given rate; but vertical currents, particularly on a hot day, can change the rate considerably.)

The disadvantage of ordinary pilot-balloon observations is that they cannot be made when visibility is poor, and single theodolite observations cannot be made during precipitation. In addition, soundings are terminated as balloons enter clouds and are carried out of sight by strong winds. Electronic equipment (the rawindsonde), which is used by the Weather Bureau and by the military weather services, overcomes these disadvantages but is very expensive for routine use at industrial sites. Also, existing electronic sounding equipment is not designed for efficiently obtaining data at low levels as required in air pollution studies.

Upper wind soundings are primarily of interest where forecasting may be required or where it is desirable to correlate local wind conditions with the flow patterns on upper air charts. Such sounding data may also have climatic significance where there is the possibility of effective stack heights considerably higher than a meteorological tower or where an explosion could conceivably send a cloud to high elevations.

Neutral-lift balloons may also be used where there are double-theodolite sounding facilities. These carefully weighed-off balloons move freely with larger eddies and may provide information on local air trajectories and diffusion conditions.[59]

## 4. TEMPERATURE SOUNDING EQUIPMENT

4.1 *Wiresondes.* Not all atomic energy facilities require a meteorological tower, and only a few should ever require a sounding program for obtaining temperatures and winds above the top of a meteorological tower. Blimps have been used to lift ceramic resistance-temperature elements (thermistors) to elevations up to about 1200 ft. Average sounding heights range from 700 to 800 ft.

With all tethered blimps, the lift increases with the wind speed. Blimps tend to fly almost directly overhead in very light or in strong winds but at a lower angle in moderate winds. A blimp holding 600 cu ft of helium has been found to give the best all-around performance at NRTS, which is nearly 5000 ft above sea level.

One or two observers per watch are sufficient for an observational program including soundings. With suitable equipment, such as a mooring mast and track (Fig. 11.12), one observer is usually enough, provided he has help with equipment maintenance.

If windy conditions can be avoided, a blimp may be held by sandbags on a ground cloth; and no hangar is required. By using a gasoline-powered generator and simple shelters for the electric winch and recorder, a mobile sounding program is feasible.

For soundings at near zero temperature and below, a three conductor nylon-coated wire, with braided fiber glass for strength, is used for a tether and to transmit the temperature signal.

A blimp cannot be flown if there is potential danger from static electricity or lightning. To avoid injury to personnel and equipment, the

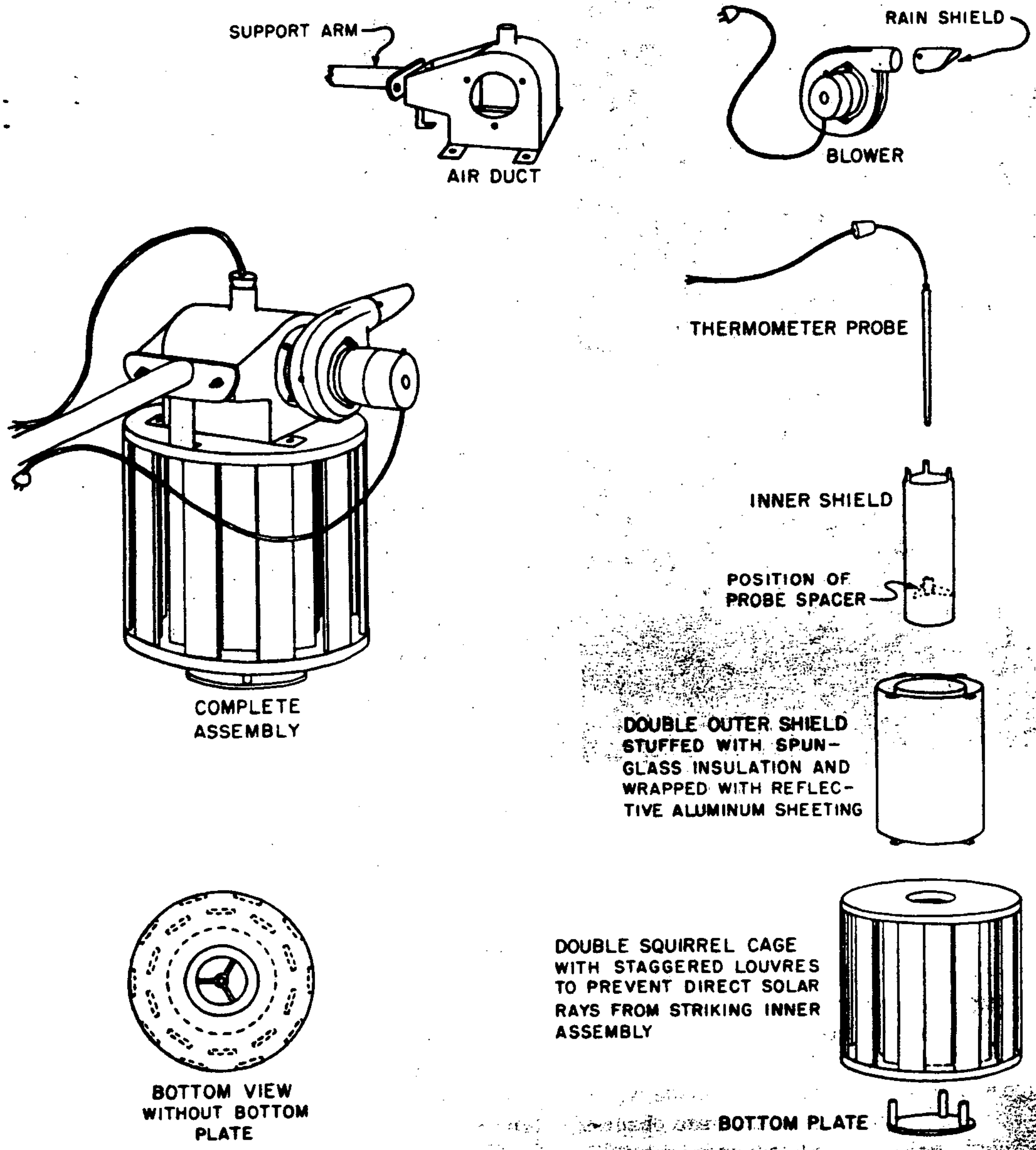


Fig. 11.7—Aspirated electrical resistance thermometer assembly.

following precautions are taken: (1) no soundings are taken beneath, or near, dark turbulent clouds; (2) the universal pulley which guides the cable from the winch to the balloon is grounded; and (3) the blimp is grounded before it is touched if it is suspected of being charged.

For some special observations, when a tower is not available, it may be feasible to secure a blimp with multiple tethers to hold an instrument in a fixed position, perhaps 200 to 500 ft above the surface. Myers[115] discusses the accuracy in height and temperature measurements and concludes that temperatures to ±0.1°F and heights to ±3 to 10% of actual elevation are readily obtainable.

4.2 *Soundings by Miscellaneous Methods.* Whenever a limited number of temperature

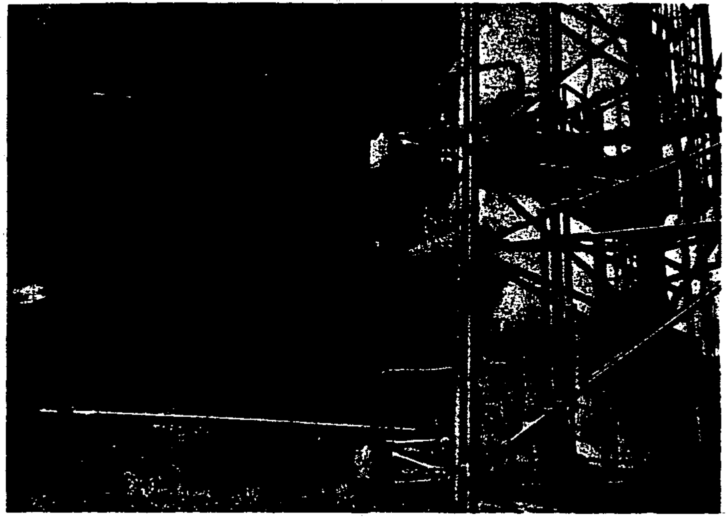
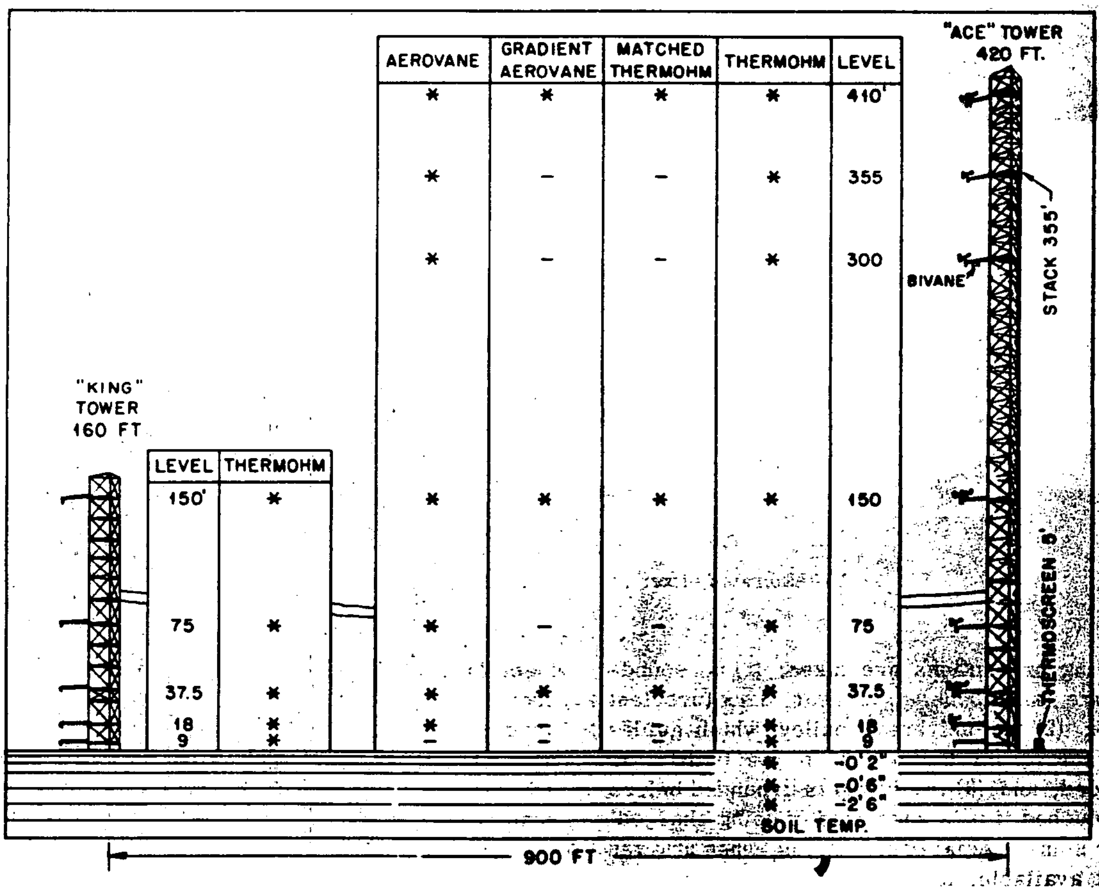


Fig. 11.8—Instrument booms on the Brookhaven tower. Thermohm shields are below the ends of the booms. Three Aerovanes are also shown. The counterweighted booms can be pivoted and drawn into the platforms for servicing (BNL).



| LEVEL | THERMOHM |
|---|---|
| 150' | * |
| 75 | * |
| 37.5 | * |
| 18 | * |
| 9 | * |

| AEROVANE | GRADIENT AEROVANE | MATCHED THERMOHM | THERMOHM | LEVEL |
|---|---|---|---|---|
| * | * | * | * | 410' |
| * | - | - | * | 355 |
| * | - | - | * | 300 |
| * | * | * | * | 150 |
| * | - | - | * | 75 |
| * | * | * | * | 37.5 |
| * | - | - | * | 18 |
| - | - | - | * | 9 |
|  |  |  | * | -0'2" |
|  |  |  | * | -0'6" |
|  |  |  | * | -2'6" |
|  |  |  | SOIL TEMP. |  |

Fig. 11.9—Brookhaven tower facilities. Cables between towers are 100 ft above the surface.

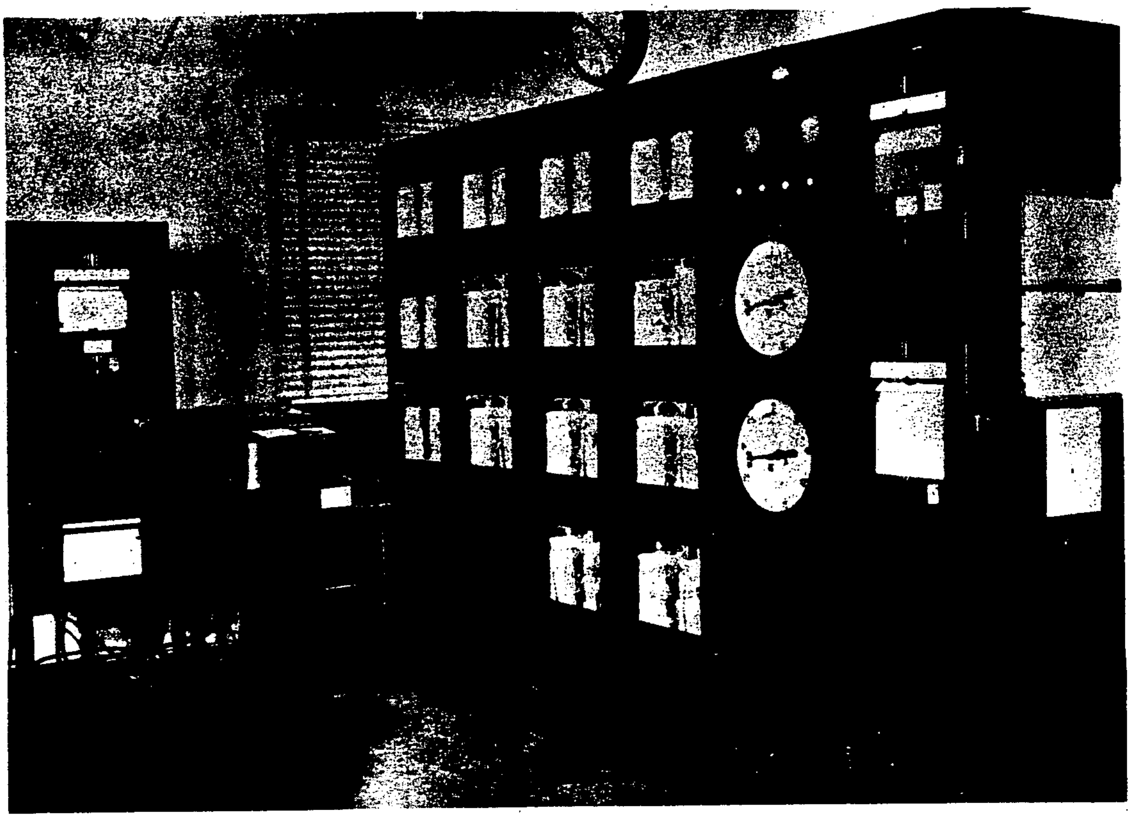


Fig. 11.10—Instrument panel at Brookhaven.

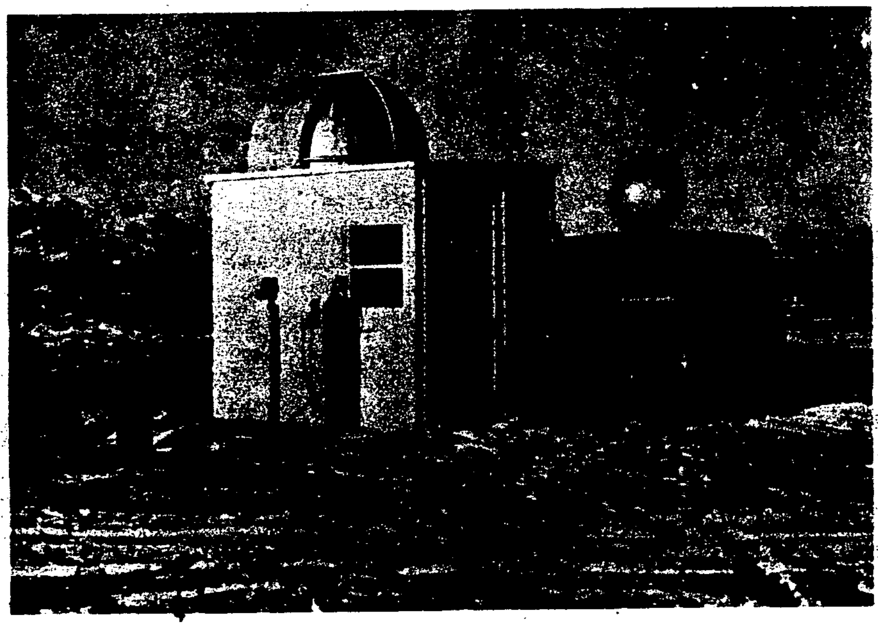


Fig. 11.11—NRTS pilot-balloon station.

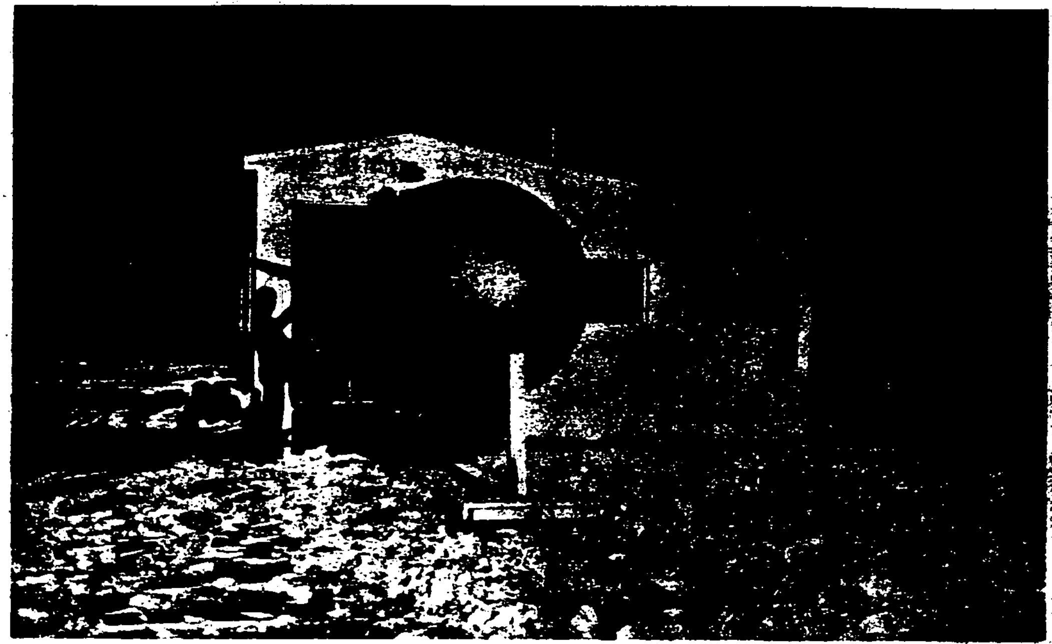


Fig. 11.12 — Low-level temperature sounding station at NRTS, showing mooring mast and track.

soundings are required and captive blimp equipment is not available, airplane soundings may be used. A light aircraft with properly installed temperature measuring equipment can operate very effectively. An airplane can obtain soundings under windier conditions and, of course, can reach higher elevations than the blimps. Another method worthy of consideration is the use of helicopters.[121]

Radiosondes are probably not feasible for a routine sounding program at an industrial site. Since both the transmitter and balloon are expended, the cost of soundings is likely to be prohibitive. Also, a radiosonde is not designed to give the detailed low-level information required for air pollution studies. Nevertheless radiosondes can be modified as has been done by Gifford[64] and can be used in a limited way in surveys of short duration.

## 5. OTHER SPECIALIZED INSTRUMENTS

### 5.1 *Resistance Thermometers and Thermocouples.*

Although hygrothermographs are suitable instruments to use where no electric power is available and where accuracies of ±2°F and ±5% relative humidity are satisfactory, many investigations will require greater accuracy. Modern temperature measuring techniques use potentiometer recorders with thermocouples or servobalanced Wheatstone bridges with resistance bulbs. Both systems are capable of accuracies of ±0.1°F when properly designed and properly used. Resistance thermometers give trouble-free operation and are desirable for many industrial observational programs. A commercial resistance thermometer element will retain its calibration indefinitely, and the response characteristics which, in practice, are slower than for thermocouples are actually an advantage in many applications. (For stack meteorology measurements of temperature difference resistance bulbs should be matched to within ±0.5°F.)

It is important to note that when [illegible] differentials are measured with [illegible] mometers, nonlinear measuring elem[illegible] nickel) may introduce errors with [illegible] mean temperature. Proper [illegible] (copper and platinum) can [illegible] crepancy. On the other hand, [illegible] respond quickly and are [illegible] closely when temperature [illegible] quired over small intervals. Tempe[illegible] ferences in a 50-ft interval must be [illegible] with an accuracy of better than 0.25°F in order to distinguish between adiabatic and isothermal lapse rates. Temperature, temperature difference, and wet-bulb depression are easily obtained on a Brown multipoint recorder, or other similar recorder, which switches ranges and cold-junction compensation resistors. The Tennessee Valley Authority has a number of these [illegible] in successful operation.

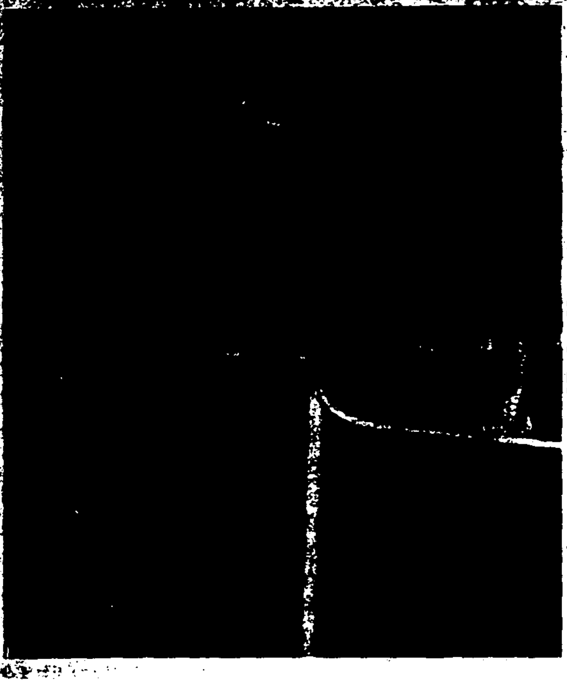


Fig. 11.13—Thermal radiation shield and aspirator assembly used at ORNL.

The most important factor affecting the accuracy of temperature measurements is the exposure. Much experimental work has been done in this field to arrive at a satisfactory housing for a resistance bulb, thermocouple, or liquid-in-glass thermometer, which will shut out radiation and which will not change the temperature of the air before it is measured. Also, nearly every investigator has worked out his own design. The small mass of a thermojunction is a factor which makes adequate ventilation and shielding of such sensing element less difficult than the larger resistance thermometers. At Oak Ridge and at NRTS, temperature measurements are made in individually aspirated and shielded housings. The shield used at NRTS is shown in Fig. 11.7. An installation of the aspirators at Oak Ridge is shown in Fig. 11.13. The outside shield is of tubing plated with a thin wash of gold to give reflectance in the long wave and visible regions. Specifications for this instrument have been given by Myers,[81] and a detailed drawing is shown in Fig. 11.14.

Gill[82] has discussed the shielding and aspiration problem and has chosen gold leaf covered bakelite tubes with an aspiration rate of 10 meters/sec. The Lake Mead design[3] is said to require no artificial ventilation in a wind speed greater than 1 mph. There is need for a shield of standard design so that precise temperature measurements may be compared. Gill's aspirator and shield, if ventilation were furnished by an individual blower, seems to be very sound.

5.2 *Thermistors.* In addition to tethered blimp temperature soundings, other uses have been made of radiosonde type thermistors. The output can be linearized by using the output of an unbalanced Wheatstone bridge to compensate for the nonlinearity of the thermistor element. Adequate design information for this type of circuit is given by Beakley.[9] A mobile indicator using a linearized thermistor is described by Myers.[81]

The stability of thermistors used in the regular radiosonde instruments is quite good. A group of 10 were calibrated at intervals of 3 months, and there were only two which had shifted by more than 0.2°F.

5.3 *Low Speed Anemometers.* Since very low wind speeds may be of prime importance at many sites, the conventional generator-anemometer, whose starting speed is about 2 mph, may not be satisfactory. This difficulty has been overcome by such instruments as photocell and hot wire anemometers.

Beckman and Whitley, Inc., San Carlos, Calif., have produced for the commercial market a light-weight plastic cup anemometer,[152] using a photocell transducer to reduce drag and a condenser-discharger relay type frequency meter to smooth the output of pulses. The instrument appears to be well designed and is available in a-c or battery powered models. The starting speed of the anemometer is 0.8 mph.

A photocell anemometer developed at Oak Ridge is a conversion of a standard Navy type

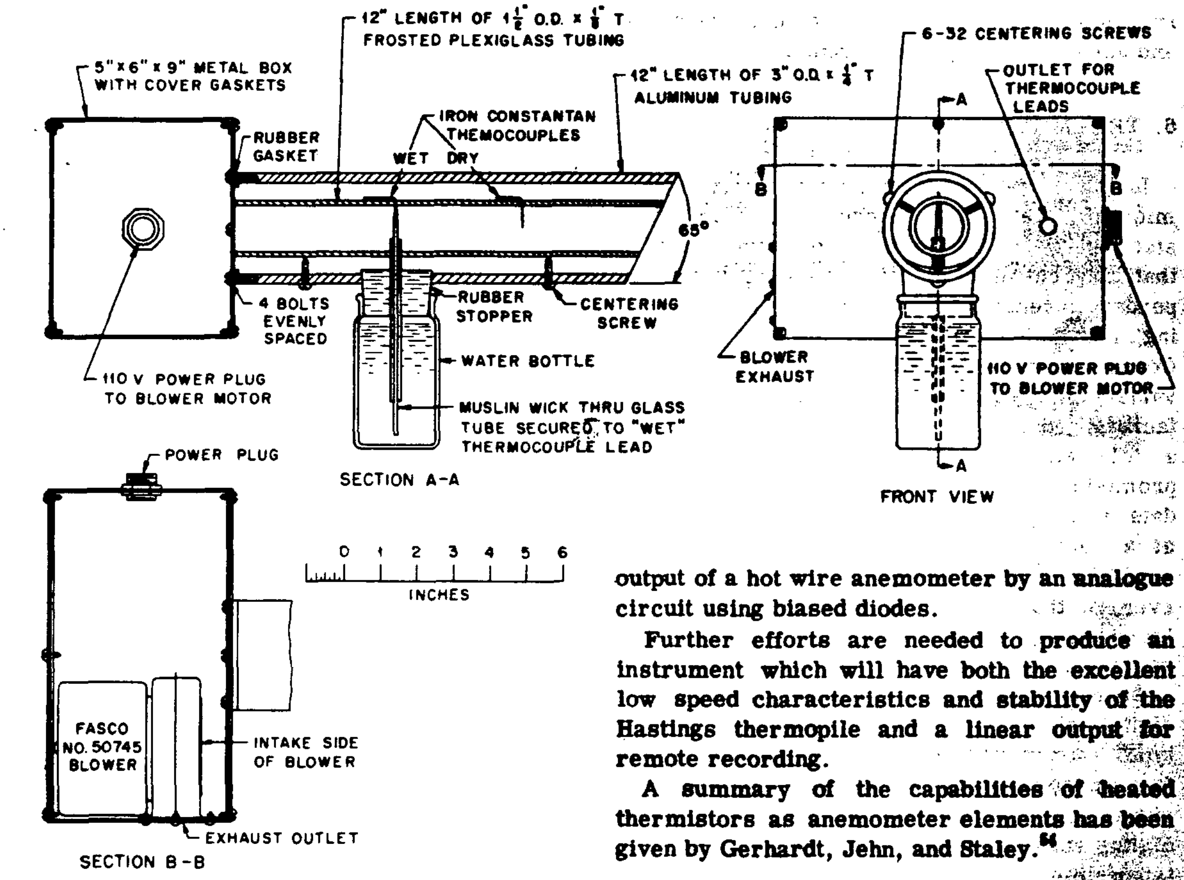


Fig. 11.14—Thermocouple psychrometer aspirator unit.

conical cup anemometer (Instruments Corporation, #428), which replaces the gearing and contacting arrangement with a phototube and integrator. The device produces a smooth d-c output proportional to wind velocity. The starting speed is estimated to be 0.5 mph.

Hastings Instrument Company has designed a series of heated thermopile anemometers which are quite sensitive and stable. Temperature compensation is introduced by an unheated thermocouple in the center tap lead. Holland and Myers[81] and Gill[82] have used these airmeter instruments with considerable success. In the former case linear recording was accomplished by utilizing a tapped slide wire in the potentiometer recorder. Gill photographed a panel of meters at minute intervals to obtain records.

A similar type of work has been done by Stewart and MacCready[134] in linearizing the output of a hot wire anemometer by an analogue circuit using biased diodes.

Further efforts are needed to produce an instrument which will have both the excellent low speed characteristics and stability of the Hastings thermopile and a linear output for remote recording.

A summary of the capabilities of heated thermistors as anemometer elements has been given by Gerhardt, Jehn, and Staley.[64]

5.4 *Bivanes*. The general principle of a vane mounted so that it can rotate about both the vertical and horizontal axes is quite simple, but the actual production of a fast-response light-weight vane which is suitable for continuous operation and for remote recording is a difficult problem.

The bivane dates back to 1927 when G. I. Taylor used a light-weight instrument constructed by W. H. Dines. The design was improved, and the Porton vane was produced in England for use in the classic investigation conducted at that Chemical Warfare establishment. Bivanes such as this require the attention of an observer.

Gill[75] and Mazzarella[106] have produced models of bivanes which are automatic and suitable for routine use. Mazzarella designed a bivane whose response characteristics are similar to the "Aerovane" wind transmitter in use at Brookhaven. This bivane was in actual use only a short time at BNL until the tail assembly was changed to an annular fin. There are now two additional bivanes in operation there of improved design in terms of their response and aerodynamic characteristics.

## 6. TELEMETERING

In the course of the extensive survey of the microclimate of Oak Ridge, where up to 15 stations were operated, it became apparent that a great number of man-hours were expended in reading instrument charts and applying corrections to obtain data for analysis. Consequently, a study was made in 1950 of a variety of equipment and methods which would facilitate data collection and processing; and a telemetering system seemed to be most promising. An advantage would be that less data would be lost if all recording were done at a central location where any malfunction would be caught during the working day. However, at that time commercially available telemetering equipment was found to be lacking in regard to cost and speed of measurement.

At this point Foster's[48] announcement of a digital telemetering system called the "Metrotype" was made. This system seemed suitable for meteorological purposes. Any electrical signal could be read and printed in any chosen digital scale directly on a teletype or electric typewriter.

This made available a commercial system which would read and tabulate. Each digit was printed at the maximum speed of the teletypewriter, taking about 160 msec. Additional printers could be connected with no change in the equipment, using normal teletype communication facilities. Some experience had been gained with an industrial d-c amplifier manufactured by Manning, Maxwell, and Moore which would transmit a 0- to 5-ma electrical signal over 20 miles of telephone line. The union of the digital converter and the stable d-c amplifier made possible the assembly of a system which performed the function originally desired. In the period that followed (1950-1952), operational experience with the Manning, Maxwell, and Moore "Microsen" amplifier was accumulated; and appropriate transducers were designed and tested for an industrial network.

At the present time a system is installed in the Weather Bureau Office at Oak Ridge which will be the permanent data collecting system for that area. This "Weather Information Telemeter System" (WITS) will provide a maximum of 90 channels (9 stations, 10 channels each) which will use one telephone line from the printer to each of the remote stations.

The rain gauge used is a pressure type developed at Oak Ridge. It is heated to 40°F in the winter to prevent freezing and holds 1 in. of rain. It automatically dumps when 1.00 in. has accumulated and is also dumped at midnight to provide daily totals.

A provision has been made to punch IBM cards automatically after the system has been in use for a long enough period to prove its dependability. The final automatic data system aimed at will combine the collection of digital data, the card punching for statistical studies, and the filing of the digital data and the punch card summaries on microcards.

## 7. CALIBRATION FACILITIES

7.1 *Temperature and Relative Humidity.* One of the operations which is essential to successful micrometeorological measurements is periodic calibration checks of the instrumentation. A well-stirred liquid bath with a precision thermometer (see Fig. 11.15) is not difficult to assemble; and yet it is capable of doing excellent work in the calibration of thermocouples, resistance thermometers, and liquid-in-glass thermometers.

Hygrothermographs can be calibrated by using an insulated box with circulation of the air over a heater or a coolant with some success. Constant-humidity atmospheres may be obtained by circulating air over various salts. (The Handbook of Chemistry and Physics, Chemical Rubber Publishing Company, lists suitable salts to cover the range from 9 to 99.7% relative humidity.)

7.2 *Wind Speed.* For calibration purposes either a small wind tunnel or a means of rotating the anemometer shaft at a constant measured speed is highly desirable.

A well designed wind tunnel has been constructed by Gill[75] which would be very worth while for any meteorological group which attempts to make precision wind measurements.

Much valuable information concerning specialized instrumentation in the field of micrometeorology is found in the work of Baum.[8]

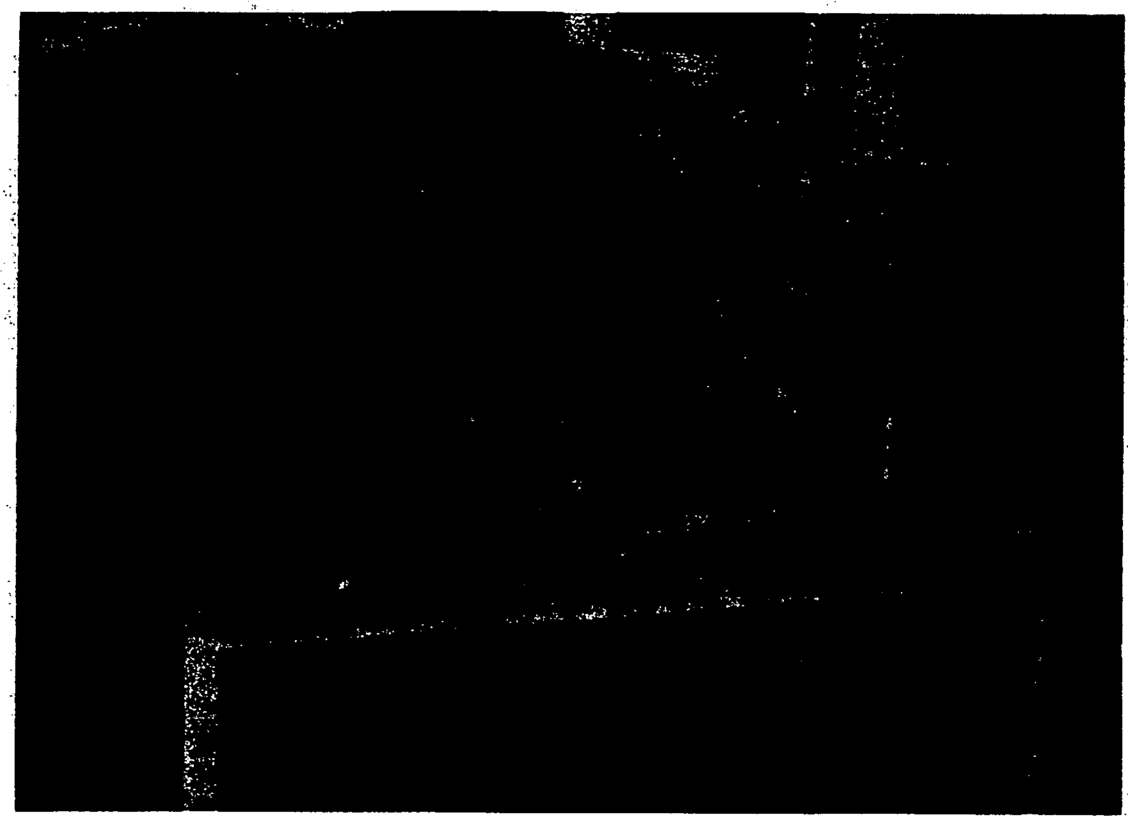


Fig. 11.15—Temperature calibration equipment used for meteorological instruments at Oak Ridge (ORNL).

## 8. DIFFUSION EXPERIMENTAL EQUIPMENT

8.1 *Controlled Releases of Smoke.* In addition to operating meteorological instruments, nearly all meteorological programs at atomic energy sites have included smoke experiments. Besides releasing smoke and photographing it in a conventional manner, or with a time-lapse motion picture camera (as at Brookhaven and Argonne National Laboratory), the following techniques have also been employed or are under development:

1. Concentrations have been measured with photoelectric light-scattering meters or densitometers.[43,66,97]

2. Concentrations are estimated by a fluorometric technique whereby oil fog, which is of itself fairly fluorescent, is sampled with a transmission fluorometer.[9]

3. Fluorescent particles have been released at a controlled rate and collected either on filters or sticky surfaces. A microscope with ultraviolet light is used for observation of the particles and counting. The fluorescent particle technique has been widely used and has many practical applications. It is impossible to list all the numerous reports which are concerned with fluorescent particle behavior. Many are concerned with national defense and are difficult to obtain. However, descriptions of equipment and techniques are available in papers by Crozier and Seely,[30] Perkins et al.,[119] Braham and Seely,[14] Allen,[1] and by du Pont meteorologists at Savannah River.[43]

4. A halogen gas (Freon) has been released, and the concentration has been measured with a leak detector. The leak detector is very sensitive to small concentrations, but serious difficulties are encountered in its use because of background readings due to relative humidity, undetermined atmoshperic impurities, etc.[114]

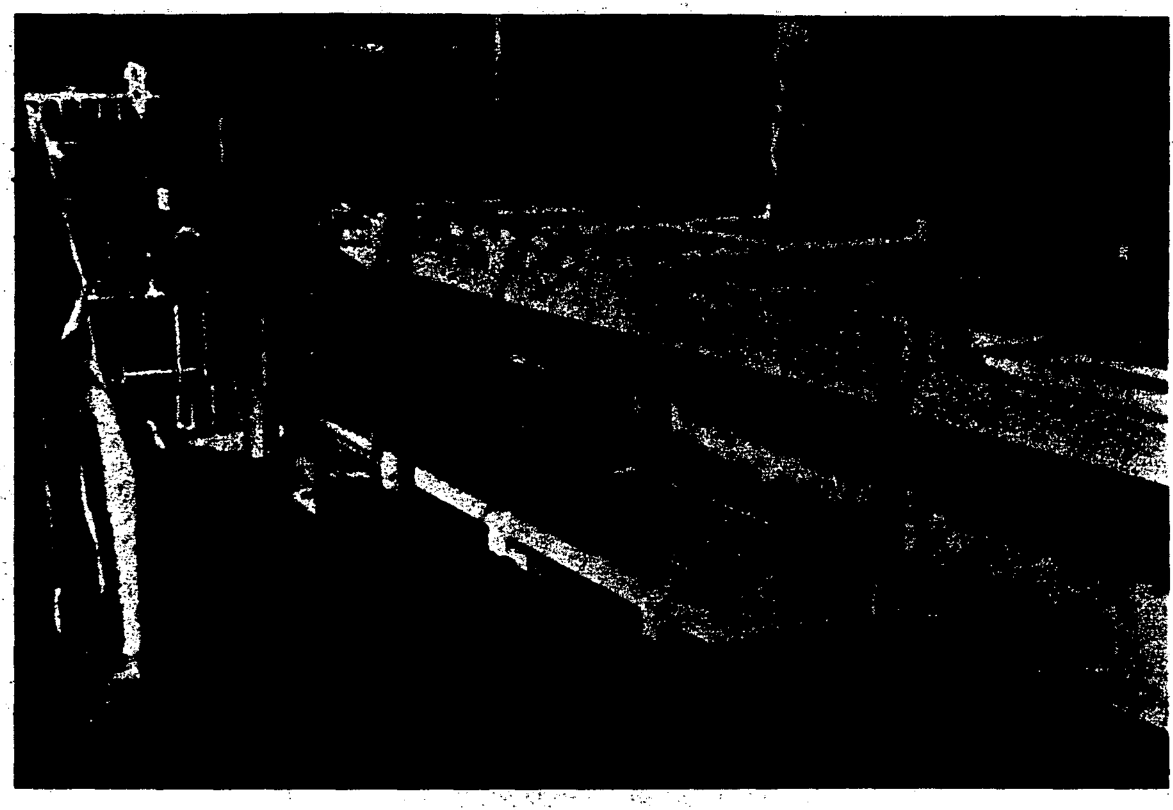


Fig. 11.16—Test section, Consolidated Edison wind tunnel, College of Engineering, New York University. An oil-fog smoke is issuing from the stack.

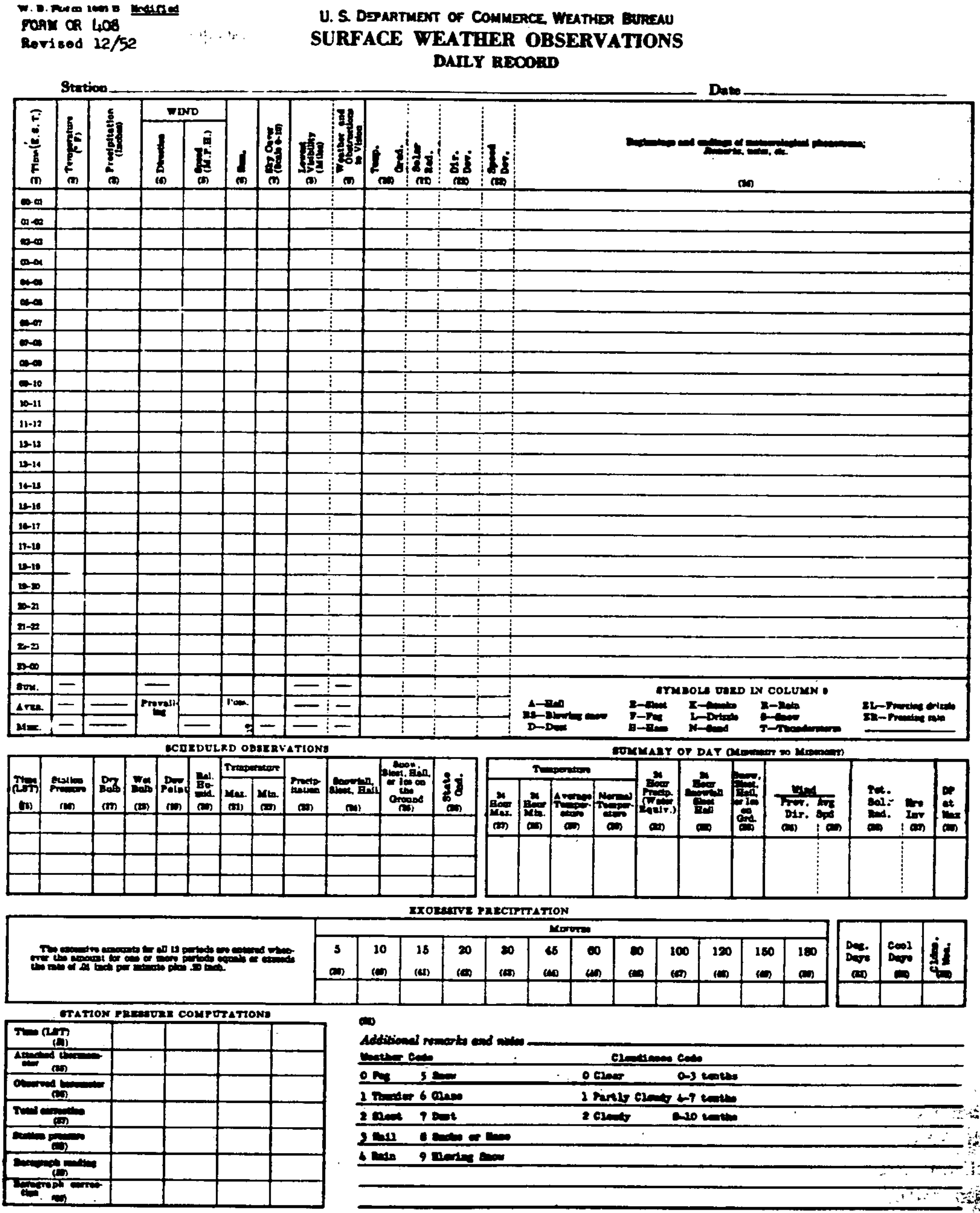
5. An aluminum cylinder of argon was placed in an atomic pile and irradiated until it reached equilibrium. The radioactive gas was then released into the pile-cooling air, and measurements were made by sensitive radiation instruments. Since the ground concentrations are normally a factor of 1000 or more below tolerance, it was considered safe to boost the output by a factor[80] of 10.

6. At ANL the meteorological section has devised an experimental stack whose height, emission rate, and, eventually, effluent temperature can be carefully measured and controlled. This stack has been erected near a meteorological tower instrumented to obtain temperature and wind profiles. Oil smoke emissions are recorded by a photogrammetric technique. The coincidence of precise meteorological and stack data should enable some very useful investigations. A description of the stack installation is to be published in the *Bulletin of the American Meteorological Society.*

Actual release of effluents is of particular value where the terrain is very irregular or where buildings disturb air flow since in such instances theoretical estimates may be greatly in error.

In industry generally there has been much success with monitoring devices, such as developed by Thomas,[148] for very low concentrations of the sulfur-containing gases such as sulfur dioxide, hydrogen sulfide, and the mercaptans. Those and other devices, as mentioned by Thomas (and Magil[102]), may be used in air pollution experiments.

8.2 *Wind Tunnel Techniques.* Some progress has been made on the use of wind tunnel techniques for estimating effluent behavior. So far the wind tunnel has been most useful for studying air flow near buildings and similar obstructions. In the wind tunnel at New York University (Fig. 11.16), there are facilities for controlling the wind velocity and the vertical temperature



W. B. Form 1001 B Modified
FORM OR 408
Revised 12/52

U. S. DEPARTMENT OF COMMERCE, WEATHER BUREAU
SURFACE WEATHER OBSERVATIONS
DAILY RECORD

Station ______________________ Date ____________

| Time (L.S.T.) | Temperature (°F) | Precipitation (Inches) | WIND Direction | WIND Speed (M.P.H.) | | Sky Cover (Scale 0-10) | Lowest Visibility (Miles) | Weather and Obstructions to Vision | Temp. Grad. | Solar Rad. | Dir. Dev. | Speed Dev. | Beginnings and endings of meteorological phenomena; Remarks, notes, etc. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 00-01 | | | | | | | | | | | | | |
| 01-02 | | | | | | | | | | | | | |
| 02-03 | | | | | | | | | | | | | |
| 03-04 | | | | | | | | | | | | | |
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| 19-20 | | | | | | | | | | | | | |
| 20-21 | | | | | | | | | | | | | |
| 21-22 | | | | | | | | | | | | | |
| 22-23 | | | | | | | | | | | | | |
| 23-00 | | | | | | | | | | | | | |
| Sum. | — | | — | | | — | — | — | | | | | |
| Avgs. | — | — | Prevailing | | Pos. | | — | — | | | | | |
| Max. | — | — | | — | | — | — | — | | | | | |

SYMBOLS USED IN COLUMN 9

A—Hail
BS—Blowing snow
D—Dust
E—Sleet
F—Fog
H—Haze
K—Smoke
L—Drizzle
N—Sand
R—Rain
S—Snow
T—Thunderstorm
ZL—Freezing drizzle
ZR—Freezing rain

SCHEDULED OBSERVATIONS

| Time (LST) | Station Pressure | Dry Bulb | Wet Bulb | Dew Point | Rel. Humid. | Temperature Max. | Temperature Min. | Precipitation | Snowfall, Sleet, Hail | Snow, Sleet, Hail, or Ice on the Ground | State Gnd. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |

SUMMARY OF DAY (MIDNIGHT TO MIDNIGHT)

| Temperature 24 Hour Max. | Temperature 24 Hour Min. | Temperature Average Temperature | Temperature Normal Temperature | 24 Hour Precip. (Water Equiv.) | 24 Hour Snowfall Sleet Hail | Snow, Sleet, Hail, or Ice on Grd. | Wind Prev. Dir. | Wind Avg Spd | Tot. Sol. Rad. | Hrs Inv | DP at Max |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |

EXCESSIVE PRECIPITATION

The excessive amounts for all 12 periods are entered whenever the amount for one or more periods equals or exceeds the rate of .01 inch per minute plus .20 inch.

| Minutes 5 | 10 | 15 | 20 | 30 | 45 | 60 | 80 | 100 | 120 | 150 | 180 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |

| Deg. Days | Cool Days | [illegible] |
|---|---|---|
| | | |

STATION PRESSURE COMPUTATIONS

| | | | | |
|---|---|---|---|---|
| Time (LST) | | | | |
| Attached thermometer | | | | |
| Observed barometer | | | | |
| Total correction | | | | |
| Station pressure | | | | |
| Barograph reading | | | | |
| Barograph correction | | | | |

*Additional remarks and notes* ____________

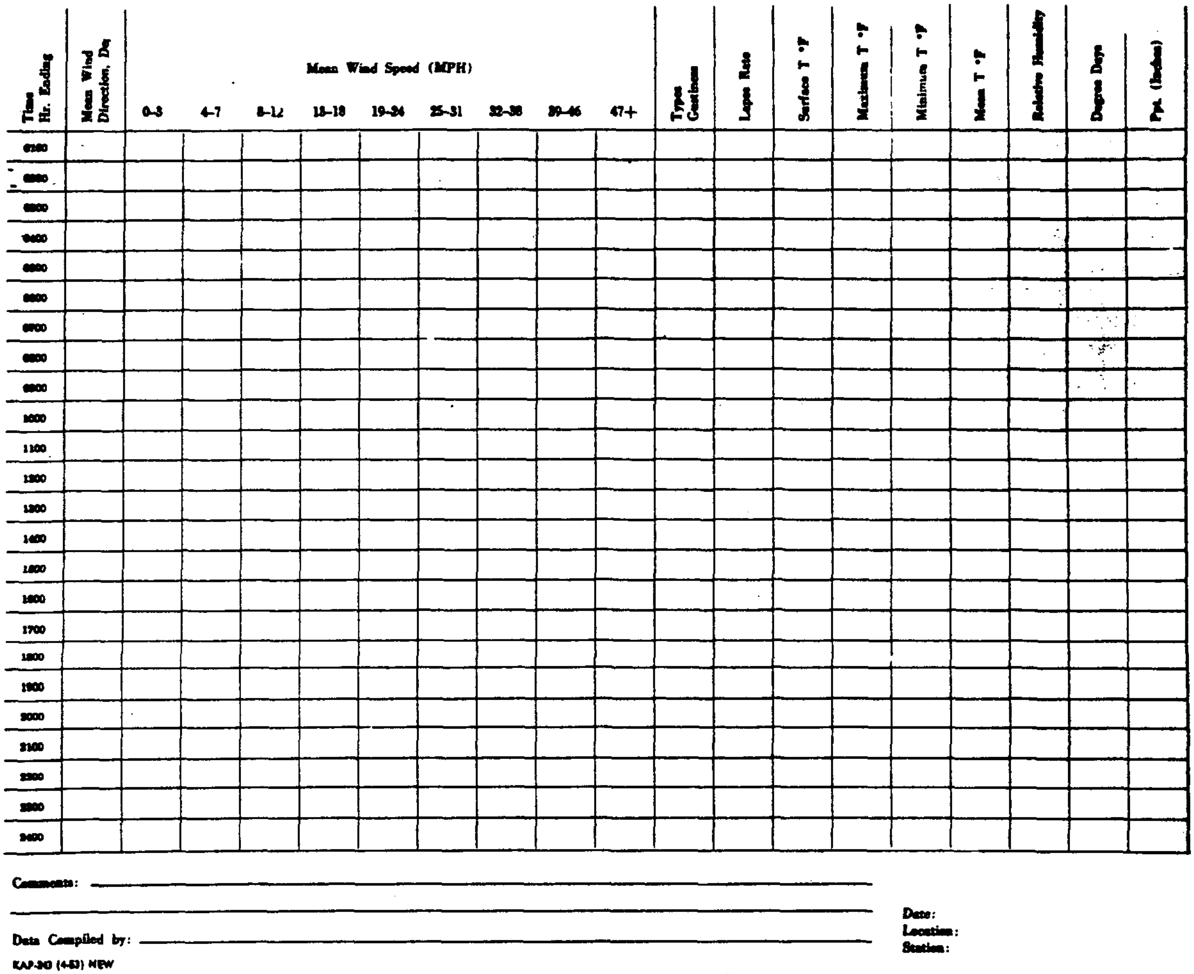
Weather Code — Cloudiness Code
0 Fog 5 Snow — 0 Clear 0-3 tenths
1 Thunder 6 Glaze — 1 Partly Cloudy 4-7 tenths
2 Sleet 7 Dust — 2 Cloudy 8-10 tenths
3 Hail 8 Smoke or Haze
4 Rain 9 Blowing Snow

Fig. 11.17—Daily weather record.

profile. Wind tunnel techniques for air pollution investigations have been described by von Hohenleiten and Wolf,[149] Rupp et al.,[127] Bryant,[17] Leverett et al.,[92] Hewson,[72] Rouse,[126] Strom,[134] Davidson,[34] and Halitsky et al.[78]

## 9. METEOROLOGICAL RECORDS

A record system should be designed to accommodate the most comprehensive of the planned meteorological programs. The amount



| Time Hr. Ending | Mean Wind Direction, Dg | Mean Wind Speed (MPH) | | | | | | | | | Types Gustiness | Lapse Rate | Surface T °F | Maximum T °F | Minimum T °F | Mean T °F | Relative Humidity | Degree Days | Ppt. (Inches) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0-3 | 4-7 | 8-12 | 13-18 | 19-24 | 25-31 | 32-38 | 39-46 | 47+ | | | | | | | | | |
| 0100 | | | | | | | | | | | | | | | | | | | |
| 0200 | | | | | | | | | | | | | | | | | | | |
| 0300 | | | | | | | | | | | | | | | | | | | |
| 0400 | | | | | | | | | | | | | | | | | | | |
| 0500 | | | | | | | | | | | | | | | | | | | |
| 0600 | | | | | | | | | | | | | | | | | | | |
| 0700 | | | | | | | | | | | | | | | | | | | |
| 0800 | | | | | | | | | | | | | | | | | | | |
| 0900 | | | | | | | | | | | | | | | | | | | |
| 1000 | | | | | | | | | | | | | | | | | | | |
| 1100 | | | | | | | | | | | | | | | | | | | |
| 1200 | | | | | | | | | | | | | | | | | | | |
| 1300 | | | | | | | | | | | | | | | | | | | |
| 1400 | | | | | | | | | | | | | | | | | | | |
| 1500 | | | | | | | | | | | | | | | | | | | |
| 1600 | | | | | | | | | | | | | | | | | | | |
| 1700 | | | | | | | | | | | | | | | | | | | |
| 1800 | | | | | | | | | | | | | | | | | | | |
| 1900 | | | | | | | | | | | | | | | | | | | |
| 2000 | | | | | | | | | | | | | | | | | | | |
| 2100 | | | | | | | | | | | | | | | | | | | |
| 2200 | | | | | | | | | | | | | | | | | | | |
| 2300 | | | | | | | | | | | | | | | | | | | |
| 2400 | | | | | | | | | | | | | | | | | | | |

Comments:

Data Compiled by:

KAP-30 (4-53) NEW

Date:
Location:
Station:

Fig. 11.18—Daily record sheet.

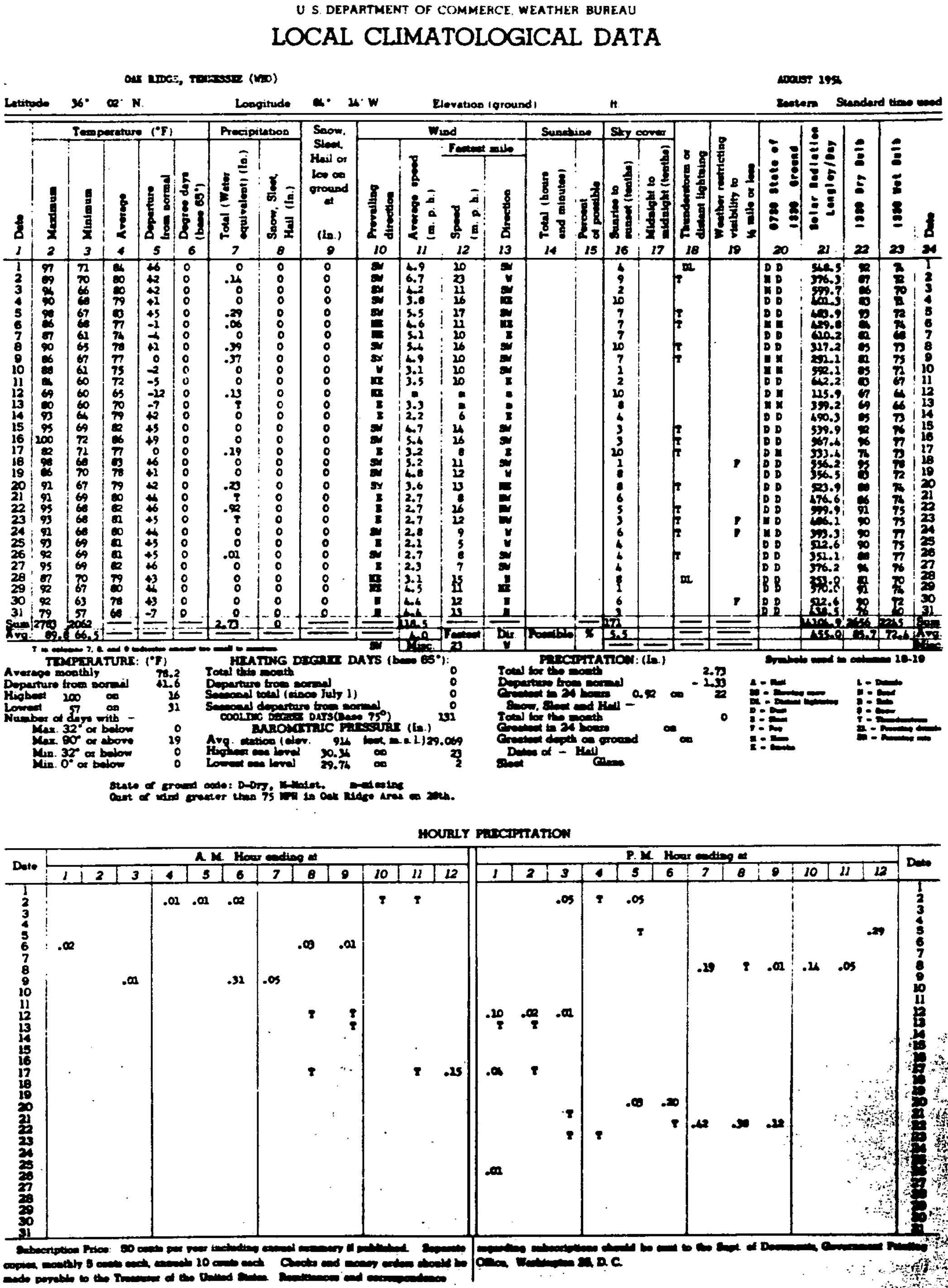
and variety of data recorded will depend on the purpose of the installation and the number of stations established. Since, in the atomic energy industry, the most complete meteorological program will usually be required in connection with diffusion estimates, examples of these types of records will be given the most consideration.

9.1 *Daily Records*. Although almost any data sheet can be devised to contain the measured data, a particularly convenient one is the Weather Bureau Form 1001B. Figure 11.17 shows this form as adapted by the Weather Bureau Office at Oak Ridge to contain stability data (cols. 10, 12, and 13). This form has the advantage of wide usage and ready adaptability. Furthermore, since engineering and human comfort data are usually expected from a meteorological program, these data can easily be recorded (daily maximum, minimum, degree days, rainfall, etc.).

Another daily record form successfully used at the Knolls Atomic Power Laboratory is shown in Fig. 11.18.

9.2 *Monthly Records*. Here again a standard Weather Bureau form, Form 733-1, is available and can contain much information. Completion of the entire form would, of course, be optional and would depend mostly on the need for the more usual type of meteorological data. An example of a completed Form 733-1 for Oak Ridge is shown in Fig. 11.19, together with the machine-processed supplement (Fig. 11.20).

Additional detailed information may be desirable for interpretation of radioactive monitoring records or environmental studies, and



U. S. DEPARTMENT OF COMMERCE, WEATHER BUREAU

LOCAL CLIMATOLOGICAL DATA

OAK RIDGE, TENNESSEE (WBO) AUGUST 1954

Latitude 36° 02' N. Longitude 84° 14' W Elevation (ground) ft. Eastern Standard time used

| Date 1 | Temperature (°F) Maximum 2 | Minimum 3 | Average 4 | Departure from normal 5 | Degree days (base 65°) 6 | Precipitation Total (Water equivalent) (In.) 7 | Snow, Sleet, Hail (In.) 8 | Snow, Sleet, Hail or Ice on ground at (In.) 9 | Wind Prevailing direction 10 | Average speed (m. p. h.) 11 | Fastest mile Speed (m. p. h.) 12 | Fastest mile Direction 13 | Sunshine Total (hours and minutes) 14 | Percent of possible 15 | Sky cover Sunrise to sunset (tenths) 16 | Midnight to midnight (tenths) 17 | Thunderstorm or distant lightning 18 | Weather restricting visibility to ½ mile or less 19 | 0730 State of 1930 Ground 20 | Solar Radiation Langley/Day 21 | 1930 Dry Bulb 22 | 1930 Wet Bulb 23 | Date 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 97 | 71 | 84 | +6 | 0 | 0 | 0 | 0 | SW | 4.9 | 10 | SW | | | 4 | | DL | | D D | 548.5 | 92 | 74 | 1 |
| 2 | 89 | 70 | 80 | +2 | 0 | .14 | 0 | 0 | SW | 6.7 | 23 | W | | | 9 | | T | | M D | 376.3 | 87 | 72 | 2 |
| 3 | 94 | 66 | 80 | +2 | 0 | 0 | 0 | 0 | SW | 4.2 | 11 | SW | | | 2 | | | | M D | 599.7 | 86 | 70 | 3 |
| 4 | 90 | 68 | 79 | +1 | 0 | 0 | 0 | 0 | SW | 3.8 | 16 | NE | | | 10 | | | | D D | 601.3 | 83 | 72 | 4 |
| 5 | 98 | 67 | 83 | +5 | 0 | .29 | 0 | 0 | SW | 5.5 | 17 | SW | | | 7 | | T | | D D | 483.9 | 93 | 72 | 5 |
| 6 | 86 | 68 | 77 | -1 | 0 | .06 | 0 | 0 | NE | 4.6 | 11 | NE | | | 7 | | T | | M M | 429.8 | 84 | 74 | 6 |
| 7 | 87 | 61 | 74 | -4 | 0 | 0 | 0 | 0 | NE | 5.1 | 10 | E | | | 7 | | | | D D | 610.2 | 82 | 68 | 7 |
| 8 | 90 | 65 | 78 | +1 | 0 | .39 | 0 | 0 | SW | 5.4 | 16 | SW | | | 10 | | T | | D D | 317.2 | 85 | 73 | 8 |
| 9 | 86 | 67 | 77 | 0 | 0 | .37 | 0 | 0 | SW | 4.9 | 10 | SW | | | 7 | | T | | M M | 291.1 | 82 | 75 | 9 |
| 10 | 88 | 61 | 75 | -2 | 0 | 0 | 0 | 0 | W | 3.1 | 10 | SW | | | 1 | | | | M M | 592.1 | 85 | 71 | 10 |
| 11 | 84 | 60 | 72 | -5 | 0 | 0 | 0 | 0 | NE | 3.5 | 10 | E | | | 2 | | | | D D | 642.2 | 83 | 67 | 11 |
| 12 | 69 | 60 | 65 | -12 | 0 | .13 | 0 | 0 | NE | m | m | m | | | 10 | | | | D M | 115.9 | 67 | 64 | 12 |
| 13 | 80 | 60 | 70 | -7 | 0 | T | 0 | 0 | E | 3.3 | m | m | | | 8 | | | | M M | 359.2 | 69 | 66 | 13 |
| 14 | 93 | 64 | 79 | +2 | 0 | 0 | 0 | 0 | E | 2.2 | 6 | E | | | 4 | | | | D D | 490.3 | 85 | 73 | 14 |
| 15 | 95 | 69 | 82 | +5 | 0 | 0 | 0 | 0 | SW | 4.7 | 14 | SW | | | 3 | | T | | D D | 539.9 | 92 | 76 | 15 |
| 16 | 100 | 72 | 86 | +9 | 0 | 0 | 0 | 0 | SW | 5.4 | 16 | SW | | | 3 | | T | | D D | 567.4 | 96 | 77 | 16 |
| 17 | 82 | 71 | 77 | 0 | 0 | .19 | 0 | 0 | E | 3.2 | 8 | E | | | 10 | | T | | D M | 333.4 | 76 | 73 | 17 |
| 18 | 98 | 68 | 83 | +6 | 0 | 0 | 0 | 0 | SW | 5.2 | 11 | SW | | | 1 | | | F | D D | 556.2 | 95 | 78 | 18 |
| 19 | 86 | 70 | 78 | +1 | 0 | 0 | 0 | 0 | SW | 4.8 | 12 | W | | | 8 | | | | D D | 356.5 | 83 | 72 | 19 |
| 20 | 91 | 67 | 79 | +2 | 0 | .23 | 0 | 0 | SW | 3.6 | 13 | NE | | | 8 | | T | | D D | 523.9 | 88 | 74 | 20 |
| 21 | 91 | 69 | 80 | +4 | 0 | T | 0 | 0 | E | 2.7 | 8 | NW | | | 6 | | | | D D | 476.6 | 86 | 74 | 21 |
| 22 | 95 | 68 | 82 | +6 | 0 | .92 | 0 | 0 | E | 2.7 | 16 | NW | | | 5 | | T | | D D | 599.9 | 91 | 75 | 22 |
| 23 | 93 | 68 | 81 | +5 | 0 | T | 0 | 0 | E | 2.7 | 12 | NW | | | 3 | | T | F | M D | 406.1 | 90 | 75 | 23 |
| 24 | 91 | 68 | 80 | +4 | 0 | 0 | 0 | 0 | SW | 2.8 | 9 | W | | | 6 | | T | F | M D | 393.3 | 90 | 77 | 24 |
| 25 | 93 | 69 | 81 | +5 | 0 | 0 | 0 | 0 | E | 2.1 | 5 | W | | | 4 | | | | D D | 512.6 | 90 | 75 | 25 |
| 26 | 92 | 69 | 81 | +5 | 0 | .01 | 0 | 0 | SW | 2.7 | 8 | SW | | | 4 | | T | | D D | 351.1 | 88 | 77 | 26 |
| 27 | 95 | 69 | 82 | +6 | 0 | 0 | 0 | 0 | E | 2.3 | 7 | SW | | | 4 | | | | D D | 376.2 | 94 | 76 | 27 |
| 28 | 87 | 70 | 79 | +3 | 0 | 0 | 0 | 0 | NE | 3.1 | 15 | N | | | 8 | | DL | | D D | 353.0 | 81 | 70 | 28 |
| 29 | 92 | 67 | 80 | +4 | 0 | 0 | 0 | 0 | NE | 4.5 | 11 | NE | | | 1 | | | | D D | 370.0 | 91 | 74 | 29 |
| 30 | 92 | 63 | 78 | +3 | 0 | 0 | 0 | 0 | N | 4.4 | 12 | N | | | 6 | | | F | D D | 512.6 | 90 | 72 | 30 |
| 31 | 79 | 57 | 68 | -7 | 0 | 0 | 0 | 0 | N | 4.4 | 13 | N | | | 3 | | | | D D | 458.5 | 76 | 60 | 31 |
| Sum | 2783 | 2062 | — | — | — | 2.73 | 0 | — | — | 118.5 | — | — | | — | 172 | | — | — | | 14104.9 | 2656 | 2245 | Sum |
| Avg. | 89.8 | 66.5 | — | — | — | — | — | — | — | 4.0 | Fastest | Dir. | Possible | % | 5.5 | | — | — | | 455.0 | 85.7 | 72.4 | Avg. |
| | | | | | | | | | SW | Misc. | 23 | W | | | — | — | — | — | | | | | Misc. |

T in columns 7, 8, and 9 indicates amount too small to measure.

**TEMPERATURE: (°F)**
Average monthly 78.2
Departure from normal +1.6
Highest 100 on 16
Lowest 57 on 31
Number of days with –
Max. 32° or below 0
Max. 90° or above 19
Min. 32° or below 0
Min. 0° or below 0

**HEATING DEGREE DAYS (base 65°):**
Total this month 0
Departure from normal 0
Seasonal total (since July 1) 0
Seasonal departure from normal 0
COOLING DEGREE DAYS(Base 75°) 131

**BAROMETRIC PRESSURE (In.)**
Avg. station (elev. 914 feet, m. s. l.) 29.069
Highest sea level 30.34 on 23
Lowest sea level 29.74 on 2

**PRECIPITATION: (In.)**
Total for the month 2.73
Departure from normal - 1.33
Greatest in 24 hours 0.92 on 22
Snow, Sleet and Hail –
Total for the month 0
Greatest in 24 hours on
Greatest depth on ground on
Dates of – Hail
Sleet Glaze

**Symbols used in columns 18-19**
A - Hail
BS - Blowing snow
DL - Distant lightning
D - Dust
E - Sleet
F - Fog
H - Haze
K - Smoke
L - Drizzle
N - Sand
R - Rain
S - Snow
T - Thunderstorm
ZL - Freezing drizzle
ZR - Freezing rain

State of ground code: D-Dry, M-Moist. m-missing
Gust of wind greater than 75 MPH in Oak Ridge Area on 28th.

HOURLY PRECIPITATION

| Date | A. M. Hour ending at 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | P. M. Hour ending at 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Date |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| 2 | | | | .01 | .01 | .02 | | | | T | T | | | | .05 | T | .05 | | | | | | | | 2 |
| 3 | | | | | | | | | | | | | | | | | | | | | | | | | 3 |
| 4 | | | | | | | | | | | | | | | | | | | | | | | | | 4 |
| 5 | | | | | | | | | | | | | | | | | T | | | | | | | .29 | 5 |
| 6 | .02 | | | | | | | .03 | .01 | | | | | | | | | | | | | | | | 6 |
| 7 | | | | | | | | | | | | | | | | | | | | | | | | | 7 |
| 8 | | | | | | | | | | | | | | | | | | | .19 | T | .01 | .14 | .05 | | 8 |
| 9 | | | .01 | | | .31 | .05 | | | | | | | | | | | | | | | | | | 9 |
| 10 | | | | | | | | | | | | | | | | | | | | | | | | | 10 |
| 11 | | | | | | | | | | | | | | | | | | | | | | | | | 11 |
| 12 | | | | | | | | T | T | | | | .10 | .02 | .01 | | | | | | | | | | 12 |
| 13 | | | | | | | | | T | | | | T | T | | | | | | | | | | | 13 |
| 14 | | | | | | | | | | | | | | | | | | | | | | | | | 14 |
| 15 | | | | | | | | | | | | | | | | | | | | | | | | | 15 |
| 16 | | | | | | | | | | | | | | | | | | | | | | | | | 16 |
| 17 | | | | | | | | T | | | T | .15 | .04 | T | | | | | | | | | | | 17 |
| 18 | | | | | | | | | | | | | | | | | | | | | | | | | 18 |
| 19 | | | | | | | | | | | | | | | | | | | | | | | | | 19 |
| 20 | | | | | | | | | | | | | | | | | .03 | .20 | | | | | | | 20 |
| 21 | | | | | | | | | | | | | | | T | | | | | | | | | | 21 |
| 22 | | | | | | | | | | | | | | | | | | T | .42 | .38 | .12 | | | | 22 |
| 23 | | | | | | | | | | | | | | | T | T | | | | | | | | | 23 |
| 24 | | | | | | | | | | | | | | | | | | | | | | | | | 24 |
| 25 | | | | | | | | | | | | | | | | | | | | | | | | | 25 |
| 26 | | | | | | | | | | | | | .01 | | | | | | | | | | | | 26 |
| 27 | | | | | | | | | | | | | | | | | | | | | | | | | 27 |
| 28 | | | | | | | | | | | | | | | | | | | | | | | | | 28 |
| 29 | | | | | | | | | | | | | | | | | | | | | | | | | 29 |
| 30 | | | | | | | | | | | | | | | | | | | | | | | | | 30 |
| 31 | | | | | | | | | | | | | | | | | | | | | | | | | 31 |

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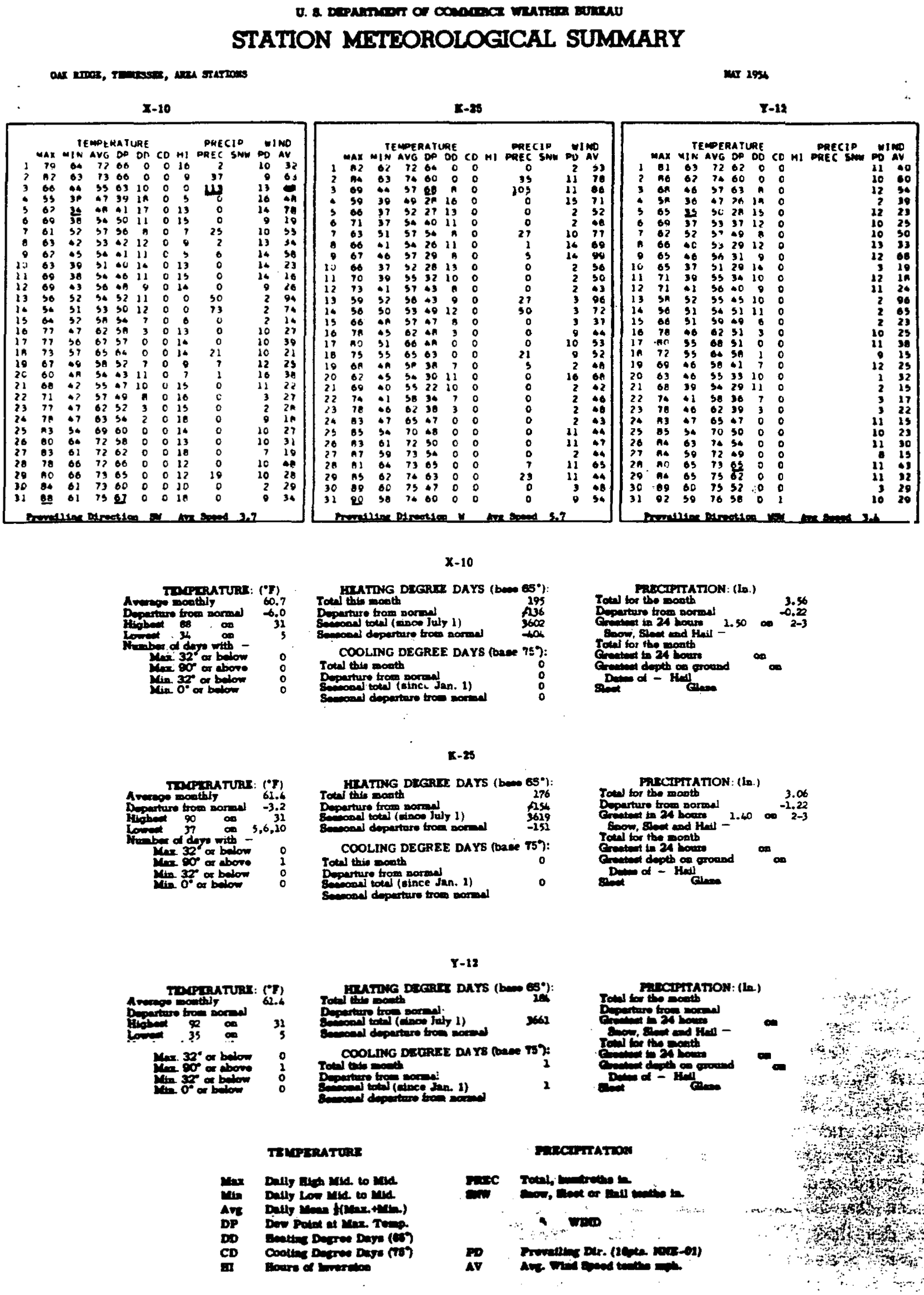
Fig. 11.19—Monthly meteorological summary.



U. S. DEPARTMENT OF COMMERCE WEATHER BUREAU

## STATION METEOROLOGICAL SUMMARY

OAK RIDGE, TENNESSEE, AREA STATIONS

MAY 1954

### X-10

| | TEMPERATURE | | | | | | | PRECIP | | WIND | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | MAX | MIN | AVG | DP | DD | CD | HI | PREC | SNW | PD | AV |
| 1 | 79 | 64 | 72 | 66 | 0 | 0 | 16 | 2 | | 10 | 32 |
| 2 | 82 | 63 | 73 | 66 | 0 | 0 | 9 | 37 | | 9 | 63 |
| 3 | 66 | 44 | 55 | 63 | 10 | 0 | 0 | 113 | | 13 | [illegible] |
| 4 | 55 | 38 | 47 | 39 | 18 | 0 | 5 | 0 | | 16 | 48 |
| 5 | 62 | 34 | 48 | 41 | 17 | 0 | 13 | 0 | | 14 | 78 |
| 6 | 69 | 38 | 54 | 50 | 11 | 0 | 15 | 0 | | 9 | 19 |
| 7 | 61 | 52 | 57 | 56 | 8 | 0 | 7 | 25 | | 10 | 55 |
| 8 | 63 | 42 | 53 | 42 | 12 | 0 | 9 | 2 | | 13 | 34 |
| 9 | 62 | 45 | 54 | 41 | 11 | 0 | 5 | 6 | | 14 | 58 |
| 10 | 63 | 39 | 51 | 40 | 14 | 0 | 13 | 0 | | 14 | 23 |
| 11 | 69 | 38 | 54 | 46 | 11 | 0 | 15 | 0 | | 14 | 16 |
| 12 | 69 | 43 | 56 | 48 | 9 | 0 | 14 | 0 | | 9 | 26 |
| 13 | 56 | 52 | 54 | 52 | 11 | 0 | 0 | 50 | | 2 | 94 |
| 14 | 54 | 51 | 53 | 50 | 12 | 0 | 0 | 73 | | 2 | 74 |
| 15 | 64 | 52 | 58 | 54 | 7 | 0 | 6 | 0 | | 2 | 14 |
| 16 | 77 | 47 | 62 | 58 | 3 | 0 | 13 | 0 | | 10 | 27 |
| 17 | 77 | 56 | 67 | 57 | 0 | 0 | 14 | 0 | | 10 | 39 |
| 18 | 73 | 57 | 65 | 64 | 0 | 0 | 14 | 21 | | 10 | 21 |
| 19 | 67 | 49 | 58 | 52 | 7 | 0 | 9 | 7 | | 12 | 25 |
| 20 | 60 | 48 | 54 | 43 | 11 | 0 | 7 | 1 | | 16 | 38 |
| 21 | 68 | 42 | 55 | 47 | 10 | 0 | 15 | 0 | | 11 | 22 |
| 22 | 71 | 42 | 57 | 49 | 8 | 0 | 16 | 0 | | 3 | 27 |
| 23 | 77 | 47 | 62 | 52 | 3 | 0 | 15 | 0 | | 2 | 28 |
| 24 | 78 | 47 | 63 | 56 | 2 | 0 | 18 | 0 | | 9 | 18 |
| 25 | 83 | 54 | 69 | 60 | 0 | 0 | 14 | 0 | | 10 | 27 |
| 26 | 80 | 64 | 72 | 58 | 0 | 0 | 13 | 0 | | 10 | 31 |
| 27 | 83 | 61 | 72 | 62 | 0 | 0 | 18 | 0 | | 7 | 19 |
| 28 | 78 | 66 | 72 | 66 | 0 | 0 | 12 | 0 | | 10 | 48 |
| 29 | 80 | 66 | 73 | 65 | 0 | 0 | 12 | 19 | | 10 | 28 |
| 30 | 84 | 61 | 73 | 60 | 0 | 0 | 10 | 0 | | 2 | 29 |
| 31 | 88 | 61 | 75 | 67 | 0 | 0 | 18 | 0 | | 9 | 34 |

Prevailing Direction SW Avg Speed 3.7

### K-25

| | TEMPERATURE | | | | | | | PRECIP | | WIND | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | MAX | MIN | AVG | DP | DD | CD | HI | PREC | SNW | PD | AV |
| 1 | 82 | 62 | 72 | 64 | 0 | 0 | | 0 | | 2 | 53 |
| 2 | 84 | 63 | 74 | 60 | 0 | 0 | | 35 | | 11 | 78 |
| 3 | 69 | 44 | 57 | 68 | 8 | 0 | | 105 | | 11 | 88 |
| 4 | 59 | 39 | 49 | 28 | 16 | 0 | | 0 | | 15 | 71 |
| 5 | 66 | 37 | 52 | 27 | 13 | 0 | | 0 | | 2 | 52 |
| 6 | 71 | 37 | 54 | 40 | 11 | 0 | | 0 | | 2 | 48 |
| 7 | 63 | 51 | 57 | 54 | 8 | 0 | | 27 | | 10 | 77 |
| 8 | 66 | 41 | 54 | 26 | 11 | 0 | | 1 | | 14 | 69 |
| 9 | 67 | 46 | 57 | 29 | 8 | 0 | | 5 | | 14 | 99 |
| 10 | 66 | 37 | 52 | 28 | 13 | 0 | | 0 | | 2 | 56 |
| 11 | 70 | 39 | 55 | 32 | 10 | 0 | | 0 | | 2 | 50 |
| 12 | 73 | 41 | 57 | 43 | 8 | 0 | | 0 | | 2 | 43 |
| 13 | 59 | 52 | 56 | 43 | 9 | 0 | | 27 | | 3 | 96 |
| 14 | 56 | 50 | 53 | 49 | 12 | 0 | | 50 | | 3 | 72 |
| 15 | 66 | 48 | 57 | 47 | 8 | 0 | | 0 | | 3 | 37 |
| 16 | 78 | 45 | 62 | 48 | 3 | 0 | | 0 | | 9 | 44 |
| 17 | 80 | 51 | 66 | 48 | 0 | 0 | | 0 | | 10 | 53 |
| 18 | 75 | 55 | 65 | 63 | 0 | 0 | | 21 | | 9 | 52 |
| 19 | 68 | 48 | 58 | 38 | 7 | 0 | | 5 | | 2 | 48 |
| 20 | 62 | 45 | 54 | 30 | 11 | 0 | | 0 | | 16 | 68 |
| 21 | 69 | 40 | 55 | 22 | 10 | 0 | | 0 | | 2 | 42 |
| 22 | 74 | 41 | 58 | 34 | 7 | 0 | | 0 | | 2 | 46 |
| 23 | 78 | 46 | 62 | 38 | 3 | 0 | | 0 | | 2 | 48 |
| 24 | 83 | 47 | 65 | 47 | 0 | 0 | | 0 | | 2 | 43 |
| 25 | 85 | 54 | 70 | 48 | 0 | 0 | | 0 | | 11 | 44 |
| 26 | 83 | 61 | 72 | 50 | 0 | 0 | | 0 | | 11 | 47 |
| 27 | 87 | 59 | 73 | 54 | 0 | 0 | | 0 | | 2 | 44 |
| 28 | 81 | 64 | 73 | 65 | 0 | 0 | | 7 | | 11 | 65 |
| 29 | 85 | 62 | 74 | 63 | 0 | 0 | | 23 | | 11 | 44 |
| 30 | 89 | 60 | 75 | 47 | 0 | 0 | | 0 | | 3 | 48 |
| 31 | 90 | 58 | 74 | 60 | 0 | 0 | | 0 | | 9 | 54 |

Prevailing Direction W Avg Speed 5.7

### Y-12

| | TEMPERATURE | | | | | | | PRECIP | | WIND | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | MAX | MIN | AVG | DP | DD | CD | HI | PREC | SNW | PD | AV |
| 1 | 81 | 63 | 72 | 62 | 0 | 0 | | | | 11 | 40 |
| 2 | 86 | 62 | 74 | 60 | 0 | 0 | | | | 10 | 60 |
| 3 | 68 | 46 | 57 | 63 | 8 | 0 | | | | 12 | 54 |
| 4 | 58 | 36 | 47 | 26 | 18 | 0 | | | | 2 | 39 |
| 5 | 65 | 35 | 50 | 28 | 15 | 0 | | | | 12 | 23 |
| 6 | 69 | 37 | 53 | 37 | 12 | 0 | | | | 10 | 25 |
| 7 | 62 | 52 | 57 | 49 | 8 | 0 | | | | 10 | 50 |
| 8 | 66 | 40 | 53 | 29 | 12 | 0 | | | | 13 | 33 |
| 9 | 65 | 46 | 56 | 31 | 9 | 0 | | | | 12 | 68 |
| 10 | 65 | 37 | 51 | 29 | 14 | 0 | | | | 3 | 19 |
| 11 | 71 | 39 | 55 | 34 | 10 | 0 | | | | 12 | 18 |
| 12 | 71 | 41 | 56 | 40 | 9 | 0 | | | | 11 | 24 |
| 13 | 58 | 52 | 55 | 45 | 10 | 0 | | | | 2 | 96 |
| 14 | 56 | 51 | 54 | 51 | 11 | 0 | | | | 2 | 65 |
| 15 | 66 | 51 | 59 | 49 | 6 | 0 | | | | 2 | 23 |
| 16 | 78 | 46 | 62 | 51 | 3 | 0 | | | | 10 | 25 |
| 17 | 80 | 55 | 68 | 51 | 0 | 0 | | | | 11 | 38 |
| 18 | 72 | 55 | 64 | 58 | 1 | 0 | | | | 9 | 15 |
| 19 | 69 | 46 | 58 | 41 | 7 | 0 | | | | 12 | 25 |
| 20 | 63 | 46 | 55 | 33 | 10 | 0 | | | | 1 | 32 |
| 21 | 68 | 39 | 54 | 29 | 11 | 0 | | | | 2 | 15 |
| 22 | 74 | 41 | 58 | 36 | 7 | 0 | | | | 3 | 17 |
| 23 | 78 | 46 | 62 | 39 | 3 | 0 | | | | 3 | 22 |
| 24 | 83 | 47 | 65 | 47 | 0 | 0 | | | | 11 | 15 |
| 25 | 85 | 54 | 70 | 50 | 0 | 0 | | | | 10 | 23 |
| 26 | 84 | 63 | 74 | 54 | 0 | 0 | | | | 11 | 30 |
| 27 | 84 | 59 | 72 | 49 | 0 | 0 | | | | 8 | 15 |
| 28 | 80 | 65 | 73 | 65 | 0 | 0 | | | | 11 | 43 |
| 29 | 84 | 65 | 75 | 62 | 0 | 0 | | | | 11 | 32 |
| 30 | 89 | 60 | 75 | 52 | 0 | 0 | | | | 3 | 29 |
| 31 | 92 | 59 | 76 | 58 | 0 | 1 | | | | 10 | 29 |

Prevailing Direction WSW Avg Speed 3.4

### X-10

TEMPERATURE: (°F)
Average monthly 60.7
Departure from normal -6.0
Highest 88 on 31
Lowest 34 on 5
Number of days with –
Max. 32° or below 0
Max. 90° or above 0
Min. 32° or below 0
Min. 0° or below 0

HEATING DEGREE DAYS (base 65°):
Total this month 195
Departure from normal +136
Seasonal total (since July 1) 3602
Seasonal departure from normal -404

COOLING DEGREE DAYS (base 75°):
Total this month 0
Departure from normal 0
Seasonal total (since Jan. 1) 0
Seasonal departure from normal 0

PRECIPITATION: (In.)
Total for the month 3.56
Departure from normal -0.22
Greatest in 24 hours 1.50 on 2-3
Snow, Sleet and Hail –
Total for the month
Greatest in 24 hours on
Greatest depth on ground on
Dates of – Hail
Sleet Glaze

### K-25

TEMPERATURE: (°F)
Average monthly 61.4
Departure from normal -3.2
Highest 90 on 31
Lowest 37 on 5,6,10
Number of days with –
Max. 32° or below 0
Max. 90° or above 1
Min. 32° or below 0
Min. 0° or below 0

HEATING DEGREE DAYS (base 65°):
Total this month 176
Departure from normal +154
Seasonal total (since July 1) 3619
Seasonal departure from normal -151

COOLING DEGREE DAYS (base 75°):
Total this month 0
Departure from normal
Seasonal total (since Jan. 1) 0
Seasonal departure from normal

PRECIPITATION: (In.)
Total for the month 3.06
Departure from normal -1.22
Greatest in 24 hours 1.40 on 2-3
Snow, Sleet and Hail –
Total for the month
Greatest in 24 hours on
Greatest depth on ground on
Dates of – Hail
Sleet Glaze

### Y-12

TEMPERATURE: (°F)
Average monthly 62.4
Departure from normal
Highest 92 on 31
Lowest 35 on 5
Max. 32° or below 0
Max. 90° or above 1
Min. 32° or below 0
Min. 0° or below 0

HEATING DEGREE DAYS (base 65°):
Total this month 184
Departure from normal
Seasonal total (since July 1) 3661
Seasonal departure from normal

COOLING DEGREE DAYS (base 75°):
Total this month 1
Departure from normal
Seasonal total (since Jan. 1) 1
Seasonal departure from normal

PRECIPITATION: (In.)
Total for the month
Departure from normal
Greatest in 24 hours on
Snow, Sleet and Hail –
Total for the month
Greatest in 24 hours on
Greatest depth on ground on
Dates of – Hail
Sleet Glaze

| TEMPERATURE | | PRECIPITATION | |
|---|---|---|---|
| Max | Daily High Mid. to Mid. | PREC | Total, hundredths in. |
| Min | Daily Low Mid. to Mid. | SNW | Snow, Sleet or Hail tenths in. |
| Avg | Daily Mean ½(Max.+Min.) | | |
| DP | Dew Point at Max. Temp. | | WIND |
| DD | Heating Degree Days (65°) | | |
| CD | Cooling Degree Days (75°) | PD | Prevailing Dir. (16pts. NNE-01) |
| HI | Hours of Inversion | AV | Avg. Wind Speed tenths mph. |

Fig. 11.20—Machine processed summary of micro-net data.

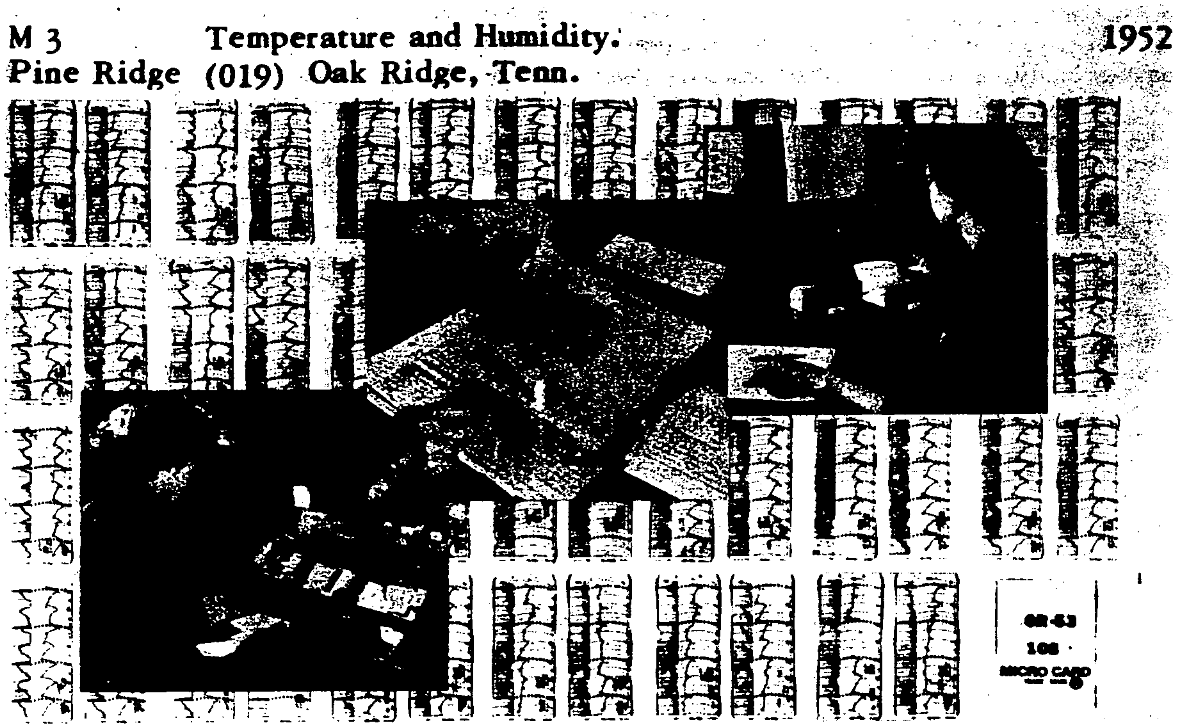


Fig. 11.21—Punch card tabulation and Microcard storage of meteorological data.

more information is a necessity for the preparation of a diffusion climatology. These needs are usually answered by special tabulations of wind data, by hours, by wind direction and speed for inversions, precipitation, specific operations, etc. The particular format should be devised to suit the requirements. A convenient visual presentation of the summarized data is in the form of a wind rose, an example of which was shown in Fig. 3.3.

9.3 *Cumulative Records.* These data may be on an annual basis with cumulative averages prepared each year or when the length of record warrants, or they may represent the entire period of record.

The format of the standard Weather Bureau annual summary, although well suited for general purposes, is not usually sufficient to present the diffusion climate of a site. A much more detailed examination is usually required. Various presentations have been made, and rather than attempt a lengthy description the reader is referred to the following: "A Meteorological Survey of the Oak Ridge Area," Report ORO-99; "Summary of Meteorological Data Taken at Argonne National Laboratory, Du Page County, Illinois;" and "The Climatology of Stack Gas Diffusion at the National Reactor Testing Station," Report IDO-10020, Waste Disposal.

9.3 *Data Handling.* A glance at any of the above publications will show that the hand processing of the many correlations, summaries, etc., can be an expensive and time consuming clerical task. Hand tabulation has the additional disadvantage that, if new conditions arise demanding a different type of tabulation, the entire body of record must be reworked.

The obvious answer is machine processing of data. Considerable success, at relatively low cost, has been achieved by using punch cards. Many large installations will already have machine units that can easily handle the meteorological data, and the various companies specializing in machine processing of data are usually available to advise in the design and operation of a punch card program. The Weather Bureau has rather comprehensive data processing facilities and can often assist in designing programs. Information on these services can be obtained by writing to Chief, U. S. Weather Bureau, Washington 25, D. C.

An additional problem may arise at the larger multiple-station sites in the storage of data. An ingenious solution to this problem has been utilized at Oak Ridge. Figure 11.21 shows examples of the "Microcard" data storage used at that station. Between 5 and 10 years of complete meteorological data for a station can be placed in one 3- by 5-in. file drawer.

Although many meteorological programs for the atomic energy industry will be limited in scope and of relatively short (2 to 4 years) duration, others eventually become part of the operational management of the site. This is particularly true at large sites, changing experimental facilities, and near populated areas. Much time and effort can be saved by designing a meteorological program with equipment and records that will serve the future, as well as the immediate, meteorological requirements.

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# 12

# Climatological Data for Site Selection and Planning

Prior to the construction and operation of atomic energy plants, climatic data may be required for site selection, planning, and plant design. The data are collected and analyzed in a survey report in such a manner that they will provide information useful for stack gas diffusion estimates and engineering and construction needs.

An outline suggesting information to be included in the survey is given in this chapter. This is followed by a listing of sources of climatic data.

## 1. SITE METEOROLOGICAL SURVEY REPORTS

The outline that is given below is offered as a guide in the preparation of meteorological survey reports for industrial plant sites and should be regarded as flexible. The major headings divide the outline into two separate categories, and a report would be expected to cover one or both of these categories. For example, a plant having no effluent source would not be concerned with "diffusion climatology." Categories 1 and 2 of the outline are sometimes prepared as separate reports. Within each category the items listed should be considered as minimal. Other items may be added, depending on the nature of the plant and its environment. The degree of treatment, of course, will depend largely upon the availability of data. Since it is often desired to isolate some atomic energy plants, locations are often chosen for which meteorological observations are not available. In hilly or mountainous country or near large bodies of water, large differences in weather conditions, particularly in the diffusion parameters, may exist over short distances. Existing meteorological records, even if taken close to the chosen site, may not be representative. Often a few observations at the exact site, taken at times selected by a meteorologist, will be more valuable than any amount of speculation on the basis of data from a nonrepresentative station.

At locations where records of wind and temperature lapse rate are not available, the diffusion microclimate can often be inferred, in a qualitative manner, from other data. Since minimum diffusion is usually associated with small air movement and atmospheric stability, other phenomena also associated with these conditions may give a rough picture of relative diffusion conditions, although not of their magnitude. The frequency and duration of ground fog, smoke, and/or low visibility may be so related to diffusion. A good indicator is also the occurrence of ground frost. At locations remote from stations with meteorological records, this element may be the only information available since these data can be obtained from agricultural sources. Also, the ecology of a site may reveal to the expert plant associations that would indicate frequent and persistent ground inversions. Advantage should be taken of all such indirect data when attempting to evaluate probable diffusion conditions.

1. Diffusion climatology.
    a. Introductory material.
        (1) Important terrain features (using maps, cross sections, etc.).
        (2) Locations of populations or important installations relative to plant site.
        (3) Positions and representativeness of nearest meteorological stations.

- b. Vertical temperature gradient (radiosonde or other temperature sounding data).
  - (1) The diurnal regime and seasonal variations.
  - (2) Local effects of geographic features.
  - (3) Effects of weather and ground conditions.
  - (4) Frequency distribution at successive levels (i.e., surface to 100 ft, 100 to 200 ft, etc.).
- c. Winds (surface and winds aloft data).
  - (1) Diurnal and seasonal variations.
  - (2) Wind frequencies (wind roses) for lapse and inversion conditions (or day and night).
  - (3) Wind frequencies (wind roses) for precipitation.
  - (4) Frequency and duration of calms.
  - (5) Local wind circulations (mountain winds, sea breezes, etc.).
  - (6) Vertical wind structure (or comparison of surface wind data with winds at stack level).
- d. Stack gas diffusion estimates.
  - (1) Maximum ground concentrations (or least dilution factor) and the most frequent locations of concentration maxima.
  - (2) Concentrations at various points of importance in the environs of the plant.
  - (3) Areas affected during periods of poor diffusion.
  - (4) Areas affected by morning fumigations.

2. Engineering climatology.
   - a. Introductory material (probably not required if categories 1 and 2 are combined into one report).
     - (1) Important terrain features (maps, cross sections, etc.).
     - (2) Effects of geography and topography on climate.
   - b. Summaries of measured elements (these should include normals or the average maxima, minima, means, and expectancies of extremes).
     - (1) Temperature.
     - (2) Humidity (relative humidity and wet-bulb temperature).
     - (3) Surface winds.
     - (4) Barometric pressure.
     - (5) Precipitation.
   - c. Summaries of observed elements (include frequencies by seasons, if available and if important to operations on the site).
     - (1) State of ground (bare and dry, loose dirt, moist, wet, frozen, snow cover, etc.).
     - (2) Fog, haze, and smoke. (Frequency, duration, and seasonal distribution.)
     - (3) Cloudiness.
     - (4) Blowing snow or dust, dust devils.
     - (5) Ground frost.
   - d. Weather and concrete.
     - (1) Excessive drying rates (wind and low humidity).
     - (2) Freeze-thaw cycles.
   - e. Human comfort, heating and air conditioning.
     - (1) Effective temperatures (wind, temperature, and humidity).
     - (2) Degree days.
     - (3) Tropical days.
   - f. Especially adverse weather phenomena (include expectancies by months or seasons, past case histories of damage, and, where possible, suggestions for avoiding damage).
     - (1) Destructive winds, tornadoes.
     - (2) Excessive precipitation, floods.
     - (3) Extreme or prolonged heat or cold.
     - (4) Thunderstorms, lightning.
     - (5) Hail storms.
     - (6) Ice storms.
     - (7) Sand storms.
     - (8) Blowing or drifting snow.
   - g. Special summaries for specific problems. Special problems may require data or summaries not covered above. Such requirements should be anticipated as far in advance as possible and the necessary information obtained.

## 2. SOURCES OF CLIMATIC DATA

Climatological data may be usually obtained from or through the U. S. Weather Bureau to fulfill most preliminary site evaluations or basic engineering design requirements. At present, there are some 12,000 observing stations in this country; most of them are under the supervision of the U. S. Weather Bureau, but some are operated by other federal agencies and by various industrial concerns in con-

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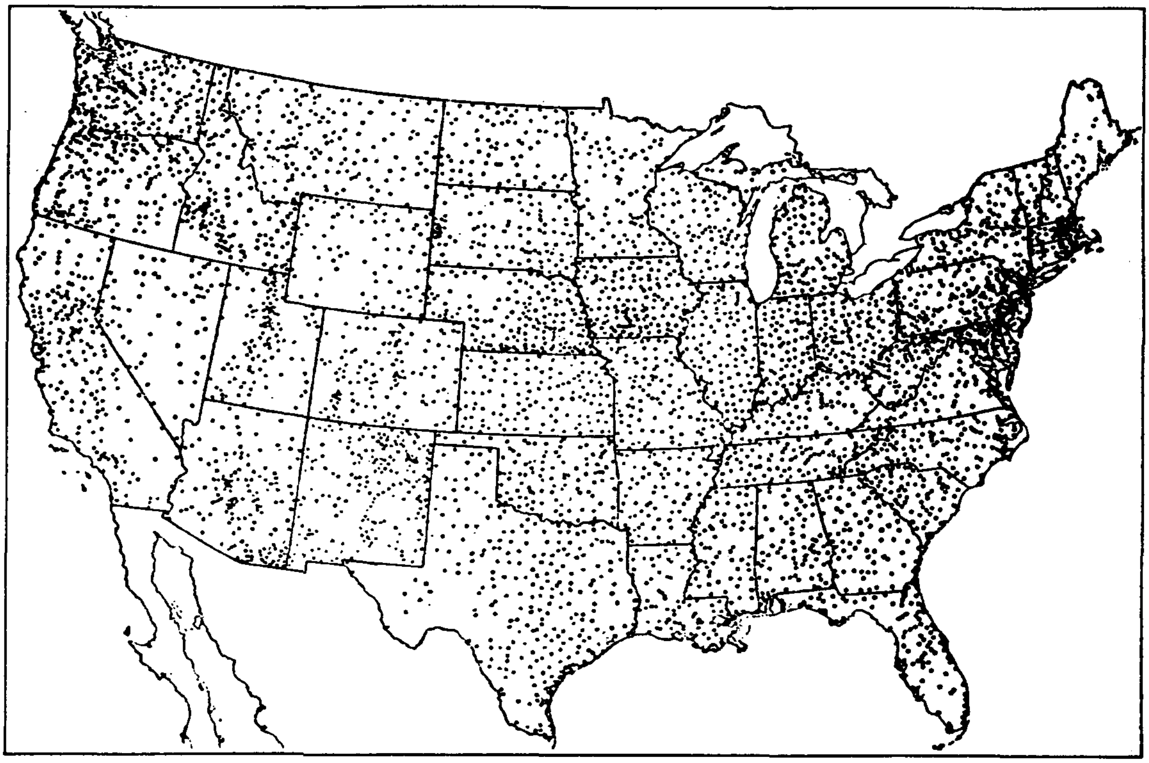

Fig. 12.1—Climatological stations of the Weather Bureau. (Data included in the 1941 Yearbook maps and tables.)

nection with their local plant problems. Much of these data have been, or are being, routinely processed and published so that many requests may be immediately answered. Other requests may require special tabulations or analysis. It is the purpose of this section to describe briefly the various sources which are available and to suggest what procedure should be followed in requesting climatological data.

2.1 *Published Data from the Weather Bureau.* As a routine public service, the Weather Bureau publishes the following current climatic summaries:

(a) *Climatological Data.* Monthly and annual by sections (states): For each of about 11,000 observing stations in the United States (Fig. 12.1), monthly and annual summaries are published which contain such items as average and extreme temperatures; degree days; frequencies of temperatures above or below certain important thresholds; total monthly precipitation; greatest amount of precipitation in a 24-hr period; number of days when precipitation is 0.10 in. or more, 0.50 in. or more, and 1.00 in. or more; total monthly snowfall; and maximum depth of snow on ground. The total daily precipitation and the daily maximum and minimum temperature are also included. Departures from normal† are given for monthly mean temperatures and total precipitation. The data for the period through 1930 are also summarized by decades in the Climatological Summary for the United States (Bulletin W).

(b) *Local Climatological Data.* Monthly and annual by stations: For about 300 Weather Bureau offices, annual, monthly, and monthly supplement reports (based on hourly observations) are published for each station, which include the same items as above plus the following. (1) Monthly summary: daily prevailing

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†Except for first-order Weather Bureau stations long-term means, rather than normals, are used. The period of record used in computing these means is not homogeneous, but they can be evaluated to some extent by reference to the station index which gives the number of years of record.

wind and average speed, fastest daily wind speed and direction, total hours of sunshine, average daily sky cover, occurrence of thunderstorms, average, highest, and lowest monthly barometric pressure, and hourly precipitation amounts. (2) Monthly supplement summary: wind direction and speed occurrences, ceiling and visibility occurrences, temperature and wind speed vs. relative humidity occurrences, hourly occurrences of various precipitation amounts, hourly occurrences of sky cover, wind, and relative humidity, hourly temperatures, and six-hourly observations of sky cover, pressure, psychrometric data, and wind. (3) Annual summary: a review of meteorological data for the current year by months for all the items published in the monthly summary plus a few additional items; means and extremes of these same meteorological variables for entire period of record; monthly and seasonal degree days for entire period of record;† and average monthly temperature, precipitation, and snowfall for entire period of record.†

(c) *Climatological Data National Summary.* To summarize the climatological data presented in the local climatological data publications and to include other meteorological data which is of more importance when considered nationally, both a monthly and annual national summary are also routinely published. (Prior to 1950 these data were published in the Monthly Weather Review.) Briefly, they contain the following information. (1) Monthly: condensed climatological summary by states of the average, maximum, and minimum temperature and departure from normal temperature records; the average, greatest, and least precipitation and departure from normal precipitation; for each of the about 250 Weather Bureau stations, average pressure, temperature, precipitation, wind, sky conditions, and relative humidity statistics; the total heating degree days for each station for the month, season, and long-term mean; all severe storms, together with estimated property damage and a brief description of each storm during the month; maximum river stage data during flood periods on all main rivers; monthly pressure, temperature, relative humidity, and average wind direction and speed at various levels for upper air radiosonde stations; and solar radiation data for some 72 locations in the United States. Eleven climatic charts are also routinely published. (2) Annual: yearly summary of the material presented in the monthly climatological data national summary, with the addition of the following items: total evaporation and wind movement by months for some 280 different locations, excessive precipitation (short duration rainfall) for various stations, and a more complete breakdown of severe storms.

(d) *Daily River Stages at River-gauge Stations on the Principal Rivers of the United States.* This report is published annually and lists the daily and monthly river-gauge observations.

(e) *Airway Meteorological Atlas for the United States (U. S. Weather Bureau 1941).* For a selected group of stations in the United States, this publication contains monthly surface wind rose charts, diurnal variation and seasonal percentage charts of fog, ceiling heights, visibilities, precipitation and thunderstorms, wind velocities, seasonal upper air wind roses and wind resultants for 9 levels, and altitudes of various types of clouds by months.

(f) *Reports of the Chief of the Weather Bureau and the Meteorological Yearbook.* The first of these publications covers the years from 1895 to 1934; the second covers the years from 1935 to 1949. They contain various climatological data for all first-order stations for each year.

(g) *Climate and Man (1941 Yearbook of Agriculture).* This book reviews the weather of each state and presents some statistical data for many individual communities. Forty-five climatological charts for the entire United States are also included.

(h) *Climatological Record Books (U. S. Weather Bureau).* These were prepared by many first-order stations and contain 20-yr summaries of data by element (most observed elements). Microfilm copies of all these books are on file at the National Weather Records Center, and photographic enlargements of pertinent pages can be furnished upon request.

(i) *Maximum Station Precipitation (Weather Bureau Technical Paper No. 15).* This report presents the maximum station precipitation

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† Except where the period of record exceeds 50 years. In these cases the latest 5 decades are shown.

for 1, 2, 3, 6, 12, and 24 hr by months for all recording type rain gauges in the United States (eventually some 3000 records will have been summarized). It is divided into separate state reports, and the following have been published to date: Utah, Idaho, Florida, Maryland-Delaware-District of Columbia, New England States, New Jersey, South Carolina, Virginia, Georgia, and New York. The remaining state reports are being prepared for publication.

Many other publications are available for specific problems but they are too numerous and specialized for individual listing here.

2.2 *Published Data from Other Sources.* It is impossible to list all the climatological studies which have been prepared by some group for particular areas or points of interest in the United States, but a few such sources of reports follow.

(a) *Department of Defense Installations.* Many military installations have taken meteorological observations at one time or another in the past, and in many cases, especially for the U. S. Naval or Air Force bases, climatological reports may have been prepared. These may be usually obtained through the U. S. Weather Bureau.

(b) *Air Pollution Investigations.* Many cities are now conducting thorough air pollution studies in which meteorology is one important phase. Reports have been prepared for Los Angeles, St. Louis, Chicago, Pittsburgh, Donora, Detroit, Cincinnati, etc. These reports may be originally published in some technical journal or locally by an air pollution group or by some private investigator. They may be obtained usually through any large technical or meteorological library.

(c) *Academic Institutions.* At some 20 colleges or universities (see Weatherwise, Vol. 6, No. 5, October 1953) in the United States, a meteorological unit has been established. Many of these schools have conducted meteorological or climatological surveys in their localities and have published some excellent reports. For example, some of the basic meteorological work on the Los Angeles smog problem was performed by members of the Meteorology Department of the University of California. These reports are usually available at all large technical or meteorological libraries. These university meteorological departments should also serve as a good source of meteorological help and assistance for many atomic energy problems.

(d) *AEC Reports.* Atomic energy areas with already existing meteorological programs have, for the most part, summarized all the available meteorological data or climatological reports for their respective areas. These groups can also offer much help in advising new groups who are faced with atomic energy meteorological problems for the first time.

(e) *Meteorological Journals.* Many climatological studies are published in various meteorological journals, three of which are the "Bulletin of the American Meteorological Society" and the "Journal of Meteorology," published by the American Meteorological Society, 3 Joy Street, Boston, Mass., and the "Monthly Weather Review," published by the U. S. Weather Bureau.

(f) *Bibliography.* A comprehensive survey of meteorological literature, including climatological publications, is carried out by the American Meteorological Society and published in "Meteorological Abstracts and Bibliography." Information on this publication can be obtained by writing: American Meteorological Society, Office of the Executive Secretary, 3 Joy Street, Boston 8, Mass.

2.3 *Punch Card Data.* Although much of the meteorological data which is being collected by the government in the United States at the present time is being placed on IBM punch cards,† tabulated and published in one of the sources listed above, it should be realised that this program has only been under way for some five years and that many of the old records which are required for a complete climatological survey may not have been processed for immediate use. However, the original data are available and may be placed on punch cards for all sorts of tabulations very readily. With these meteorological data on punch cards, practically any type of tabulation may be routinely prepared. Two of those most frequently requested in current work for the AEC

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† See Topics, U. S. Weather Bureau (News Bulletin), The National Weather Records Center, Vol. 12, No. 9, pp. 114-116 and J. A. Copeland, The Gold Mine at Asheville, Weatherwise, Vol. 6, No. 2, pp. 33 and 57, 1953.

are precipitation wind roses and temperature inversion tabulations. In the former, all hourly observational IBM cards when precipitation was observed are first sorted out, and then a wind rose is prepared. These wind tabulations may be prepared for any specific hour or period of the day, depending upon the particular problem being investigated. For the inversion study the twice daily radiosonde (upper-air) observations may be summarized to show the frequency of stable, unstable, or isothermal conditions at the observation time.

2.4 *Methods of Obtaining Meteorological Information and Assistance.* All the Weather Bureau climatological publications routinely issued which have been described above may be purchased directly from the Superintendent of Documents, Government Printing Office, or library copies may be borrowed directly from most meteorological libraries. The local Weather Bureau offices throughout the country may also have additional publications or reports on their locality which may be examined or in some cases borrowed for a short period of time. For more complete information on what government climatological material is available, the Chief, U. S. Weather Bureau, Washington 25, D. C., should be contacted.

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# A

# Selected Equations, Parameters, and Conversion Factors

## A.1 GENERAL NOMENCLATURE

$\chi$ = concentration (grams per cubic meter, curies per cubic meter, etc.)
Q = source strength (instantaneous; grams, curies, etc.)
= emission rate (continuous; grams per second, curies per second, etc.)
= emission rate (continuous line source; grams per second per meter, etc.)
$C_x$, $C_y$, $C_z$ = diffusion coefficients [$(\text{meters})^{n/2}$] in the x, y, and z planes, respectively
C = generalized diffusion coefficient [$(\text{meters})^{n/2}$] for isotropic turbulence, i.e., $C = C_x = C_y = C_z$
n = nondimensional parameter associated with stability
x, y, z = downwind, crosswind, and vertical coordinates measured from a ground point beneath a continuous source and from the center of the moving cloud in the instantaneous case (meters)
t = time (seconds)
$\bar{u}$ = mean wind speed (meters per second)
h = height of source or, alternatively, height of plume

## A.2 CONCENTRATION

Continuous point source (see Chap. 4, Sec. 2.1):

$$\chi_{(x,y)} = \frac{2Q}{\pi C^2 \bar{u} x^{2-n}} \exp\left(-\frac{y^2 + h^2}{C^2 x^{2-n}}\right)$$

(Note that Q is doubled to allow for reflection by the ground.)

Instantaneous elevated point source (see Chap. 4, Sec. 1.6):

$$\chi_{(x,y)} = \frac{2Q}{\pi^{3/2} C^3 (\bar{u}t)^{3(2-n)/2}} \exp\left[-\frac{x^2 + y^2 + h^2}{C^2 (\bar{u}t)^{2-n}}\right]$$

Continuous infinite elevated crosswind line source (see Chap. 1, Sec. 2.2):

$$\chi_{(x)} = \frac{2Q}{\pi^{1/2} C \bar{u} x^{(2-n)/2}} \exp\left(-\frac{h^2}{C^2 x^{2-n}}\right)$$

## A.3 FINITE VOLUME CORRECTION

Instantaneous source (see Chap. 4, Sec. 2.3):

$$(\bar{u}t)_0 = \left(\frac{2Q/\chi(0)}{\pi^{3/2}C^3}\right)^{2/3(2-n)} \qquad \text{(ground source)}$$

Continuous source:

$$x_0 = \left(\frac{2Q/\chi(0)}{\pi C^2\bar{u}}\right)^{1/(2-n)} \qquad \text{(ground source)}$$

where $x_0$ or $(\bar{u}t)_0$ = distance upwind from a real source required to produce the required volume at the point (0,0,0) and $t = 0$

$\chi(0)$ = central concentration

## A.4 FORMULAE FOR SPECIAL CASES

Instantaneous point source (see Chap. 4, Sec. 2.4):

$$d_{\max} = \left(\frac{2h^2}{3C^2}\right)^{1/(2-n)}$$

$$\chi_{\max} = \frac{2Q}{(2/3\ e\pi)^{3/2}h^3}$$

$$\text{TID} = \frac{2Q}{\pi C^2\bar{u}(\bar{u}t)^{2-n}} \exp\left[-\frac{h^2}{C^2(\bar{u}t)^{2-n}}\right]$$

$$\text{TID}_{\max} = \frac{2Q}{\pi e\bar{u}h^2}$$

$$d_{\max\ \text{dosage}} = \left(\frac{h^2}{C^2}\right)^{1/(2-n)}$$

where $d_{\max}$ = distance, downwind from the source, of the maximum concentration

$\chi_{\max}$ = concentration at $d_{\max}$

TID = total integrated dosage (see Chap. 4, Sec. 2.6a)

Continuous point source (see Chap. 4, Secs. 2.4, 2.6a, and 2.6c):

$$d_{\max} = \left(\frac{h^2}{C^2}\right)^{1/(2-n)}$$

$$\chi_{\max} = \frac{2Q}{e\pi\bar{u}h^2} \qquad [\text{anisotropic, multiply by } (C_z/C_y)]$$

$$2y_0 = 2\left(\ln \frac{100}{p}\right)^{1/2} C_y x^{(2-n)/2}$$

$$z_0 = \left(\ln \frac{100}{p}\right)^{1/2} C_z x^{(2-n)/2}$$

$$\chi_{\text{fumigation conc.}} = \frac{Q}{(2\pi)^{1/2}\, C_y \bar{u} H x^{(2-n)/2}}$$

$$\chi_{\text{av. conc. over long period}} = \frac{0.02Qf}{\pi^{1/2}\, C_z \bar{u} x^{(2-n)/2}} \exp\left(-\frac{h^2}{C_z^2 x^{2-n}}\right)$$

where $p$ = per cent of axial concentration
$2y_0$ = cloud width
$z_0$ = cloud height
$H$ = height of inversion
$f$ = wind direction frequency (per cent)

## A.5 PLUME RISE FROM EXHAUST STACKS

$$\Delta h_{\text{(Bryant-Davidson)}} = d\left(\frac{v_s}{u}\right)^{1.4}\left(1 + \frac{\Delta T}{T_s}\right)$$

$$\Delta h_{\text{(Holland)}} = 1.5\, v_s d + 3 \times 10^{-4}\, Q_H$$

where $\Delta h$ = rise of plume above stack (feet)
$d$ = stack diameter (feet)
$v_s$ = stack draft velocity (feet per second); in Holland equation (miles per hour)
$u$ = mean wind speed (feet per second); in Holland equation (miles per hour)
$\Delta T$ = stack gas temperature excess over ambient (°C)
$T$ = stack gas temperature (°C)
$Q_H$ = heat emission (calories per second)

## A.6 CLOUD RISE AND CLOUD VOLUME (see Chap. 6, Sec. 5.1b)

$$Z_{\max} = \left(\frac{Q_h}{2c_p\rho\pi^{1/2}C^3\theta_a'}\right)^{0.276}$$

$$V_N = \frac{\Delta\theta_1}{\Delta\theta_2} V_G$$

$$\Delta\theta_3 = \Delta\theta_2\left(\frac{Z_{\max}}{Z_s}\right)^{2.62}$$

$$V_D = \frac{\Delta\theta_2}{\Delta\theta_3} V_N$$

where $Q_h$ = heat liberated (calories)
$c_p$ = specific heat at constant pressure, 0.25 cal/g/°C
$\rho$ = air density (grams per cubic meter)
$\theta'_a$ = gradient of potential temperature (degrees centigrade per meter)
$C$ = diffusion coefficient [$(\text{meters})^{1/8}$]; C varies from 0.3 for stable to 0.6 for unstable conditions
$Z_{max}$ = height of rise of night cloud
$V_N$ = volume of night cloud (cubic meters)
$V_G$ = volume of cloud at the ground (cubic meters)
$\Delta\theta_1$ = initial excess of temperature above ambient (degrees centigrade)
$\Delta\theta_2 = Z_{max}\theta'_a$, the decrease in temperature excess (degrees centigrade)
$\Delta\theta_3$ = temperature excess at stabilization height for day cloud (degrees centigrade)
$Z_s$ = assumed stabilization height
$V_D$ = volume of day cloud (cubic meters)

## A.7 GROUND DEPOSITION

Dry fall-out (see Chap. 7, Sec. 1.3):

$$\omega_{\text{dry-max}} = \frac{nQ}{2e\pi^{1/2}C_y x^{2-(n/2)}}$$

Wash-out (see Chap. 7, Sec. 2.3):

$$\omega_{\text{rain-max}} = \frac{Q}{e\pi^{1/2}C_y x^{2-(n/2)}}$$

where $\omega$ = deposition rate (grams per square meter per second) for a steady source (Q in grams per second) or total deposition (grams per square meter) for an instantaneous source (Q in grams).

Total instantaneous wash-out, instantaneous point source (see Chap. 7, Sec. 2.4):

$$\omega = \frac{Q}{\pi C^2(\bar{u}t)^{2-n}}$$

Total instantaneous wash-out, continuous point source (see Chap. 7, Sec. 2.4):

$$\omega = \frac{Q}{(2\pi)^{1/2}C_y\bar{u}x^{(2-n)/2}}$$

where $\omega$ = ground deposition (grams per square meter, curies per square meter, etc.).

## A.8 PARAMETERS

$C^2$ [(meters)$^n$] As a Function of Height (h) and Stability Parameter (n)

| | | h, meters | | | |
|---|---|---|---|---|---|
| | n | 25 | 50 | 75 | 100 |
| Large lapse rate | 0.20 | 0.043 | 0.030 | 0.024 | 0.015 |
| Zero small temperature gradient | 0.25 | 0.014 | 0.010 | 0.008 | 0.005 |
| Moderate inversion | 0.33 | 0.006 | 0.004 | 0.003 | 0.002 |
| Large inversion | 0.50 | 0.004 | 0.003 | 0.002 | 0.001 |

## A.9 CONSTANTS AND CONVERSION FACTORS

$\pi = 3.1416$
$e = 2.7183$
1 curie = $3.7 \times 10^{10}$ dis/sec
1 r = 1 esu/0.001293 g of air
1 r = $6.77 \times 10^{10}$ Mev/m$^3$ (air at 0°C and 760 mm Hg)
1 r = $5.24 \times 10^7$ Mev/g (air)
1 r = $2.083 \times 10^9$ ion pairs/cm$^3$ (air, standard conditions)
1 r = 83.8 ergs/g (air)
1 mile = 1.6093 kilometers = 5280 ft
1 ft = 0.3048 meters
1 meter = $6.214 \times 10^{-4}$ mile
1 mph = 0.4470 meters/sec
1 Btu = 252 calories
1 cfm = $4.72 \times 10^{-4}$ m$^3$/sec
1 g = 0.0022 lb
1 g/cm$^3$ = 62.43 lb/cu ft
1 liter = 0.0352 cu ft
1 Mw-sec = $10^6$ joules
1 Mw-sec = $10^{13}$ ergs
1 Mw-sec = $6.24 \times 10^{18}$ Mev
**Fission product decay energy ($\beta$ and $\gamma$, where $\beta \simeq \gamma$) = $3.2t^{-1.21}$ Mev/sec/fission**

**Concentration to dose rate for radiative equilibrium (sea-level density):**

$$1 \text{ curie/m}^3 = \frac{1 \text{ curie/m}^3 \times 3.7 \times 10^{10} \text{ dis/sec curie} \times E \text{ (Mev/dis)}}{6.77 \times 10^{10} \text{ Mev/m}^3 \text{ r}}$$

$$= 0.547E \text{ r/sec}$$

1 curie sec/m$^3$ = 0.547E r

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