Meteorological Aspects of Atomic Radiation

Nuclear weapons produce atomic clouds which rise to heights dependent principally on the energy released and also on the type of burst (air, surface, underground, and so forth). Weapons in the kiloton range leave most of their radioactive debris in the troposphere, while megaton weapons are powerful enough to inject significant quantities of radioactive material into the stratosphere. Once the debris is injected into the atmosphere, it is rapidly spread over the earth by atmospheric processes, and eventually deposited on the surface of the earth, in a complex manner. Among the many problems are included (i) the way in which debris is mixed and transported by the atmosphere, both vertically and horizontally; (ii) the mechanism of removal from the troposphere and deposition on the ground; and (iii) the rate of penetration from the stratosphere through the tropopause and into the troposphere for eventual removal.

Categories of fallout. The problem of the removal of radioactive debris from the atmosphere and its deposition in the biosphere may be divided into three phases: (i) early or "close-in" fallout—that which occurs within the first 10 to 20 hours following a nuclear explosion; (ii) intermediate fallout—that which occurs during the first weeks following the burst; and (iii) delayed fallout—the slow removal of small particles which may continue for months and even years, particularly after a high-yield thermonuclear explosion.

The principal mechanisms by which the removal occurs are gravitational settling, scavenging of radioactive particles by falling precipitation, and deposition by diffusion resulting from the ever-present turbulent eddies of the atmosphere. Although all principal mechanisms of removal play a role in each phase of the fallout, the primary emphasis shifts from gravitational influences in the early fallout to precipitation scavenging in the intermediate phase to an as yet poorly understood combination of diffusion and scavenging in the delayed fallout.

Measurements. The most direct measurement of radioactive deposition is that made from the soil since it represents the main natural surface onto which the particles fall. Difficulties arise from the fact that rain may remove some of the activity by runoff or soaking deeper into the ground. As a measure of the true radioactivity on the ground in determining plant or animal intake of strontium-90, for example, soil sampling is obviously the most acceptable solution. But, for an accounting of the amount which has been deposited, the soil analysis may be unsatisfactory if the sampling is performed, at say, yearly or multiyearly frequency. Soil sampling on a frequent basis may be impractical.

Measurement of radioactivity by use of hand monitoring equipment is standard practice in areas where the radioactive deposition is significantly above normal background. This kind of observation is almost entirely useless outside of the areas of close-in fallout.

For daily, weekly, or monthly fallout collections, the New York Operations Office of the U.S. Atomic Energy Commission recommends the use of a 1-square-foot sheet of gummed film mounted horizontally on a stand 3 feet above the ground. An extensive, worldwide network of daily gummed film collection at about 250 locations has been operated by the AEC for several years.

Finally, since there is evidence that much of the radioactivity deposited outside of the close-in area is brought down in precipitation, the collection of whole water samples is a method of obtaining the radioactivity of particles.

Measurement of air concentration near the earth's surface has been achieved by a variety of sampling procedures. Filtration equipment of many types has been successfully employed, but the efficiency of the filter material for various particle sizes, particularly in the submicron range, must be determined before quantitative interpretation of the data can be made.

The fact that the upper atmosphere contains significant atomic debris has been known for several years. Sampling of the upper air by aircraft has been achieved by using the motion of the aircraft to pass air through a filter paper. The British report the presence of fission products at the peak altitude of their aircraft, 48,000 feet. The Japanese have measured the radioactivity by carrying aloft Geiger counters on balloons. By subtracting the cosmic ray counts from the total, the remainder is ascribed to fission products. American scientists do not view this procedure with favor for the low levels of radioactivity found over most of the world.

Instrumentation for the measurement of radioactivity by its effects on the electric properties of the atmosphere also are of use only in those regions where the fission-product concentrations are comparatively high.

Close-in Fallout

Close-in fallout is the radioactive material from an atomic explosion which is deposited on the ground within a few hundred miles of ground zero, and which is down in some 10 to 20 hours.

There is a fundamental difference between the fallout from an atomic device detonated at the ground and the fallout from one detonated so high that the fireball does not touch the ground. In the case of the surface burst, large quantities of surface material are broken up, melted, and even vaporized, and some of this material comes in intimate contact with the radioactive fission products. Then, after the atomic cloud has stopped rising and the violent updrafts associated with the explosion have subsided, the larger and heavier particles start falling back to the ground. The result is an area around ground zero and extending downwind which is covered in a more or less systematic way with radioactive particles.

In the case of an air burst in which the white-hot fireball never reaches the surface, the radioactive fission products never come into close contact with the surface material; they remain as an exceedingly fine aerosol. At first sight, this might be thought to be an oversimplification, since there have been many cases in which the fireball never touched the ground, but the surface material was ob-

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This article is, with minor changes, the text of the summary report of the Committee on Meteorological Aspects of the Effects of Atomic Radiation. It is one of six reports prepared for the Study of the Biological Effects of Atomic Radiation by the National Academy of Sciences. The members of the committee are Harry Wexler, U.S. Weather Bureau, *chairman*; Charles E. Anderson, Geophysics Research Directorate; R. R. Braham, Jr., Institute of Atospheric Physics; Merril Eisenbud, U.S. Atomic Energy Commission; D. Lee Harris, U.S. Weather Bureau; B. G. Holzman, Air Research and Development Command; H. G. Houghton, Massachusetts Institute of Technology; W. W. Kellogg, Rand Corporation; Heinz Lettau, Air Force Cambridge Research Center; N. M. Lulejian, Air Research and Development Command; R. J. List and Lester Machta, U.S. Weather Bureau; and William K. Widger, Geophysics Research Directorate. The following changes have been made in the text: some subheads have been omitted and others have been shortened; all units of measurement have been spelled out. The full texts of all six summary reports are available from the National Academy of Sciences. The texts of the technical reports will be published in monograph form by the NAS.

served to have been sucked up into the rising atomic cloud. Actually, however, in such cases a survey of the area has shown that there has been a negligible amount of radioactive fallout on the ground. Though tons of sand and dust may have been raised by the explosion, they apparently did not become contaminated by fission products.

Experience has shown that an atomic device exploded on the surface distributes about 70 to 80 percent of its fission products on the ground within a few hundred miles of the burst point. A somewhat larger percentage will take part in the close-in fallout from an underground burst, and a smaller percentage will be scavenged from a near-surface burst or tower shot.

In order to make a quantitative study of the manner in which close-in fallout occurs, one must have a knowledge of the following parameters: wind structure, yield and height burst, and kind of surface.

As each particle falls, it is carried horizontally by the wind at each level. The time during which it is falling through a given layer is inversely proportional to its rate of fall. Thus its horizontal travel during its entire fall from an initial height can be expressed as a summation of its horizontal travel in each layer. The rates of fall of atomic particles vary with particle size, shape, and density, as well as the altitude.

Although no experimental information is available on the effects of precipitation during the initial stage of the atomic cloud, it is evident that significant deposition can occur from this cause. However, the effect would be most marked from smaller yield bombs, since the bulk of the debris from larger bombs rises well beyond the rain-bearing strata.

Height and size of the atomic cloud at the time of stabilization. It is evident that the physical size of the atomic cloud will have an effect on the distribution of the close-in fallout. The height to which the debris is carried will determine how far downwind a given particle size will drift, and the horizontal extent will serve to spread the fallout over a larger area.

In the first few seconds following an atomic detonation, the fireball grows rapidly until the pressure inside the fireball is roughly that of the ambient air. At this point its temperature is still many thousands of degrees higher than that of the atmosphere around it, so it is much less dense, and the buoyancy of the atmosphere forces it to rise. However, it does not necessarily rise like a hot "bubble" or a balloon, but in most cases, it develops a strong toroidal internal circulation and rises in the form of a smoke ring.

As the smoke ring rises, its internal circulation draws air in at the bottom and incorporates this new air into the cloud. The result is a very large growth in the size of the cloud as it rises, due mostly to the entrainment of the air from each level through which it passes.

It is clear that the cloud will gradually cool during its rise, due to radiation, the entrainment of the outside air, and adiabatic expansion. When the mean temperature inside the cloud is the same as that of the ambient air at the same level, there will be no further buoyancy and the cloud as a whole will cease rising. However, at this point the kinetic energy of the toroidal circulation may still be considerable. For devices with yields of a few kilotons, the smoke ring circulation breaks up at about the same time that it reaches its point of stabilization, but for devices in the megaton range this toroidal circulation continues to pump air in at the bottom for 10 to 20 minutes.

The net result of this pumping action after stabilization is a significant increase in the horizontal size of the atomic cloud, since the air which is drawn in at the bottom is forced out radially. Observations of this effect in the case of megaton devices are hindered by the fact that the structure of the cloud becomes confused.

The atmospheric stability will vary with the season and latitude, and this accounts, in part, for the difference between the altitude of a cloud detonated in a tropical atmosphere and one of the same yield [detonated] in a middle-latitude winter atmosphere. The most noticeable difference between these two regimes is the height of the tropopause.

Distribution of radiactivity within the cloud. Since it is difficult to obtain enough samples of the radioactive debris while it is still within the cloud to determine its initial distribution, the most reliable estimates of this distribution have been based on the observed fallout and a reconstruction of what this initial distribution must have been.

It is clear from the observations of the rising cloud that almost all of the lighter debris is carried aloft in the smoke ring cloud. Apparently a certain fraction of particles are large enough to be thrown out of this ring, and these are left behind in the stem. However, in the stem there are violent updrafts for the first few minutes, so all but the very large particles will continue to be carried aloft.

For a surface or near-surface burst, the type of terrain must have a significant influence on the particle size and activity distribution within the cloud.

Prediction of close-in fallout. At the outset it would be well to state what use can be made of a prediction of the fallout area from an atomic burst. At the risk of oversimplifying the case, here are some of the pertinent factors.

1) Wind observations, now almost invariably made with sounding balloons, give winds which are not entirely representative of the winds which will affect the falling atomic debris. This is because winds change with time and place and because wind observations, as all meteorologists recognize, are subject to a certain amount of error. Forecast winds, by the same token, are usually even further in error. A number of studies have been made of this subject. For example, a recent study by the Air Weather Service indicates that mean vector errors in 24-hour forecasts range from about 60 percent of the observed wind at middle altitudes to over 70 percent of the observed wind at 100 millibars (about 53,000 feet). These mean vector errors correspond to wind errors of 18 to 29 knots. It is perhaps significant that the forecast errors at the higher levels (40,000 to 55,000 feet) are about the same as the root-mean-square deviation of the wind from the mean wind, and at lower levels (about 20,000 feet) the 24-hour forecast error is about half that of the normal climatological deviation. If one had to rely on forecasts 24-hours old, he would be just about as well off as if he used climatological data or persistence in computing the fallout.

2) The mushroom cloud from a multimegaton device may rise entirely above the normal coverage of our radiosonde and RAWIN network, since it is generally considered impractical to plot and analyze current weather data at levels above 100 millibars. . . . Thus, unless special efforts are made, there will simply be no wind data at all for the winds which will affect the debris during the first part of their fall. The effects of vertical motions in the atmosphere, possibly including currents arising from bomb-produced fires, may also be enough to alter the fallout pattern.

3) It should be fairly evident from the discussion in the preceding section that there are still a number of questions concerning close-in fallout about which we are still somewhat uncertain. Any fallout computation, even given perfect information on the wind field, will have a degree of uncertainty as a result of the assumptions on which it is based.

With these factors in mind, it appears unlikely that a weather forecaster, even given the computing aids which he would need to compute a fallout pattern, could on short notice and in a time of emergency give a detailed and reliable forecast of the close-in fallout. He could with a fair degree of assurance delineate the general sectors in which the fallout would be most likely to occur, but he could not tell where a given dose-rate contour would lie. If one is dealing with a military situation in which an enemy is dropping atomic bombs, then the forecaster's problem is further complicated

by the fact that he would presumably not have accurate knowledge of the height of burst and fission yield of the weapon.

It must be emphasized, however, that the above statements do not necessarily apply to the prediction of the fallout from a test device, where many of the uncertainties mentioned can be removed. It is possible, by the use of a special upper air-sounding network, to obtain wind information over a limited area which is considerably more reliable and current than that obtained from the routine upper air net, and which extends to a greater altitude. Moreover, there is usually no doubt about the yield and burst height of the device during a test. Thus, it is much more likely that an accurate forecast of the fallout pattern can be made under the favorable conditions which exist during a test. Even here, there remains a degree of uncertainty, as witnessed by the fallout which occurred on some inhabited atolls during the 1954 tests in the Pacific—though this might have been forecast if there had been the refined fallout computing aids which exist today.

Finally, if one does not have to make use of forecast winds at all, but can introduce all the detail of a careful synoptic analysis "after-the-fact," including the time variation of the wind at each level, and compute the fallout on a high-speed computer, it is possible to reproduce the fallout patterns which have occurred from the United States surface bursts with considerable accuracy. The radiological monitoring data show a certain amount of spread in the observations because of the detailed effects of terrain and atmospheric turbulence. When the reconstructed pattern or computed fallout patterns are compared with observed values, the minor differences are usually accounted for by small-scale features in the wind structure. Where the winds apparently behave as expected, predictions verify within a factor of 2 over most of the area. Where they do not, the peak dose rate is often correctly predicted at various distances from ground zero although displaced relative to the observed peaks.

Intermediate Fallout

Although gravitational settling continues to play an important role for many days and the downward diffusion of debris from the atomic cloud as it is moved about by the upper winds also becomes important, the primary removal of debris after the first day or two following a burst occurs in areas of precipitation. As the cloud of debris continues to be diluted by the atmosphere, concentrations decrease and it becomes necessary to collect the fallout and wait until the natural radioactivity has decayed before measurements can be made.

From Nevada test series, it has been found that less than 5 percent of the total beta radioactivity produced is collected by the gummed film network in the United States. Stewart, Crooks, and Fisher have estimated from observations in the British Isles that about half the radioactive dust in the troposphere from Nevada tests is deposited in approximately 22 days and that 80 percent of the deposition by rain occurs during the first transit of the cloud over England.

The importance of precipitation in bringing debris to the ground after the first day or so following an atomic explosion is strikingly shown in the average daily activity found on gummed films exposed in the United States during the Teapot Nevada test series in the spring of 1955. In light rain, on the average, over twice as much activity is collected by the gummed film as compared to dry days and this increase becomes more apparent as the rain gets heavier. Various studies have shown that anywhere from 4 to more than 10 times as much debris is deposited during periods of rain as compared with dry days.

On a few occasions, rain has coincided with the passage of a fresh cloud of debris from a Nevada test, resulting in local increases of background radiation to about 1 milliroentgen per hour beyond a few hundred miles from the test site.

In the absence of precipitation, the effects of turbulence as well as gravitational settling are important.

Removal of debris by impaction on natural surfaces, buildings, and so forth, resulting from the movement of air around these surfaces must be appreciable. Various studies have shown that radioactive particles are found on leaves, branches, and so forth. An experiment conducted at the Naval Research Laboratory with an 80-mesh stainless-steel wire screen and with ordinary cheesecloth faced into the wind showed that in the absence of rain as much as 10 to 100 times the activity collected on the horizontal gummed film can be collected on the screen or cloth. In a 2-month period during the Teapot series, a total of 50 percent more activity was collected on the cheesecloth than on horizontal gummed film of similar size. Studies of the vertical distribution of chloride particles also indicate a depletion near the ground over land areas, presumably a result of impaction on natural surfaces.

Delayed Fallout

In contrast to the results from the Nevada tests, measurements of radioactive debris concentrations in the troposphere showed a continued increase over England during the 10-month period following the thermonuclear tests in the Pacific in 1954. Similar increases in ground-level concentrations have also been observed by the Naval Research Laboratory in the United States and elsewhere.

This delayed fallout is a consequence of the extreme heights reached by debris from thermonuclear explosions—more than 80,000 feet—which results in the storage of large amounts of small particle-size debris in the stratosphere. The existence of such a distribution has been confirmed by aircraft measurements over the British Isles in August and September 1954 and again in early 1955 which show a very large increase in air concentration above about 35,000 feet. This debris eventually moves through the tropopause into the troposphere, from where it is removed by precipitation scavenging and by deposition.

Transport in the stratosphere. The stratospheric levels in question are mainly in a region where relatively sparse synoptic data on the structure or air currents are available. However, they are mainly in a region of hydrostatically stable air, and soundings indicate, in general, a relative high degree of steadiness of stratospheric currents.

The winds in the stratosphere seem to have a predominant zonal component. The material injected at a certain locality will spread to other longitudes faster than to other latitudes. Material injected at a certain time in a vertical column may move more rapidly, or even in a different direction, at one level with respect to another. This shearing motion of the large-scale air currents represents a powerful factor for the spreading of an originally localized cloud to all longitudes within a few weeks.

All stratospheric circulation cells undergo more or less marked changes during the course of the seasons. Superimposed on the seasonal trend are day-to-day wind fluctuations caused by migrating or oscillating pressure systems. The present-day knowledge of independent stratospheric pressure systems is very limited. But it can be assumed that the stratosphere reacts, at least partly, to the migrating cyclones and anticyclones of the troposphere. Over periods of several weeks the net effect of the stratospheric wind variability will be similar to a process of large-scale eddy diffusion acting mainly in the horizontal directions.

Diffusion in the stratosphere. One may approach the question of vertical diffusion in the stratosphere in three ways: (i) by using first principles; (ii) by using natural gaseous tracers; and (iii) by using man-made probes.

1) First principles. If asked for criteria to predict vertical mixing at the ground from meterologically observed

parameters, one would point, in all likelihood, to three items: vertical temperature gradients, wind speed, and wind shear. The greater the temperature stability, the less the vertical mixing. It is primarily on this ground that the stratosphere has been viewed as a region of quiescence in comparison with a turbulent troposphere below it.

With regard to wind speed, it seems fairly clear that an absence of horizontal kinetic energy will be associated with little or no vertical motions, but it is not evident that high wind speed necessarily will produce vertical turbulence. In any event, the lower stratosphere has a variety of speeds.

In the Richardson number, which under special conditions predicts the onset of turbulence, it is the shear rather than the wind speed which is significant. There is as large an assortment of wind shears in the stratosphere as in the troposphere, barring the layer adjacent to the jet streams in the troposphere.

One must conclude that on one count —probably the most important—stratospheric vertical mixing should be much smaller than tropospheric and that on the other two scores, it need not be.

2) Gaseous tracers. Ozone is the first such atmospheric property which comes to mind. It has been established that the ozone concentrations below the ozone maximum (about 25 kilometers) are often in excess of the photochemical equilibrium amounts. It appears that the day-to-day variation and much of the seasonal variation of total ozone reflects changes in the nonequilibrium ozone in the "protected" region below the maximum. It is generally accepted that exchange processes transport ozone downward from the region of ozone maximum. Three types of exchange process have been considered. The first involves large-scale meridional circulations in the stratosphere. There are some reasons for accepting such a meridional circulation involving both hemispheres, but the evidence is not very impressive. A second exchange process is turbulent mixing. This is difficult to evaluate because of the lack of information on the magnitude of the mixing coefficient. It does seem, however, that the mixing coefficient required to provide the needed flux of ozone is not unreasonable. The third exchange process may be called *Gross austausch* since it involves the vertical motions associated with traveling cyclones and anticyclones. There is good evidence for this effect in the correlations between total ozone and the pressure field. It also provides a qualitative explanation for the annual variation of total ozone.

With the possible exception of the large-scale meridional circulation, the exchange processes described here will operate to bring ozone into the troposphere where it is destroyed at lower levels by particulate matter. The study and measurement of the ozone exchange should be applicable to the exchange of nuclear weapon debris.

Water vapor probably has no marked sink (due to cloud formations or precipitation) near the tropopause. Thus, changes in the gradient of water vapor mixing ratio should be a clue to the comparative upper tropospheric-lower stratospheric mixing intensities. The use of moisture as a tracer suggests but does not clearly indicate little vertical mixing in the lower stratosphere.

3) Man-made probes. Both parachutes and balloons have been used regularly to measure small-scale vertical motions in the stratosphere, and the results generally reveal the stratosphere to have greater vertical motions than the troposphere. Also, aircraft report turbulence in the stratosphere. This evidence for comparatively short-period vertical motions is clouded by the question of the role of the platform. The growth of the rising balloon, for example, alters the flow around it which may be the cause for the apparent vertical motions deduced from its ascent rate. Further, as with any measure of vertical motions, the probe does not distinguish between nondispersive vertical motions like gravity waves and true diffusing elements.

Mixing through the tropopause. In a practical definition the tropopause is the level of minimum temperature of a high-altitude sounding, or the layer of maximum change of vertical lapse rate of temperature when no minimum temperature is encountered. Mean height-latitude cross sections of the atmosphere show that the tropopause is quasi-horizontal only in equatorial and polar regions, at approximately 18 and 9 kilometers, respectively. The break occurs normally between 30 and 60 degrees latitude, where the mean tropopause has either a significant slope or lacks uniqueness of definition so that multiple tropopauses are assumed by some authors even for mean conditions. Individual soundings may show considerable day-to-day fluctuations of the tropopause level in connection with the passage of cyclones and anticyclones. Therefore, the tropopause is far from being a well-defined geometric surface and can hardly be considered an internal boundary which separates two distinct kinds of air masses. Air may move vertically through the mean tropopause level, or horizontally through the tropopause breaks. However, net radiation and convection processes are assumed to exist which result in a marked tendency toward reestablishment of the tropopause at preferred levels just above the atmospheric layer in which the content of liquid and vaporous water is significant and condensation-precipitation cycles are dominant.

Four main types of exchange of air, or air properties through the tropopause may be distinguished: (i) small-scale vertical exchange, or vertical eddy diffusion; (ii) medium-scale penetration of tropospheric air into the stratosphere above extremely intense convective cells (heavy squall lines, frequently connected with tornadoes); (iii) large-scale entrainment of stratospheric air into tropospheric systems, such as cyclones, jet streams, hurricanes; and (iv) mean transport by vertical branches of large-scale to world-wide circulation cells.

Tropospheric removal. The very small particles which are originally in the stratosphere and reach the troposphere weeks, months and even years after the detonation of a thermonuclear weapon must eventually be deposited in the biosphere. However, the mechanisms by which these small particles are finally removed from the troposphere are not clear, and the data concerning this problem are inconclusive.

Investigations of the rate of removal of natural radioactivity from the lower troposphere, both in the United States and in Germany, indicate that about half the activity is removed in a period of about 1 or 2 weeks. However, the particles involved are extremely small (probably less than 0.01 micron) and are concentrated near the ground, so that the results may not be applicable to the fallout problem. On the other hand, Langmuir has shown that the collection efficiency of precipitation for very small droplets (less than 1 micron) is small, but again the results may not be applicable to the fallout problem, where electrostatic and surface tension phenomena are different. Agglomeration between natural cloud elements and radioactive particles is operative for small particles.

Conflicting evidence on the rapidity of tropospheric removal is also found in studies of the actual fallout. Stewart, Crooks and Fisher, in Britain, estimate from indirect reasoning that deposition in rain exceeds dry deposition by a factor of 20 for thermonuclear explosions. A study of gummed film results in the United States does not bear this out—average monthly deposition at 40 monitoring stations during September and October 1954 shows no correlation with either total rainfall during the month or the number of days with rain at the station. Again, using the British data, it is seen that the specific activity of the lower atmosphere showed a more than fourfold increase during the interval from 10 weeks after the Pacific tests to 50 weeks after if the data are corrected for decay. Similar increases were

found by the Naval Research Laboratory. It is hard to reconcile this increase in tropospheric concentration with the rapid cleansing of the troposphere.

Analysis of Stratospheric Storage from Radiostrontium Fallout Data

The fission product of greatest interest in terms of long-term hazard from nuclear detonations appears to be strontium-90, and estimates of the rate of deposition of this isotope in the biosphere are needed. Unfortunately, our knowledge of the physical mechanisms involved is too meager to deal with this problem on a theoretical basis. Although it has been established that a considerable amount of debris is injected into the stratosphere and that this debris slowly mixes downward into the troposphere and is eventually deposited on the ground, the average storage times in the stratosphere, and even in the troposphere, are uncertain. Among the many unknowns in attempting a theoretical analysis are the initial distribution in the stratosphere and the physical mechanism of stratospheric removal. Even if the latter were known, we are at present unable to make quantitative estimates of the rates or intensities of these physical processes. However, due to the biological uncertainties in estimating the hazard from strontium-90, a precise answer is not needed, and even a gross estimate would be useful.

W. F. Libby of the U.S. Atomic Energy Commission has published an estimate of the stratospheric storage time based on the estimated stratospheric content and on the observed deposition, with little or no reference necessary to the physical mechanisms involved. Essentially, the annual deposition is divided by the amount in the stratosphere, yielding the fractional removal during the year. If the fractional removal rate is assumed constant (that is, the stratospheric content is assumed to decrease exponentially) the mean residence time of the debris is given by the ratio of the stratospheric content to the deposition.

The basic data used by Libby are the stratospheric content immediately after the completion of the Castle tests (spring 1954) in the Pacific and the deposition of strontium-90 during the following year or so as measured in three ways: a worldwide gummed film fallout network, the strontium-90 content of Chicago rainfall, and air-filter measurements at Washington, D.C. From these results, Libby concludes that the mean storage time for debris in the stratosphere is approximately 10 ± 5 years.

Stratospheric storage not only serves to delay the fallout of debris but also to disperse it over the globe, minimizing the chance of locally high concentrations of debris. At present, the amount of strontium-90 in the stratosphere from nuclear weapon tests is far too small to approach maximum permissible concentration even if it were to be all deposited now. However, if the testing programs of the several countries producing thermonuclear weapons were to be intensified, stratospheric storage time may become a critical item in terms of hazard to mankind. For this reason, a continuing program to investigate this phenomenon is needed, including actual measurements of the radioactivity in the stratosphere and improved and more representative methods of observing fallout.

Atmospheric Radioactivity from Civilian Use of Nuclear Energy

The hazards of atmospheric contamination from the military uses of atomic energy have tended to overshadow other possible sources of contamination, principally because, to date, relatively insignificant contamination has occurred from nonmilitary sources. Certainly the near future will see a tremendous increase in the utilization of nuclear energy for peaceful purposes, including the production of electric power; medical, industrial, and agricultural applications; and nuclear propulsion of air, sea, and land vehicles.

As far as can be seen today, the largest potential use of nuclear energy will be in the production of electric power, and this discussion is based on this aspect of the problem; however, other applications could conceivably double the values used in the estimates given here. A consensus of estimates of global power requirements and of the proportion of this energy which will be supplied by nuclear sources indicates that by 1975 there will be a nuclear heat energy production of 10^8 to 10^9 kilowatts and by the year 2000 this will increase to 10^9 to 10^{10} kilowatts.

These rates of production will produce enormous amounts of fission products. However, most of these will be in solid or liquid form at present-day processing temperatures, and it can be expected that such material will not be intentionally released into the atmosphere. Of the remaining volatile fission products, storage and "cooling" of the fuel before processing can reduce the activity materially. The two volatile isotopes of most interest are 10-year krypton-85 and 8-day iodine-131. Only the 10-year krypton is sufficiently long-lived to be relatively insensitive to the cooling time of the fuel before processing. There are two aspects to the problem of radioactive hazard from these sources, large-scale contamination on a global or hemispheric basis and local or regional contamination in the areas of processing plants.

Large-scale contamination. The long half-life of krypton-85 results in the accumulation of this isotope in the atmosphere. If by the year 2000 nuclear thermal power has risen to 10^{10} kilowatts, the world inventory of radiokrypton would be of the order of 10^{10} curies. Mixed uniformly through the mass of the troposphere (4×10^{21} grams of air), the resulting sea-level concentrations would be less than 10^{-8} curies, per cubic meter. Since most of the activity is likely to be released in the middle latitudes of the northern hemisphere, large-scale concentrations of 3 to 5 times the global average could be experienced in these latitudes.

No value for the maximum permissible concentration of krypton-85 is presently available. If, from the chemical and radiological similarity, we assume that it is analogous to radioxenon, then the estimated world-wide concentration in the year 2000 is about two orders of magnitude less than the maximum permissible concentration. However, such comparisons are extremely questionable and it is important that maximum permissible concentration levels be established for krypton-85.

The problem of iodine-131 in the atmosphere is largely dependent on the fuel recharging interval and the cooling time. For each combination of fuel cycle and cooling time, it is possible to calculate the total amount of iodine-131 in the atmosphere. This is an equilibrium value assuming no removal at the source or after release. Total amounts of iodine-131 in the atmosphere based on the estimated nuclear energy production in the year 2000 are given in the Table [1].

The present maximum permissible concentration of iodine-131 is 3×10^{-9} curies per cubic meter. If the iodine-131 is mixed with the whole mass of the troposphere, then 10^{10} curies would produce the maximum permissible concentration. However, the assumption of world-wide tropospheric mixing is unwarranted for an isotope with a half-life of 8 days. Assuming the term large-scale contamina-

Table 1. Total iodine-131 (curies) in the atmosphere per 10^{10} kilowatts of nuclear energy.

Fuel recharging frequency	Decay time before release		
	None	10 days	100 days
Once a year	6×10^9	3×10^9	10^9
Ten times a year	6×10^{10}	3×10^{10}	10^7
Continuous	2×10^{11}	10^{11}	4×10^7

tion in the case of iodine-131 can at most involve a 20°- or 30°-band of latitude in the northern hemisphere, and that vertical mixing may be incomplete, then even for large-scale considerations, an atmospheric burden of 10^8 or 10^9 curies of iodine-131 may approach the maximum permissible concentration, and appropriate cooling or decontamination measures must be used.

Local contamination. It is evident that consideration of the average contamination over major portions of the globe cannot approach the hazard to be found in local areas downwind from sources of contamination. Locally, higher concentrations that would exist 10 to 100 miles from fuel processing plants (assuming something of the order of 1 percent of the world's fuel to be processed at any single site) could add an additional factor of 10 to 100 in the case of krypton-85 and several thousand in the case of iodine-131. Also, transitory excess concentrations due to unfavorable meteorological conditions could raise local concentration by an additional one to two orders of magnitude.

These effects are cumulative so that concentrations of iodine-131 about 10^4 times the global average could occur regularly near fuel processing plants in the northern temperate latitudes, rising occasionally to 10^5 or 10^6 times the global average during unfavorable meteorological conditions. Deposition by precipitation could increase the possibilities of harmful effects. Further detailed analysis would be required in order to indicate under what conditions the concentrations of krypton, iodine, or other isotopes would exceed permissible limits. In any case, it seems that a combination of reasonably conservative fuel cooling periods, some progress in off-gas cleaning, and a judicious choice of fuel processing locations is indicated to minimize the adverse effects of unfavorable meteorological conditions. At the larger plants, meteorological scheduling of gas releases may be required. These principles are applied today and will become increasingly important.

Accidental releases. There is the possibility, even if remote, that a large high-power reactor or fuel processing facility could be damaged or destroyed by accident and release part or all of the contained fission products to the atmosphere. The results of such an event could well be catastrophic and extend over great distances. Estimates of areas of damage range upwards of thousands of square miles for very large reactors. By the year 2000 the release of only about 1 percent of the world-wide strontium-90 inventory that could then exist, even if mixed uniformly throughout the global troposphere, could produce concentrations on the order of 5×10^{-10} curies per cubic meter or about twice the currently recommended maximum permissible concentration. This same 1 percent, if deposited on the surface, could seriously contaminate the entire area of the earth. It is more likely, in the event of such a catastrophe, that the activity would remain concentrated in a much smaller area near the source. Still, the operation of any significant fraction of the earth's nuclear reactors without proper safeguards would be of concern to all.

Conclusions. Solution to the radioactive air pollution problem is the same as in other air pollution problems—prevention of the escape of pollutants to the atmosphere. Thus, primary consideration must be given to engineering features limiting the escape of hazardous gases either during normal operations or accidents. As an additional safety factor, meteorological research to locate plants in areas where unexpected releases will do the least damage is desirable. Finally, it should be pointed out that the release of a hazardous substance by any country may affect other countries, particularly in the same latitude belt. International control to establish and maintain high standards of safe plant operation is essential.

Use of Radioactivity in Atmospheric Studies

Natural radioactivity. There exist two important sources of naturally occurring radioactivity in the atmosphere: (i) cosmic ray interactions in the stratosphere and (ii) the rock and soil of the earth's outer crust. The study of the cosmic-ray-induced products entails considerable difficulties because of the low level of activity. On the other hand, the radioactive substances which originate in the earth can be detected and measured with relative ease.

Radon and thoron are released as gases in the radioactive decay of radium and thorium, which are found in all rock and soil. The concentration of these gases and their distribution in the atmosphere are determined by their half-lives and by meteorological conditions. Although it is considered generally that the relative amounts of the various natural activities are dependent on meteorology, very few correlations with specific meteorological parameters have been made, in spite of the fact that measurements have been carried out over a period of many years. At the present time, insufficient data are available to make reliable estimates of the global distribution of radioactivity in the air over land, although it is known that at some distance from large land masses the radioactivity concentration is exceedingly low. Measurements indicate that the amount of radon decreases rapidly with altitude to about one half the surface value at 1 kilometer.

Radon and thoron and their daughter products would seem to provide an easily detectable tracer for the study of the vertical *Austausch.* Ground-level measurements indicate that exchange phenomena within even a few feet of the surface have marked effects on the concentration of radioactivity. Such measurements might well be carried on in conjunction with micrometeorological observations. From consideration of the lifetimes of the radioactive isotopes which are involved, it is obvious that even for relatively low wind velocities, horizontal transport of these radioactivities over distances of several hundred miles is entirely possible. The study of simultaneous variations in concentration over these distances should be valuable if the locations were carefully selected to avoid the effects of terrain. Land to sea measurements should be especially interesting.

Instances of increases in radon concentration coincident with air pollution have been reported. Since atmospheric radioactivity and pollution are strongly affected by the stability of the lower atmosphere, this effect is not surprising. For the same reason, it is quite possible that a relationship could be established with the tropospheric scattering of electromagnetic radiation.

Experiments have shown that the radon and thoron decay products are attached to submicron particulates. The details of the attachment process are not well understood—for example, the relationship between various ionic species or the number and kind of nuclei. These radioactivities exist in the form of a readily detectable submicron aerosol which generally follows the surface wind pattern. These small particles, and incidentally other pollution, appear to be removed from the lower atmosphere in a matter of days, principally through precipitation. Further study of this removal process, carried out at different locations and for a variety of climatological conditions, would perhaps shed some light on the scavenging efficiency of precipitation.

The natural radioactivity of precipitation is considerable and is easily measurable. The mechanism for the entrainment of the radioactive particles in rain droplets is not certain. From theoretical considerations, the probability for attachment of these very small particles in rain is quite low. It has been suggested that the radioactive ions could themselves act as condensation nuclei. On the other hand, there is the possibility that clouds of charged radioactive particles could act as a sort of "trigger" for electric phenomena leading to cloud electrification and precipitation. Experimentally, the difficulties of working with large volumes

of rainwater are partially offset by the large activities encountered. The actual air volume swept out by precipitation is very great and it would seem that there are possibilities for tracing air masses by using natural radioactivity.

Traditionally, atmospheric radioactivity has been associated with atmospheric electricity and might well supplement studies in this field. The radon and thoron decay products are charged and can be collected by electric means. They are estimated to cause about one-half of the ionization in the lower atmosphere. Certain of the theories of atmospheric and cloud electrification are quite sensitive to changes in the ion concentration. Since large changes in the radioactivity concentration are the rule, further studies carried out in conjunction with atmospheric electric measurements should be valuable.

The most extensively studied of the cosmic-ray-induced isotopes found in the atmosphere have been carbon-14, tritium, and beryllium-7. Probably both short-term increases in fossil carbon dioxide from industrial sources and the long-term global distribution could be detected using sensitive techniques. Tritium is present in the air principally in the form of tritiated water and will probably find its most useful applications to hydrology, although more extensive sampling of precipitation is no doubt desirable. Because of its relatively short half-life, beryllium-7 may be of very great importance in the study of the rate of mixing between the stratosphere and troposphere. Unfortunately, there is a great lack of experimental information suitable for correlation with meteorological phenomena.

Debris from weapons tests. The debris injected into the atmosphere from the testing of nuclear weapons can provide a useful tool for investigating atmospheric phenomena. However, two basic limitations on the usefulness of the approach must be recognized. (i) The source strength and distribution in space is largely unknown. Such important information as the distribution of particles with altitude, the exact configuration of the stabilized cloud, the relation of particle size to activity, the fractionation of elements within the cloud, and so forth, is not available. (ii) Sampling techniques are imperfect. Air-concentration measurements are difficult because of the low concentrations and small particle sizes involved. Ground collections result from either deposition of the particles themselves or by precipitation scavenging.

Using the gummed-paper collection system described in [the first section of this report], it has been possible to obtain certain valuable meteorological information on such items as a measure of the cross-equatorial transport and some feature of the general circulation from U.S. Pacific tests, scavenging by the upper portions of rain clouds of the particulate fission products, an estimate of rapidity of the removal of particulates from the troposphere, and an estimate of the rate of transport from the stratosphere to troposphere.

Using aircraft sampling procedure, it has been possible to obtain estimates of the rate of lateral spread of an atmospheric contaminant and verifications of meteorological trajectories. By following the tritium released by the Castle series of weapons tests, it has been possible to estimate the removal time for atmospheric water molecules.

It is likely that the potential of even the existing unclassified information on radioactivity released by weapons tests has not been exhausted. This potential would be enhanced by disclosure of additional information on weapons, debris measurements, and source strengths. For example, the weapons tests offer an opportunity to determine storage and transit time parameters for surface water sheds of almost any size. By comparing the amount and level of radioactivity in rainfall and runoffs as a function of time following a weapons test, it would be possible to measure those parameters which are vital to studies of ground water, river runoff, and flood forecasting.

Artificially introduced radioactive tracers. Artificially introduced radioactive tracers can serve meteorology in at least three fields: (i) through the delineation of the air flow and rates of diffusion; (ii) in hydrometeorology, including studies of condensation, precipitation, evaporation, and hydrology; and (iii) in atmospheric electricity.

As a tracer of air motions, radioactive substances are in competition with fluorescent dye particles, sulfur dioxide, and other nonradioactive substances. Their advantages lie in the possibility of being able to treat large-scale atmospheric phenomena which otherwise require too large amounts of source material, in being able to utilize tracers which partake in the particular process under investigation and, in certain cases, in our ability to detect the presence of the tracer instantaneously in the field. In any specific experiment, it will be necessary to weigh economic, safety, and scientific factors in the use of radioactive tracers over nonradioactive tracers.

Regions in which it would be highly desirable to further knowledge concerning air trajectories are in the neighborhood of jet streams, in cols, in hurricanes to measure both the three-dimensional airflow and to define the air comprising the eye, and in the antarctic. In the field of diffusion, the use of radioactive tracer material can further knowledge of diffusion near the ground for air pollution studies, and so forth, and of diffusion in the stratosphere and tropospheric and stratospheric mixing.

The radioactive tracer material which appears to be most promising for the above meteorological studies is tritium. Tritiated water would be washed out, thus making for additional complications. Tritium in the form of ordinary hydrogen is acceptable although costs of analysis of the sample might be high. For the large-scale experiment to establish the tropospheric-stratospheric exchange, tritiated methane has been suggested. Tritium has the advantageous properties of emitting a weak beta particle, of being available without difficulty, and of having a reasonably long half-life.

Water molecules are readily marked by tritium so that in any experiment in which the travel of water vapor is desired it becomes feasible to introduce tritiated water as a tracer. If sufficient amounts of tritium were available, a large-scale experiment to study the hydrologic cycle could be devised. Even on smaller scales, tritiated water could be used to study such features as the evaporation from a ponded lake, water sources for dew, contributions of local transportation or evaporation from local bodies of water to precipitation elements, and so forth.

Activation analysis techniques extend the possibilities for studying very small particles (such as sodium chloride) that play an important role in condensation and ice formation. Radiosilver can be introduced in a preparation of silver iodide to determine the presence of silver iodide in the precipitation which was alleged to be stimulated by it. By releasing another tracer which would be scavenged with equal efficiency by precipitation, it might be possible to determine whether the silver iodide has played a role in the formation of the precipitation.

Finally, the ionizing properties of radioactive substances can be used to make local changes in the electric fields of the atmosphere to determine whether or not such changes affect weather processes.

Atomic Explosions and Weather

From the beginning of time, man has looked beyond the field of meteorology in the hope of finding some explanation for the vagaries of weather. Many inventions of man—gunpowder, radio, airplanes, and television—have been blamed for changes in weather and climate. It is only natural that atomic and thermonuclear explosions, being among the most dramatic achievements of mankind, would come in for their share of the blame.

There seems to have been an increase in unusual and undesirable weather in the past decade. When submitted to rigorous statistical tests, these apparent abnormalities do not exceed the limits that can be expected by chance and are consistent with accepted meteorological principles involving large-scale (hemispheric) weather patterns which could not be directly affected by the explosions. The failure to detect statistically significant changes in the weather during the first 10 years of the atomic age is no proof that physically significant changes have not been produced by the explosions, but it does show that a careful physical analysis of the effects of atomic and thermonuclear explosions on the atmosphere must be made.

The energy of even a thermonuclear explosion is small when compared with most large-scale weather processes. Moreover, it is known that much of this energy is expended in ways that cannot directly affect the atmosphere. Even the fraction of the energy which is directly added to the atmosphere is added in a rather inefficient manner from the standpoint of affecting the weather. Meteorologists and others acquainted with the problem are readily willing to dismiss the possibility that the energy released by the explosions can have any important direct effect on the weather processes. However, there remains the possibility that the explosion will serve as a trigger mechanism to divert some much larger natural store of energy from the path it would otherwise have followed.

Three general means by which this might be accomplished have been considered. (i) The debris thrown into the air by the explosion may have some catalytic effect on the behavior of clouds and thereby change the regime of cloudiness or precipitation over wide areas. (ii) The radioactive nature of the debris will change the electric conductivity of the air, and this may have some effect on more directly observable meteorological phenomena. (iii) The debris thrown into the stratosphere by the explosion may interfere with the passage of solar radiation and thereby serve to decrease the temperature of the earth.

Our present knowledge of atmospheric physics makes difficult a final authoritative evaluation of any of these possibilities. The results of studies and experiments conducted by various organizations show the following:

1) The debris which has been thrown up into the atmosphere by past detonations was found to be ineffective as a cloud-seeding agent. Since the techniques for testing nucleating efficiency are not entirely satisfactory, the condensation and freezing nuclei produced by nuclear explosions and their effect on the formation of clouds and the precipitation process must be continually investigated.

2) The amount of ionization produced by the radioactive material is insignificant in affecting general atmospheric conditions. Various theories on the possible connection between the electric properties of the atmosphere and the precipitation process are still in the developmental stage.

3) Dust thrown into the air by past volcano eruptions decreased the direct solar radiation received at the ground by as much as 10 to 20 percent. The contamination of the atmosphere by past nuclear tests has not produced any measurable decrease in the amount of direct sunlight received at the earth's surface. There is a possibility that a series of explosions designed for the maximum efficiency in throwing debris into the upper atmosphere might significantly affect the radiation received at the ground.

4) Much of the increase in severe storms reported in recent years can be traced directly to the improved methods of reporting severe storms that normally occur.

No statistically significant changes in the weather during the first 10 years of the atomic age have been found, yet careful physical analysis of the effects of nuclear explosions on the atmosphere must be made if we are to obtain a definite evaluation of this problem. Although it is not possible to prove that nuclear explosions have or have not influenced the weather, it is believed that such an effect is unlikely.

News of Science

British Report on Radiation Hazards

The Medical Research Council of Great Britain recently published a report of a special committee under the title *The Hazards to Man of Nuclear and Allied Radiations* (see editorial in this issue of *Science*). The conclusions of the report were as follows:

On the basis of the considerations in this report we feel justified in drawing the following conclusions in relation to the use of ionizing radiations in peacetime:

1) *Limitation of the use of all sources of radiation.* Adequate justification should be required for the employment of any source of ionizing radiation on however small a scale.

2. *Dose levels to the individual.* (i) In conditions involving persistent exposure to ionizing radiations, the present standard, recommended by the International Commission on Radiological Protection, that the dose received shall not exceed 0.3 r weekly, averaged over any period of 13 consecutive weeks, should, for the present, continue to be accepted. (ii) During his whole lifetime, an individual should not be allowed to accumulate more than 200 r of *"whole-body"* radiation, in addition to that received from the natural background, and this allowance should be spread over tens of years; but every endeavor should be made to keep the level of exposure as low as possible. (iii) An individual should not be allowed to accumulate more than 50 r of radiation *to the gonads,* in addition to that received from the natural background, from conception to the age of 30 years; and this allowance should not apply to more than one-fiftieth of the total population of this country.

3) *Dose level to the population.* Those responsible for authorizing the development and use of sources of ionizing radiation should be advised that the upper limit, which future knowledge may set to the total dose of extra radiation which may be received by the population as a whole, is not likely to be more than twice the dose which is already received from the natural background; the recommended figure may indeed be appreciably lower than this.

4) *Fallout from test explosions of nuclear weapons.* (i) The present and foreseeable hazards from *external* radiation due to fallout from the test explosions of nuclear weapons, fired at the present rate and in the present proportion of the different kinds, are negligible.