Chapter 1

Introduction to the Meteorology–Atomic Energy Relation

1-1 INTRODUCTION

The waste products of our civilization must be disposed of. Receptacles for this debris are the earth's land masses, water bodies, and atmosphere. The science of meteorology is important in the study of the disposition of waste products in the atmosphere.

Wastes that are released to the atmosphere consist of particles and gases. Atmospheric residence times for some of these materials may be very short, hours or even minutes. For other materials residence times may be measured in terms of years. Regardless of the residence time, the movement of gases and particles in the atmosphere will be, in large measure, governed by the motions of the atmosphere. Some atmospheric motions dictate the paths to be followed by airborne contamination; other motions determine the extent to which the contaminants will be diluted. The study of the effects of atmospheric motions on suspended pollutants is a branch of the science of meteorology variously categorized under the headings "air-pollution meteorology" or "atmospheric diffusion."

The total amount of debris released during routine atomic processes and conceived as possible from accidents is minuscule when compared with the amount of pollutants produced throughout the world by combustion. The extraordinarily poisonous nature of the radioactive materials involved, however, dictates that even small quantities be treated with respect. For instance, it has been estimated that some of the radioactive materials found in a reactor are 3 million to 2 billion times as toxic as chlorine, the most common poison used by industry. It has been calculated that, if it were possible for all the many controls and safety features in a large power reactor to fail so as to produce a disastrous release of radioactivity, this release could conceivably kill thousands of people and cause economic losses of billions of dollars. Although, in actual practice, such an accident is made to have a vanishingly small probability of occurring, the theoretical potential for such an accident is probably greater than for any work of man other than the explosion of a fission or fusion weapon.

The nuclear safety criteria that have evolved in the United States are therefore elaborate and comprehensive. Every facet of the safety problem is given a searching examination in which conservatism is the keynote. The examination starts during the design of the particular facility, continues through site selection and extends through construction and actual operation. This degree of care is exercised in the review of proposals for both routine and experimental operations. The examination is performed by individuals and groups drawn from a number of disciplines. Physicists, chemists, and a variety of engineers contribute to the safety analysis of the design and construction phases of the facility. Legal experts are alert for any inadvertent violations of the regulations governing atomic energy programs and for infringements on the health and safety of the general public. Finally, specialists in health physics, biology, hydrology, seismology, and meteorology examine the environmental aspects of the atomic facility. Virtually the entire safety analysis is performed at least twice: once by the proposing organization, which develops the detailed information, and again by the licensing agency, which critically reviews every step.

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The basic question to which both the first edition of Meteorology and Atomic Energy and the present edition are addressed remains: "How can the available knowledge of the atmosphere be used to aid in solving problems of health, safety, and economics which arise in the peaceful exploitations of nuclear fission or fusion processes?" Although the answer to this question is categorical in part, there is still a tentative and even speculative remainder.

1-2 METEOROLOGY, DIFFUSION, AND ATMOSPHERIC POLLUTANTS

Recorded evidence of man's concern with the extent and effects of air pollution caused by his activities goes back several centuries. The increasingly heavy use of coal for home heating as well as for industrial power in Great Britain has led to episodes of extreme pollution in cities such as London. Luke Howard, the author of a number of books dealing with the weather in the vicinity of London, has described one of the cases of severe pollution which occurred in 1812:

> London was this day involved, for several hours, in palpable darkness. The shops, offices, etc. were necessarily lighted up; but the streets not being lighted as at night, it required no small care in the passenger to find his way, and avoid accidents. The sky, where any light pervaded it, showed the aspect of bronze. Such is, occasionally, the effect of the accumulation of smoke between two opposite gentle currents, or by means of a misty calm. I am informed that the fuliginous cloud was visible, in this instance, for a distance of forty miles. Were it not for the extreme mobility of our atmosphere, this volcano of a thousand mouths would, in winter be scarcely habitable.

The problem of air pollution from sources "of a thousand mouths" continued to gain in importance with the continued growth of the large metropolitan areas. Shortly after the beginning of this century, the large urban areas became the primary sources and receptors for these contaminants. The increase in size and diversity of the myriad of industrial processes in our civilized society guarantees the contribution of a steadily growing quantity of unpleasant or even toxic pollutants to the already overburdened urban atmosphere.

The increasing level of environmental air pollution has not gone unobserved. There have been numerous instances in the last few hundred years of attempts at pollution-level control by legislation aimed at restricting the emission of pollutants at the source. It has only been in the last half century, however, that the meteorologist has become directly involved in the study of the atmospheric problems in this field. The advent of the atomic energy industry during this period has provided a major focus for the development of air-pollution meteorology because prediction and control before the fact are essential in this new field.

The air-pollution meteorologist, much as his other meteorological colleagues, is interested in the movement of the atmosphere over scales from fractions of a second to a number of years and from a fraction of a meter to the circumference of the earth. He is interested in the mean motions of the atmosphere, i.e., those which indicate the direction and rate of bulk transport of atmospheric pollutants. He is also interested in turbulent fluctuations about these means. These turbulent eddies are the motions that disperse a pollutant as it travels with the mean motion.

The sources of atmospheric pollutants occur over an equally broad range of scales. Smoke from forest fires in British Columbia has darkened skies in western Europe. Dust from the 1883 volcanic eruption at Krakatoa was observed in the atmosphere over a period of many months during which it spread from the source near the equator to cover most of the northern hemisphere. The accumulated pollutants from an aggregation of human activities have darkened skies over cities and occasionally have caused widespread sickness and death. Noxious materials released from small industrial complexes, or even from a single stack, have resulted in human indisposition and economic penalty.

Air-pollution meteorology is concerned with all scales and types of releases of material to the atmosphere. The air-pollution meteorologist associated with the atomic energy industry draws on the experience and experimental evidence provided by the broad field of air pollution but concentrates his interest and effort in specific problem areas. These areas are dictated by the characteristics of the possible radionuclide releases, planned or accidental, from existing or proposed facilities. Some of the special characteristics frequently associated with the release of contaminants to the atmosphere from nuclear energy facilities are given in the following paragraphs.

Most, although certainly not all, pollutant releases from atomic facilities can be approximated by a continuous flow or an instantaneous puff from a point or small-volume source. These source configurations have been the subject of numerous investigations, both theoretical and experimental, dealing with the resulting downstream concentration and exposure patterns. Much of the information in subsequent chapters will be devoted to this topic. Problems associated with larger scale or more complex sources, such as those characteristic of urban pollution, are not yet generally encountered in the nuclear field.

Most releases originate from sources in the first hundred meters above the ground, and virtually all receptors for atmospheric pollutants are located within this same layer. Natural lids to vertical dispersion in the atmosphere frequently guarantee that surface-released pollutants will remain near the surface for protracted periods. It is not surprising therefore that much of the meteorological development for the atomic energy field has dealt with the lowest thousand meters of the atmosphere with particular emphasis on the lowest hundred meters. The very lowest layer of the atmosphere is of particular interest for other, purely meteorological reasons, which will be discussed in Chap. 3. Applications of atomic energy to provide auxiliary power for space vehicles, of course, create problems involving possible high-altitude sources, and this is an area into which air-pollution meteorology will expand in the future.

Because of various engineering and conceptual safeguards, postulated ground-level releases from atomic facilities, even under the worst assumed conditions, are usually sufficiently small that concentrations of interest would not extend to great distances from the source. Much attention has been concentrated therefore on the time history of these releases within the first few kilometers from the source. Interest in longer range travel has been increasing in recent years, but techniques for dealing with these longer range (>10 to 20 km) problems are still in a relatively undeveloped state.

Thus many of the past and present requirements of the atomic energy industry have resulted in meteorological investigation that is largely confined to transport and diffusion over a limited horizontal, vertical, and temporal range. Exceptions to this broad generalization will be noted in the appropriate chapters.

1-2.1 The Role of the Meteorologist in the Atomic Energy Industry

From a meteorological viewpoint all atomic facilities fall into two broad and overlapping categories: (1) those which have a planned and predictable effluent to the atmosphere and (2) those in which any significant effluent would be due solely to an accident. In the first category are such diverse systems as boiling-water reactors, fuel-processing plants, and any one of a large number of atomic experimental systems. A primary representative of the second group is the well-contained pressurized-water reactor. The magnitude of any of the releases can vary greatly in theory if not in practice. Simply stated, the role of the meteorologist is to evaluate the effects of weather and terrain on the concentration of the effluent as it travels from source to receptor. Assuming that limiting levels have been established for concentration of the released radioactive species, the meteorologist participates in the engineering by providing answers to the questions: "To what extent can the atmosphere be effectively utilized to dispose of pollutant materials?" for the first category of facilities and "How much of a safety factor can the atmosphere provide?" for the second.

The first consideration of meteorology in the atomic energy field was probably the "meteorological reconnaissance" of the Hanford, Wash., area, now the site of the Pacific Northwest Laboratory of the Battelle Memorial Institute. Dr. Arthur Compton of the Metallurgical Laboratory of the University of Chicago asked Dr. Phil Church, now Chairman of the Department of Atmospheric Sciences of the University of Washington, to make a meteorological survey of the Hanford area in preparation for the installation of the production reactors. The request was made in January of 1943. By March of that year, the first surveys of the area had been completed, the sources of existing data had been investigated, and plans had been formulated for an experimental study. In preparation for this study, a wind and stability measurement network was installed and balloon wind measurements to heights of 1000 m were conducted. Oil fog generators were soon installed, and a massive program of diffusion experiments was initiated. By December of 1944, a 120-m tower had been installed. This tower is still in use.

It is to the credit of the founders of this new technology that the potential problem was realized very early in the U. S. program and early action was initiated to study and forecast the geophysical aspects of the movement of radionuclides in the atmosphere, in the ground, and in water bodies. The primary motivation for these at times costly studies has been the extreme interest and concern for the safety and well-being of workers in the nuclear industry and the general population.

The science of meteorology enters the atomic energy field at three reasonably distinct phases in the life history of any typical facility: (1) during the choice of site and adaptation of design and operating procedure to its special characteristics, (2) during routine operations, and (3) in the unlikely event of an accident.

The choice of the site for a nuclear reactor is a complicated decision that depends not only on the factors that govern site selection for conventional industries, such as the availability of land, water, and labor and a market for the product in the general region under consideration, but also on such factors as the nature of the particular facility in regard to its potential for routine or accidental releases of radionuclides, the population distribution about the site, and, finally, the environmental characteristics of the surrounding area. Among these characteristics are meteorology, hydrology, and seismology. The final choice of the site is not usually based solely on any one of these characteristics. As an example, a particular site might be extremely undesirable from a meteorological point of view alone. The possible risk from an accidental release, however, could be very small if the region were neither populated nor farmed or if the reactor were of a type with which there existed much operating experience at other locations over many years and whose inherent stability and safety were very well established. Moreover, additional engineering safeguards might be incorporated to balance the deficiencies of the site. Again, if proximity of the site to the nearest populated areas were an important economic factor, meteorology would be one of the tools used to decide just how great a distance between the facility and the population would be necessary to ensure safety in the case of the most severe credible accident.

The choice of the site may depend on the routine release of radionuclides from the facility rather than on accidental release. Here again the dispersive capacity of the atmosphere at the location can be considered to determine the usefulness of the site. Further, the release of normal effluents can sometimes be carried out under positive meteorological control; i.e., the release can be adjusted to the current state of the atmosphere so that the effluent is diluted to previously determined safe levels. Because the atmosphere is usually enormously efficient in diluting material released into it, it would be, within limits, economically unwise to ignore completely or to fail to utilize properly this dispersive capacity.

Thus from this cursory treatment of the subject it would appear that the extent of the program necessary to evaluate the environment of a given site is not subject to any simple set of rules. Many of the small facilities of conventional design that are in operation have had minimal site-evaluation programs. In many cases these evaluations were carried out without the direct participation of meteorological specialists. On the other hand, some of the large reactors or those with unique problems of population distribution or unconventional design have had site evaluation studies that involved rather large staffs of meteorologists, long series of observations at the site, and rather detailed research into some of the characteristics of the environment. Often these studies continued for periods as long as a few years before the actual commencement of operations at the facility.

Once the atomic facility has been completed and routine operations have begun, the role of the meteorologist is usually considerably reduced. Again, with many of the smaller or more conventional reactors, meteorological aid has been completely dispensed with. The experience gained in running the systems in these cases has indicated that the effect of any routine effluent is negligible; thus the plant has little effect on its environment. However, there are atomic facilities, primarily at the various national laboratories and test sites, from which routine releases may be large enough that continuous meteorological advice is required. It is not unusual for particularly high release processes or experiments to be carried out under meteorological control. Usually in such cases the meteorologists at the particular sites will have prepared in advance forecasting schemes that will allow the rapid computation of the expected wind direction and diffusion conditions. Most civilian power or test reactors, however, have been designed so as to require no further meteorological assistance once they are operative.

The third function meteorology must be prepared to perform in the interest of safety would occur during an unplanned release of radionuclides from any nuclear system. Presumably, if the estimate of the possible release of material made during the site evaluation is not exceeded and if the weather conditions at the time of the accident are not more limiting than had been postulated, the safety of the surrounding population and environment will not be threatened. Even in such cases, however, immediate prediction of the direction of movement and the rate of diffusion is extremely useful if only to assist the radiological-monitoring organization to establish promptly and fully the actual extent of environmental contamination. Such information may frequently be estimated by a meteorologist from the simplest instrumentation at the site or even from the weather data that could be furnished by the nearest U. S. Weather Bureau station. The use of such raw data by a staff prepared by a minimal meteorological training program will be much better than no meteorological input at all. A meteorologist at a well-equipped weather station can offer considerably greater help in an accident situation by making rapid quantitative estimates of the extent and severity of contamination and by effectively utilizing early radiological-survey results to reassess the situation. Moreover his services may be of great use in the postmortem evaluations of some of the details of the accident, including deductions regarding the magnitude of the release based on the observed contamination patterns. In the unlikely event of a really severe accident, the services of the meteorologist would be invaluable for carrying out any large-scale countermeasure programs.

Of the three areas encompassing the use of meteorology in the interest of safety, the initial site evaluation is currently the area of greatest meteorological involvement. This is certainly due in part to the legal requirement made in the interest of safety that the environment of the proposed site be carefully scrutinized and that a formal hazards evaluation be prepared for submission to the Atomic Energy Commission.

1-2.2 A Brief History of the Meteorology–Atomic Energy Relation

1-2.2.1 History of the Atomic Energy Industry. The atomic energy industry had its beginning in the published reports of Hahn and Strassman and Meitner and Frisch in 1938 and 1939 on the discovery of fission. By 1942, with the help of Enrico Fermi and a number of other scientists, a pile of graphite and uranium was made to go "critical" (have a sustained chain reaction by fissioning with neutrons) under the stadium at Stagg Field in Chicago. This first reactor, known as a critical assembly because of its low power level, was called Chicago Pile 1 (CP-1). It was later moved to the grounds of the Argonne National Laboratory. The initial work was performed under the code name Manhattan Engineer District. Because of its low power (about 200 watts), this reactor generated a small inventory of fission products; so its inherent hazard potential was not great. Nevertheless the probability of an accident should have been considered rather high in view of the lack of knowledge and experience on the part of the designers and the extremely experimental nature of the reactor.

In 1943 the X-10 air-cooled graphite reactor was built at Oak Ridge, Tenn., also by the Manhattan Engineer District. This reactor operated at a power of 1.0 to 2.0 Mw and served as a prototype for the plutonium-production reactors on which construction was begun at Hanford, Wash., during the following year. This reactor had a rather large fission-product inventory, and, because of its experimental nature and the lack of knowledge and experience, the probability of an accident was rather large. However, because of the inherent slow response of this type of reactor and because the control system was designed to make it even slower, safe operation was an important consideration from the start.

In 1944 construction of the Hanford reactors for the production of plutonium began. Because these reactors were designed to generate pound quantities of an element in a short period of time by the formation of individual atoms, they had to operate at comparatively large powers. These reactors were somewhat different from the Oak Ridge Graphite Reactor; so engineers did not have a sufficient foundation of knowledge and experience to have confidence in the reactor behavior. Also built at this time was the Hanford 305 Test Reactor, a 30-watt graphite test reactor that was used to make certain tests of the graphite moderator and of the uranium slugs.

As soon as a charge of fuel came out of the plutonium-production reactors, a large source of gaseous effluents was encountered. For the plutonium produced to be removed from the uranium and other fission products, it was necessary to dissolve the fuel by various chemical reactions. During the early stages of this process, all the noble-gas fission products, notably radioactive isotopes of xenon and krypton, were released. It was not feasible to remove them by a filter system; they were released to the atmosphere in rather large quantities.

As part of this same separation process, large quantities of radioactive iodine were also evolved. In time methods were developed for filtering or otherwise removing most of the iodine from the effluent. Iodine remained one of the most important elements in the effluent as far as biological effect was concerned. Because of the high volatility of its oxide, ruthenium was also occasionally lost in large quantities in the gases from the chemical-separation plants at Hanford.

The reactors at Hanford were operated in such a manner that the loss of fission products from the fuel during normal operation was minimal. There was some production of ^{14}C and ^{41}Ar in the gases used to cool the graphite at various stages in the development of the reactors. These effluents never acquired great importance, however, because there was no way in which a large unexpected release could occur. Carbon-14 and ^{41}Ar were always released as fast as they were formed, and the rate of formation was known and controlled.

Another source of radioactive effluent from the Hanford reactors was created in the process of changing the fuel. The fuel was changed by pushing new fuel slugs into one end of the horizontal process tubes and forcing the spent fuel out the other end into a canal of water. Owing to the heat generated by the fission products and to the pyrophoric nature of the uranium and plutonium contained in the fuel, however, a fuel element would occasionally catch fire while it was falling from the process tube to the canal. When the fuel caught fire, krypton, iodine, and other fission-product elements were driven off, and the release occurred in an area in which ventilation control and efficient filtering were difficult. Therefore great care was taken to prevent these fuel fires.

In 1944 two experimental reactors were built to investigate other configurations for producing chain reactions. One of these was a homogeneous water-boiler reactor at Los Alamos (HYPO) operated at a power level of 5.5 kw. From such a reactor the xenon and krypton are released as they are formed once the ability of the water to dissolve them has been exceeded. The volume of these gaseous nuclides is extremely small; so they can be stored for extended periods while they decay, and thus the residual radioactivity in the final effluent is minimal.

Also in 1944 a heavy-water-moderated reactor (the CP-3) was built at Palos Park, Ill. It operated at a power level of 300 kw. Because this reactor employed clad fuel that was never removed from water while the fuel was hot, there was little effluent from it. Its fission-product inventory, which was, of course, proportional to its power level, was the largest accumulated up to that time. The risk was accepted as necessary at the time because of the national-defense aspects. What was learned from this reactor helped in the design and construction of the Savannah River production reactors in the 1950's.

In 1946 the Atomic Energy Commission was formed to carry out the research and development required to obtain useful power by means of atomic energy. In this year the first reactor designed to produce power was built at the Los Alamos Scientific Laboratory. Called "Clementine," it operated at a power level of 20 kw on plutonium fuel with mercury for coolant. Even by today's standards this would be an unusual reactor of advanced design with unknown properties which should be treated with caution and respect. The location at Los Alamos provided the degree of isolation that was deemed appropriate at the time. The potential effluent from an accident included plutonium and radioactive mercury as well as the volatile fission products. Although plutonium is not at all volatile, its relative biological hazard is so great that its effective hazard is often on a par with the products that it produces during fission.

In 1948 an assembly known as PPA was constructed at Knolls Atomic Power Laboratory (KAPL) near Schenectady, N. Y. This was the first critical experiment in the military reactor program. The same year the Advisory Committee on Reactor Safeguards was established by the AEC to evaluate sites for new reactors, and the role of meteorology in the atomic energy program took on more importance.

In 1950 the AEC reactor program expanded greatly. A number of reactors were completed that year including the Los Alamos Water Boiler (SUPO), the 20-Mw gas-cooled graphite reactor at Brookhaven National Laboratory, the Low Intensity Training Reactor (LITR), the Bulk Shielding Reactor, and a homogeneous critical facility at Oak Ridge National Laboratory.

In 1951 KAPL built the Thermal Test Reactor No. 1 (TTR-1), and Argonne built the Experimental Breeder Reactor—I (EBR-I) at the National Reactor Testing Station (NRTS), which had been established in Idaho. The latter reactor produced the first electricity generated by atomic energy in this country. Los Alamos also built their "Little Eva" that same year.

In 1952 the Materials Testing Reactor (MTR) was completed at NRTS, and engineering testing in addition to physics testing for reactors was made possible. The same year two additional small homogeneous reactors were built, including one at a new site, the Atomics International Critical Experiment Laboratory at Santa Susana, Calif. The foundations of the atomic energy industry were now laid, and the industry was ready to expand rapidly. During this same period the naval reactors program was initiated at KAPL and at Bettis, the Atomic Power Division of Westinghouse, and there were naval and aircraft reactor programs, both operating at NRTS. Research reactors were being built at universities, and more production reactors were constructed at Savannah River. The number of locations was increasing, the types of reactors were increasing, and the power level of each unit was increasing. The hazard of effluent from the reactors during normal operation and in the event of an accident was becoming of greater importance to the public.

The experience meteorologists gained at the government facilities furnished the information that enabled them to make an intelligent appraisal of conditions at new locations where privately owned reactors were being built. Most of these reactors have contributed insignificant amounts of radioactivity to the environment because of the nature of their operation. The necessity for removing air and radiolytic gas from the primary system presents the problem in some reactors of avoiding the release of fission products by the same process. Attempts to control the fission-product release by delaying the effluent en route to the stack have only been partially successful, and considerable quantities of short-lived fission products may be released when delays of only a few minutes are used. The problem can be essentially eliminated by using holdup tanks that delay the release for a day or two.

During the past decade there has been a continuing increase in the number and type of reactors and, most important, a significant increase in power levels. Thermal power levels of 500 to 1000 Mw and higher are becoming relatively common for reactors designed to generate electricity. Furthermore there has also been a significant upsurge in the construction of large reactors for electrical power on a private-ownership basis at sites in no way connected with AEC operations.

In addition to the direct increase in reactor number and power level, there has been a diversification of reactor types, particularly in the power-reactor-prototype power range. These types include those with a variety of coolants including high-temperature gas, liquid metals, organics, and heavy water. Advanced types with liquid or slurry fuels and continuous fission-product removal systems have been designed. The gaseous effluents from these new reactors are not likely to be different in kind but will probably be different in quantity and mode of release.

It appears that in the future three major developments will influence the need for knowledge of atmospheric transport and dilution of reactor-produced effluents: (1) the increase in the number of large power reactors located close to large population centers and the concurrent proliferation of potential sources; (2) the entry of private industry into the fuel-processing field at several U. S. locations; and (3) the possibility that very large reactors, perhaps in excess of 10,000 Mw(t) power, will be advantageous for some applications, such as combined desalinization and power production. The waste-disposal requirements, including the safe and judicious use of atmospheric dispersal, can only increase.

1-2.2.2 The Development of Diffusion Theory. The early theoretical framework for atmospheric diffusion was based on macroscale analogies to the molecular processes of heat and momentum transfer. In such systems the diffusion transfer of a property is described by the product of the gradient of the property and a coefficient of diffusivity. Transport is assumed to occur along the gradient from regions of high values of the property to regions of lower values. The estimation of diffusion then resolves itself into a search for representative values of the coefficient of diffusivity and a search for the solutions of differential equations that represent the distribution of the property in space and its variation in time. The use of the gradient-transfer approach revealed that the diffusion coefficients varied with the space scale of the phenomena as well as with height above the surface and physical state of the atmosphere. In spite of these and other shortcomings, the description of diffusion by gradient-transfer processes has found considerable application in both research and studies oriented to practical problems.

In the early 1920's the British scientist G. I. Taylor introduced the concept of diffusion by continuous motion, which suggested that the final position of an elementary particle in a turbulent medium could be determined from a knowledge of the turbulent velocities acting upon it during its travels from source to destination. If the particles were those in a smoke cloud and were expected to faithfully follow the motions of the air in which they were embedded, the statistical time history of smoke concentration within the cloud could be forecast from a knowledge of the spectrum of the existing atmospheric turbulence. Although this essentially kinematical–statistical approach does not concern itself with the dynamical and thermodynamical causes of the turbulent motions, it has been responsible for furnishing many of the working diffusion techniques that will be discussed in the remainder of this volume. The well-known Sutton equations of diffusion are a direct result of Taylor's theorem. Another technique currently gaining favor in applied diffusion studies uses wind-speed and direction-fluctuation measurements and the Taylor hypothesis to yield a direct indication of atmospheric diffusion. Both the techniques resulting from gradient-transfer considerations and those based on the Taylor theorem will be discussed in considerable detail in Chap. 3.

Progress in diffusion meteorology has always been intimately associated with progress in the fundamental studies of atmospheric turbulence. Throughout the development of the classical diffusion theory, there has been the recognition that these semiempirical and statistical representations of turbulence would eventually yield to more direct physical approaches. Currently there is great interest in studies of the dynamic and thermodynamic mechanisms of the generation, distribution, and decay of atmospheric turbulence. Working directly with basic physical qualities, such as heat flux, kinetic energy, and surface configuration, turbulence specialists are today rapidly constructing an edifice of theory that may be expected to produce the next generation of practical diffusion techniques.

1-2.2.3 The Development of Diffusion Experiments. The first large-scale organized effort in the field of diffusion experiments began in England in 1921 when the Meteorological Department of the Chemical Defense Experimental Station at Porton was opened. Until this date there had been no accurate and comprehensive assessments of the rate of diffusion as measured by the dispersal of gases and smokes in the atmosphere. The pioneering work of this department in the use of smoke plumes and puffs led directly to the most important result of published studies carried out during the first 10 years of diffusion experiments: the determination of the shape of the crosswind distribution of material released from a point source. The Gaussian character of the average crosswind concentration distribution was rapidly established by the use of techniques that are quite primitive by today's standards.

Experimental determinations of diffusion processes have increased significantly in number and sophistication during the last 20 years. These experiments have been of three very general types. First are the studies of the very largest scale of diffusion and transport which use as source material the products of nuclear detonations or natural cataclysms injected into the troposphere or stratosphere. The second group contains the smaller man-made sources. These consist of instantaneous or continuous point, line, or area sources, usually observed to horizontal distances of about 10 km and typically represented by the release of effluent from an industrial process via a stack or fissure in a container. Finally, there are the primary micrometeorological experiments, the goal of which is the understanding of basic atmospheric processes. Although the practical interest in this volume is focused on the second of these groups, the contributions from micrometeorological studies are essential to the theory and suggest much of the practice for the applied investigations.

As will be evident from the detailed discussion in Chap. 4, one of the outstanding features of many of the experiments on man-made sources has been the large sampling grid networks, containing hundreds of samplers mounted on towers and at the surface. Quantitative values of the downstream concentration of emitted tracer are therefore available over the entire horizontal as well as over some of the vertical extent of the emitted plume or puff. Extremely sensitive techniques were developed for identifying and measuring these concentrations, and the concurrent observations of the meteorological variables then furnished the necessary data for evaluating the various theoretical or empirical formulations. Most of the diffusion measurements have been made within the first few kilometers from the source. There have, however, been experiments at greater distances, including some as far as 100 km from the source. Transport and diffusion at distances greater than 10 km is still a field for further experimentation, and detailed studies at distances greater than 100 km have yet to be carried out.

Many large diffusion experiments have been conducted in the United States and abroad. They can be divided into two major types: (1) experiments to determine the characteristics of a particular site and (2) experiments to gain basic meteorological knowledge. Some of these experiments have been designed to furnish additional values of Sutton's coefficients. Other experiments have yielded greater insight into the relations between wind fluctuation and pollutant dispersal. The rate at which airborne material is deposited on surface features has also been the subject of some series of experiments, and a number of important experiments have been conducted to clarify some of the basic physical processes of atmospheric turbulence. On a very large scale, high-level debris from the various nuclear-weapon tests has been used to delineate some of the characteristics of transport and diffusion in the stratosphere. In these cases the space scale has been global, and the time scale has been a few years.

Although much has been learned from the various experiments, there are still areas that have received no more than cursory attention. Experiments in long-range diffusion from surface sources are still largely in the future. Diffusion in the vicinity of topographic inhomogeneities, such as land–water boundaries or irregular terrain, needs experimental research. The increasing interest in placing power reactors in locations dictated by economic necessity indicates that the atmospheric characteristics over cities will receive increasing experimental attention.

1-2.2.4 The Development of Sensors for Turbulence and Diffusion Estimates. The equipment used in atmospheric diffusion studies has also become more advanced during the last 20 years or so. It may be said that there have been no basically new meteorological sensors developed in this period. Rather, progress has been most apparent in the fields of sensor engineering. As a result the instruments available as off-the-shelf items today have accuracies and sensitivities that were available only in specially engineered systems a few years ago. Moreover many of the high-precision instruments have been designed to allow continuous operation with a minimum of recalibration and repair.

Great strides have been made in the methods of accumulating and processing the data generated by the large and rapidly growing numbers of instrumental systems. Recent advances in electronics enter into every phase of the data-handling problem. It is not unusual to find instrumental systems that read out directly in terms of the processed data necessary for a specific application rather than in the raw data supplied from the sensor. Finally, the electronic computer has entered into virtually every phase of data processing in both research and operational diffusion studies.

1-2.2.5 Development of Working Techniques. The working techniques referred to in the title of this section, one of the major subjects of this volume, are those dealing with the estimation from readily available meteorological data of the diffusive potential of the atmosphere.

Of the many techniques that have been advanced to estimate diffusion in the lower atmosphere, only those of Sutton and, more recently, Pasquill have found more than limited acceptance. Both involve substitutions in a Gaussian interpolation formula that relates the downwind concentration to the vertical and horizontal concentration-distribution function in a plume or a puff as a function of travel time or distance. In both techniques these concentration-distribution functions are evaluated from actual tracer-release tests and are related to meteorological measurements taken at the time of the smoke release. Sutton's technique relates the downwind-concentration values to the vertical gradient of the wind speed, atmospheric "gustiness," and a measure of surface roughness. Pasquill relates concentration to wind-direction fluctuations and wind speed only. This approach has been adopted by an increasingly large audience. A discussion of the theory behind Pasquill's technique appears in Chap. 3; many corroborating measurements may be found in Chap. 4.

It is unfortunately true that theory has not advanced to the point at which precise diffusion estimation can be made directly from meteorological measurements. It is therefore frequently necessary to perform those diffusion experiments discussed in the last section in order to verify the theoretical predictions in those situations where the assumptions of the theory are reasonably well fulfilled and to obtain estimates of the values of the diffusion parameters in the remaining situations. The diffusion parameters measured in this way have been categorized by the meteorological conditions existing at the time of the experiment, and these empirically determined values can be used as a "working technique" that requires no atmospheric knowledge other than that available from comparatively simple instrumentation. When such parameters are used under conditions similar to those under which they were derived, fairly good estimates of downstream concentration can be obtained. A reasonably high degree of subjective skill and basic meteorological acumen is necessary if diffusion is to be estimated under anomolous conditions.

A fairly large number of diffusion-estimation techniques are based on a subjective appreciation of diffusion theory but utilize an empirical approach to the determination of the actual diffusion parameters. Although frequently successful, hopefully such techniques will become increasingly unnecessary as the physical theory of atmospheric diffusion develops.

1-2.2.6 Advances in General Meteorology. The most common question asked of meteorologists by any lay or professional group deals with the future state of the weather. Although this question is only one of a number that are asked by the atomic industry, it is both a basic and an important query. It is only fair to say that the accuracy of a typical forecast for a period of perhaps 24 hr in the future has not shown any marked improvement in the last 20 years although there has been a considerable increase in the ability to use forecast information more efficiently.

The overall situation is not, however, quite as bleak as it would seem on the basis of this information alone. For one thing the atomic energy industry depends heavily on climatological estimates of both surface and upper-air variables, and here there have been major advances in the years since World War II. There are over 14,000 surface weather observing stations currently operating in the United States and producing data that are used to compile climatologies. One thousand of these stations collect all the normally observed meteorological data, and the remaining stations collect a more limited sample. This great mass of information would be of little use if some central clearing house were not available for storing it. Fortunately the National Weather Records Center of the Environmental Science Services Administration (ESSA) not only stores but also processes this great mass of weather data in many ways that are useful to those working with atomic–meteorological problems. Therefore a great fund of climatological data is readily available for many locations in the United States and abroad.

The daily weather forecast may not have shown a great deal of improvement, but many other meteorological areas have. Fewer than 15 years ago, forecasts of severe weather, tornadoes, and violent thunderstorms were of the most general and rudimentary kind. Today this branch of prediction is highly developed with accuracy approaching a few hours in time and less than 150 km in space. Forecasts of upper-air flow patterns by numerical techniques utilizing the latest computers have also shown a very significant increase in accuracy. This information may be of considerable help in nuclear aerospace operations. Finally, data dissemination techniques have improved markedly. It is comparatively simple and frequently inexpensive to receive current data in both raw and analyzed form at any point in the country served by telephone lines.

1-2.2.7 How Much Meteorology Is Necessary? The answer to the question posed by the heading of this section is dependent on the particular site and on the nature of the facility to be operated on it. In the early days of the nuclear industry, accumulated experience in operating atomic facilities and in assessing the environment was less than it is today; so it was frequently deemed necessary to perform long and costly site evaluations for each new facility. This approach was justified by the normal caution felt when first embarking on the unknown. With increased experience in both atomic operations and diffusion meteorology has come a discernible tendency on the part of the meteorologist to identify, early in the planning stages, the salient meteorological features of the location and to concentrate on these in his analysis. This streamlining of the analytical procedure, reflecting greater confidence, is justified meteorologically by experimental experience and theoretical advances in the fields of atmospheric turbulence and diffusion.

An increase in knowledge has also taken place in the fields of atomic physics and engineering. In fact certain types of reactors and other atomic facilities have become so standardized that the meteorological evaluation can be considered of minimal importance.

On the other hand, the increase in understanding of the biological results of the uptake of radionuclides has indicated the need for increased attention to meteorological processes other than diffusion. Deposition and washout processes for instance are currently fields of increasingly strong interest. Long-term dosage calculations and dosages at great distances from the sources have also been the subject of increased attention. The quickening interest in the use of atomic power sources in the aerospace industry also results in meteorological programs of completely different scope than those for surface-based sources. Many of the problems in this field have not been identified; so the extent of meteorological involvement in these studies has yet to be fully delineated.

We have not then given a definite answer to the question of how much meteorology is necessary. We have only outlined the trends. An answer, if it exists at all, is contained in the discussions of meteorology and health physics computations in subsequent chapters and may only be realized by the application of this information to a particular problem.

1-3 OUTLINE OF THE REMAINING CHAPTERS

Chapter 2, entitled "Meteorological Fundamentals for Atmospheric Transport and Diffusion Studies," is intended as an introduction to the general field of meteorology with emphasis on those characteristics of particular interest to the study of diffusion, transport, and atmospheric pollution. This chapter should be useful to those who are coming upon the subject of meteorology for the first time. A bibliography of selected textbooks and other publications dealing in greater detail with the information in this chapter is included.

Chapter 3, "An Outline of Diffusion Theories for the Lower Layers of the Atmosphere," contains in some mathematical detail the basic physical formulations behind the practices of diffusion meteorology. This chapter is divided into three parts dealing, respectively, with the mean flow in the planetary-boundary layer, diffusion theories, and diffusion models. It should be useful both to meteorologists receiving their first exposure to this specialized field and to technicians in other disciplines. Some mathematical knowledge is assumed of the reader.

The fourth chapter, "Diffusion and Transport Experiments," describes some of the more important diffusion experiments accomplished primarily over the last 10 years. The motivation for these experiments was in many cases the necessity for practical answers to questions of local diffusivity at particular sites. As a result, the complete range of meteorological data ideally required for investigating a variety of approaches to diffusion estimation is not always available. An attempt is made in this chapter, however, to categorize diffusion data in terms of some objective measure of wind fluctuation whenever possible.

Chapter 5, "Processes Other Than Natural Turbulence Affecting Effluent Concentration," deals with those effects which reduce or otherwise change the distribution of airborne pollutants. Included in this chapter are discussions of plume rise, deposition, and washout as well as diffusion in the vicinity of structures.

Meteorological instruments and techniques are the subject of Chap. 6. Particular stress is given to the measurement of the various features of the wind in view of the current trend toward the use of wind-fluctuation techniques for the prediction of diffusion.

Chapter 7, "Radioactive-cloud Dose Calculations," introduces the reader to the aspects of nuclear technology necessary for radioactive-cloud dosage calculations. Included are discussions of terms and concepts in this field, sources of radioactive gases and aerosols, and external and internal dosage computation methods.

In Chap. 8, "Environmental Safety Analysis," the radiological information developed in Chap. 7 is used with the meteorological information presented in earlier chapters in discussions and illustrations of methods of environmental safety analyses.

An appendix listing diffusion equations, various constants, conversion factors, and other information useful to the reader and the references for the various chapters are included at the end of the volume.