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ENTRAINMENT OF A DEVELOPING PLUME
INTO CONVECTIVE CELLS

J. Robert Wayland, Jr., and Lynn T. Ritchie

April 1979

Sandia Laboratories

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ABSTRACT

The assessment of risk associated with a hypothetical nuclear reactor accident which releases radioactive material into the atmosphere requires modeling of the interaction between the developing plume and rainstorms. An important consideration is the entrainment of this plume by convective cells of a thunderstorm. A simple method for estimating the dilution of the concentration of radionuclides in an entrained plume is presented. The effects upon calculated risks when a plume is entrained into a thunderstorm showed considerable changes from those calculated using a simple homogeneous washout model.

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ENTRAINMENT OF A DEVELOPING PLUME INTO CONVECTIVE CELLS

Introduction

Assessing the consequences of a hypothetical nuclear reactor accident, in which gaseous or particulate radioactive material is released to the atmosphere, requires that the interaction between the developing plume and rainstorms be modeled. A complete model of the plume/rainstorm interaction must include the possibility of plume entrainment into convective cells, i.e., the "vacuuming up" of the plume by the strong updrafts of a convective storm. Because of the highly stochastic nature of plume entrainment, it is useful to have an order-of-magnitude estimate of the impact of entrainment upon calculated plume dispersion. The purpose of this report is to describe a method of arriving at such an estimate and develop some estimates of risks.

Background Theory of Updrafts and Plume Dilution

Studies and Models

Measurements made during a study of thunderstorms¹ indicated that their updrafts are about 1500 to 5000 metres in diameter at the base of the cloud. The height of the updraft often exceeds 10,000 m. Thus a rather tall and slender air current exists which, to modelers, has suggested a buoyant, turbulent jet. Many of the very early models of updrafts were for steadystate jets.^{2,3} Another approach is the bubble model of Scorer and Ludlam,⁴ and in one article Ludlam⁵ suggested that thunderstorm updrafts are a succession of bubbles which are formed at the cloud base. It may be that the bubbles are large-scale substructures within an updraft jet. (We will return to the bubble model later.)

The entrainment process has been studied extensively--theoretically and experimentally. In the late 1950's Morton developed the theory of convection from maintained and instantaneous sources.⁶⁻⁸ In 1962 Squires and Turner⁹ extended Morton's work in an improved model which described a cumulonimbus updraft. The assumption in the Squires-Turner model is of a steady-state, turbulent, condensing plume; the environmental air is entrained, according to this assumption, by an inflow velocity which at any height is proportional to the upward velocity of the plume. Thus air is entrained both below the cloud's base and within the cloud.

After 1970 the water balance problem began to attract additional interest. Danielsen, Bleck, and Morris¹⁰ developed a stochastic model for hail growth. A more recent model is based upon first principles with definition of the parameters of microphysical processes.¹¹ However, recent experimental work shows good agreement with steady-state, one-dimensional models.¹²

The first studies of the updraft process suggested that entrainment occurred by continuous involvement of stationary environmental (ambient) air in the peripheral eddies of the updraft.⁹ This was because it was perceived that the edge of the jet will probably not be a sharp boundary. But common sense also suggests that only when there is turbulence in the environment comparable to that in the updraft will there be a significant interchange of air at the sides of the updraft. (However, see the discussion in the next section and in Reference 12.)

A Model of Convection Plumes

For our purposes it is sufficient to use as simple a model as possible to describe the buoyant updraft, and the simplest entrainment assumption which is realistic is that the inflow into the edge of a convective updraft is proportional to a characteristic velocity of the updraft. This assumption is incorporated into the equations representing conservation of volume, momentum, and heat. The conservation of heat can most simply be specified by the equivalent deficiency of density relative to the surrounding air--which deficiency, of course, creates a buoyancy force.

This report follows the plan of development suggested by Morton and coworkers.⁶⁻⁸ In addition to the entrainment already mentioned, the other main assumptions are:

- The horizontal profiles of the fluid vertical velocity and mean buoyancy are similar in form. Each is characterized by a horizontal scale length, b , which is proportional to the radius of the plume at that height.
- Local variations of density in the plume are small compared to the reference density (ambient air at the cloud's base).

The coordinate system most useful for this problem is the cylindrical polar set (x, r) with the x -axis vertical and the source at the origin. In this simple model the vertical velocity $u = u(x, r)$ and the buoyancy force are assumed to be constant across the plume (so-called "top hat" profile). Thus the horizontal scale length, b , is the actual radius to the plume edge. Let $\rho = \rho(x, r)$ and $\rho_0(x)$ be the density inside and outside the plume, respectively, with $\rho_0(0) = \rho_1$ chosen as the reference density of the system. Then the conservation relations require that

conservation of volume,

$$\frac{d}{dx} (\pi b^2 u) = 2\pi b \alpha u, \quad (1)$$

conservation of momentum,

$$\frac{d}{dx} (\pi b^2 u^2 \rho) = \pi b^2 g (\rho_0 - \rho), \quad (2)$$

and conservation of density deficiency (equivalent to heat),

$$\frac{d}{dx} [\pi b^2 u (\rho_1 - \rho)] = 2\pi b \alpha u (\rho_1 - \rho_0) \quad (3)$$

Here α is the proportionality constant relating the rate of entrainment at the edge of the plume to vertical velocity within the plume. As a first approximation the density ρ in the left hand side of Eq. (2) can be set equal to ρ_1 . Equation (3) can be transformed with the use of Eq. (1) and the conservation relations written to:

$$\frac{d}{dx} (b^2 u) = 2\alpha b u \quad (4)$$

$$\frac{d}{dx} (b^2 u^2) = b^2 g \left(\frac{\rho_0 - \rho}{\rho_1} \right) \quad (5)$$

and

$$\frac{d}{dx} \left[b^2 u g \left(\frac{\rho_0 - \rho}{\rho_1} \right) \right] = b^2 u \frac{g}{\rho_1} \frac{d\rho_0}{dx} \quad (6)$$

Such a simple model has hidden assumptions. The use of the above entrainment principle causes an unrealistic coupling of predicted cloud top height and liquid water content. Note also that the above equations are solved for a Lagrangian system; a volume element of a steady-state jet is followed from cloud base to cloud top. And the nonlinear interactions among cloud parcels near the cloud summit have been ignored. Each of these assumptions can affect the full description of the microphysics and macrophysics of the cloud description.¹³ However, large-scale entrainment should be adequately modeled for our purposes.

Bubble Theory of Penetrative Convection

Another description of cumulus clouds that has significant support among scientists studying rainstorms is the bubble theory of penetrative convection.¹³⁻¹⁵ Time-lapse motion pictures¹⁵ and the experience of glider pilots^{16,17} suggest the existence of rising bubbles of warm air. The lower layers of a cloud mass are characterized by fuzzy boundaries which sharpen at greater heights. These

high-altitude, bubble-like shapes have nearly spherical tops for cumulus clouds. A bubble adjacent to the wake of a larger bubble may be sucked in and then rise rapidly through the wake to amalgamate into the larger bubble.¹⁴ If there is no wind, a piece of ground which supplies the energy for bubble formation will exhaust its heat in the creation of fresh bubbles. This limits fresh growth. Wind drift will help in the growth of large bubbles. The large bubbles cohere forming a dynamical system much like spherical vortices, thus preventing disintegration.

The equations of motion for a spherical bubble in a coordinate system stationary relative to the earth are¹⁵

$$\frac{dM(W + w)}{dt} = - \frac{M}{\rho} \left(\frac{\partial P}{\partial z} \right) - Mg + MF_z, \quad (7)$$

and

$$\frac{dM_u}{dt} = - \frac{M}{\rho} \left(\frac{\partial P}{\partial r} \right) + MF_r \quad (8)$$

The equations of motion of the air outside the bubble are

$$\frac{dw}{dt} = - \frac{1}{\rho_o} \left(\frac{\partial P}{\partial z} \right) - G + F_{oz}, \quad (9)$$

and

$$\frac{du}{dt} = - \frac{1}{\rho_o} \left(\frac{\partial P}{\partial r} \right) + F_{or} \quad (10)$$

The variables are W , the vertical velocity of the bubble's center of mass; w , the vertical velocity relative to the center of mass inside and relative to the earth outside the bubble; u , the horizontal velocity in either frame of reference; $P = P_o + p$, the total pressure (P_o the hydrostatic and p the aerodynamic pressure); ρ , the density; M , the bubble mass; F_z and F_r , the frictional force components per

unit mass; z , the vertical coordinate directed upward; r , the horizontal coordinate referred to the vertical axis of the bubble; and t , the time. The densities ρ and ρ_0 are different functions of z and discontinuous at the bubble surface. (These equations predict vertical velocity curves similar to those shown later in Figure 2.)

The growth in volume of the bubble is not as simple as the vertical velocity considerations. Depending upon the atmospheric conditions the radius will change very little during ascent or, at the most, increase by a factor of about five.¹⁵ Thus the dilution of entrained radioactive material is in the range of 1 to 100. This is small compared to the estimates for jets (plumes).

Furthermore, the complete entrainment of the radioactive plume into a bubble would occur only in the first stages of dispersion, i.e., within the first few miles. Squires and Turner⁹ have suggested that bubble formation is a dominant process for fair-weather cumulus clouds. A quick review of weather data suggests that, in many locations, fair-weather cumulus clouds occur 20 to 30 percent of the time in the summer.

Results of Calculations of Updrafts and Dilution of Plumes

At the source (ground level) the radius is set equal to R_0 and the momentum is essentially zero. This gives two boundary conditions. The third boundary condition is specified by giving the weight deficiency (assumed known and constant). Integration of Eqs. (4) through (6) provides the results shown in Figure 1. The initial radius is taken to be 1 km with updraft velocity initially at 2 m/s. The pressure at cloud base was assumed to be 90 kPa and the cloud base virtual temperature is 20°C. The environment (ambient air) is a saturated 100 percent relative humidity. The different results for lapse rates of 5.5°, 6°, and 7°C/km suggest the importance of this parameter. The resulting updraft velocity is shown in Figure 2 for the same initial conditions.

Figure 1. The Variation With Height of the Radius of the Updraft Plume for Different Lapse Rates. Pressure at Cloud Base 90 kPa, Initial Velocity of 2 m/s, Cloud Base Temperature of 20°C, 100% Relative Humidity.

Figure 2. The Variation With Height of the Vertical Velocity of the Updraft Plume for Different Lapse Rates. All Variables the Same As In Figure 1.

For lapse rates equal to or less than 6°C/km, changing the ground level radius by a factor of 2 had small (<5%) effect upon the radius above 1.5 km. For a lapse rate of 7°C/km, changing the initial radius by a factor of 2 caused the height obtained by the updraft to change by about 20 percent (the larger the initial radius the larger the final height).

For lapse rates equal to or less than the 6°C/km, changing the initial updraft velocity by a factor of 2 had small (<5%) effect upon the radius above 1.5 km. For a lapse rate of 7°C/km, changing the initial velocity by a factor of 2 caused the maximum velocity obtained to change by about 25 percent (the larger the initial velocity the larger the final velocity).

More complete studies^{9,10} include the thermodynamics of rainclouds. The features of the above picture were reproduced in these studies.

Measurements of thunderstorms updrafts give agreement on the general characteristics mentioned above. Davies-Jones¹² used the Squires-Turner model⁹ to analyze measurements in thunderstorm updrafts. On one critical point there is a major change. The core of the updraft follows a moist adiabatic ascent to midlevels. Thus Davies-Jones found that the cores of strong updrafts are undiluted by environmental air. All the air in the updraft would be supplied from below the cloud base. The uptake of air would be in the form of an upside-down cone with the major input from the first few kilometers.

In the above discussion, the "top hat" cross-section profile for the velocity was assumed. Of course, nature is never that sharp edged. Kyle, Sand, and Musil¹⁸ have analyzed 12 thunderstorm updrafts. The best fit to the updraft profiles was obtained for an axially symmetric jet. For the smaller updrafts, the updraft width and maximum vertical velocity are linearly related. This is not true for wider updrafts. The importance of this investigation lies in the implicit assumption of a well-mixed updraft of the "top hat" profile. These results imply an updraft that is not well mixed. The jet (plume) is eroded away on the outer edges without entraining additional air once the jet is above cloud base. The below-cloud-base air can then act as a dilution mechanism for an entrained radioactive plume.

The above general features of the updrafts suggest a method of estimating the influence on plumes. The mass flux at the base of the cloud is given by $\pi b_1^2 u_1 \rho_1$, where b_1 and ρ_1 are the radius of the updraft and density of environmental air at cloud base. The updraft velocity at cloud base, u_1 , is normally from only a few to about 10 m/s.^{1,12} The radius is in the range of about 5 km.^{1,10,12} If $u_1 = 2.5$ m/s, then the mass flux is about 2×10^8 kg/s. For an updraft lasting 30 minutes, the entrained volume is 3.6×10^{11} m³ (assuming $\rho = 1$ kg/m³). The importance of this entrained volume can be seen if the volume of the developing plume is mixed into the updraft (using the dispersion calculation of RSS¹⁹). For a constant atmospheric stability of Pasquill-Gifford class E, an uniform wind velocity of 5 m/s, the volume dilution, VD, per updraft is shown in Figure 3. Of course, the VD is greatest where the plume is smallest, i.e., close to the release site.

Figure 3. The Volume Dilution of a Developing Plume Under Atmospheric Conditions of Pasquill-Gifford Stabilization E and Uniform Velocity of 5 m/s.

Calculated Effects of Rainout

The next step in our modeling requires some knowledge of thunderstorm structure. For our purposes the work of Byers and Brahm¹ will suffice. They found that:

- The thunderstorm is composed of several distinct regions of action called "thunderstorm cells."
- Each cell has a life cycle that depends upon the growth and fall of rain and the process of entraining in the atmosphere.
- There are three fundamental stages in the life cycle of a thunderstorm.
 1. The cumulus stage in which the cell contains only updraft from base to top.
 2. The mature stage in which the fall of raindrops initiates a strong local downdraft in part of the region previously occupied by the updraft.
 3. The anvil stage in which the entire lower part of the cell contains gentle downdraft. The upper part of the cell contains drafts of negligible velocities.
- The process of entraining combined with convection results in lapse rates in the updraft and downdraft regions that approximate the lapse rates of the environment.
- With updraft lapse rate near that of the environment, it becomes very easy for rain to "trigger" a downdraft that reaches and spreads out over the surface as the cold core of the rain area.

For the present, in-cloud scavenging of material from the plume is ignored. As a conservative order-of-magnitude estimate, the entrained air is returned by the downdraft to the original uptake area. But now the plume has been diluted by an amount of up to 10^4 as suggested in Figure 3.

Normally convective cells in rainstorms do not occur singly. On the average there are four convective cells grouped together into a small mesoscale area (SMSA) of about 250 km^2 .^{1,20} During the life cycle of the SMSA there are both updrafts and downdrafts occurring. There is a rough conservation of mass. The total

updraft volume is roughly equal to the downdraft volume. For an individual cell the updraft stage lasts for about 20 to 30 minutes. The downdraft stage overlaps the updraft stage for 10 to 20 minutes. After the updraft stage is over the downdraft stage continues for another 30 to 40 minutes. During the first 20 minutes of downdraft, the flux is about 2/3 of the updraft flux and then decreases to 1/3 of the updraft flux for the final 20 minutes. Thus the life cycle of the convective cell is about one hour. There will be considerable variation of the fluxes from one cell to the next.

Consider the case of a plume which resulted from a 30 minute puff release and is moving with a mean air velocity below the cloud base. During this dispersion the developing plume encounters a developing SMSA where the plume is entrained by the convective cells within this SMSA and returned to be below the cloud base air. The structure of the convective cells will affect the dispersion of the plume.

The above general description can be modeled by applying conservation of mass and number of radioactive nuclei. The simplifying assumption is made that the time scale is short so that there will not be appreciable radioactive decay. The addition to include this effect is straightforward but tedious. Conservation of mass implies that

$$\frac{dV}{dt} = \sum_{i=1}^N \left(\frac{dv_i}{dt} \right)_V - \sum_{i=1}^N \left(\frac{dV}{dt} \right)_i \quad (11)$$

and

$$\frac{dv_i}{dt} = \left(\frac{dV}{dt} \right)_i - \left(\frac{dv_i}{dt} \right)_V \quad \text{for } i = 1, \dots, N \quad (12)$$

Here V is the volume of air in the SMSA below the cloud base; $(dV/dt)_i$ is the rate of volume of (air) flow from V into the i^{th} convective cell; $(dv_i/dt)_V$ is the volume flow rate into V from the i^{th} cell; and N is the number of cells in the SMSA. Conservation of radioactivity requires that

$$\frac{dX}{dt} = \sum_{i=1}^N K_i \frac{dv_i}{dt} - \sum_{i=1}^N K_x \frac{dV}{dt} = \Lambda_w X \quad (13)$$

and

$$\frac{dx_i}{dt} = K_x \left(\frac{dV}{dt} \right)_i - K_i \frac{dv_i}{dt} - \Lambda_i x_i \text{ for } i = 1, \dots, N \quad (14)$$

where X is the radioactivity (in Ci) in V , x_i the radioactivity in the i^{th} cell, K_x the specific radioactivity (Ci/m³) in V , and K_i the specific radioactivity in the i^{th} cell. The washout of radioactivity within V is parameterized by the washout coefficient Λ_w for below-cloud processes and Λ_i is the rainout coefficient for incloud removal of radioactive material. Initial conditions must be specified for the volumes and radioactivity in each region. The washout coefficient is of the order of 10⁻³/s.²⁰ Note that washout will not be uniform over the entire SMSA. The washout will be higher under the convective cells in which rain occurs. Typically each cell occupies about 1/10 of an SMSA.¹ The rainout coefficient is very poorly known and will probably be in the range of 2.6 x 10⁻³ to 6 x 10⁻²/min.²¹ The rainout will be more effective at removing the radioactive material that is entrained into the convective cell as the material is present at the formation of the rain droplets.

The rate of air flow from SMSA into a cell, $(dV/dt)_i$, can be estimated to be about 1.2 x 10¹⁰ m³/min. The downdraft is a little more complex in structure. The first stage has larger air flow that is gradually reduced. Not all of the entrained air will necessarily be returned to the below-cloud region. To simulate the air flow, the top-hat flux profile shown in Figure 4 was used. The observed

occurrence of multiple cells within an SMSA is approximated, in the simplest model, by three consecutive cells. The second cell starts 20 minutes after the first and the third starts 40 minutes after the first. A more realistic flow rate pattern²² is shown in Figure 5. For the purposes of gaining insights, the flow pattern of Figure 4 will be used first. The more complex pattern of Figure 5 will be used in the estimation of dilution factors of severe rainstorms on dispersing plumes. Care must be used in the selection of flow rates and the initial volume of the SMSA to insure conservation of mass.

Figure 4. The Top-Hat Updraft and Downdraft Rates Used to Simulate Air Flow in an Individual Convective Cell. The Time and Actual Flow Rates Can Vary Over a Large Range of Values. However, Conservation of Mass Requires That the Area Under the Updraft Curve Be Equal to the Area Under the Downdraft Curve If All Entrained Air is Returned to the Below-Cloud Region.

Figure 5. A More Realistic Flow Rate Pattern That Adequately Describes the General Features Of a Small "Single-Cell" Cumulonimbus Cloud Or the Convective Elements in Larger "Multi-cell" Clouds.

Consider the idealized occurrence of a plume of 3.85×10^{11} Ci being entrained within the first 10 minutes of the development of an SMSA. For the case of rain occurring in all three cells (C_1 , C_2 , C_3), the movement of the radioactivity in the SMSA is shown in Figure 6. The rainout and washout coefficients are all assumed to be independent of rainfall rate and equal to 0.06/min. As the plume

is drawn into the SMSA, C_1 quickly begins to entrain the radioactive material. The entraining updraft continues until $t = 20$ minutes when the downdraft from C_1 returns the material to the below cloud base region. But C_2 is now entraining. Thus the material within the below-cloud base is further mixed and removed by wet deposition processes. By the time the third cell begins entrainment, the below-cloud base plume has been depleted of its radioactivity by almost 2 orders of magnitude. In the final stage of the cycle of the SMSA, the downdraft of C_3 momentarily increases the below-cloud activity. In this simple example, the activity within the SMSA has resulted in an additional reduction of almost 3 orders of magnitude in the entrained radioactivity.

Figure 6. The Time History Of the Movement of Radioactive Material Into and Out of the Convective Cells of a Simplified SMSA. The Rainout and Washout Coefficients Are All Assumed to Be Equal to 0.06/min. The Flow Rate Pattern Is That Shown in Figure 4. With Three Cells (C_1 , C_2 , C_3) Starting at 0, 20, and 40 Minutes.

When the more realistic flow rate pattern (Figure 5) for individual cells is used, the results shown in Figure 7 are obtained. The overall effect on the diminishing of radioactivity is about the same as for the simplified model. The air flow pattern of Figure 5 is used for all subsequent calculations.

The variation in the dilution factors, as affected by changes in the plume entrance time into the life cycle of the SMSA and also as affected by the fraction of the entrained air remaining in the cell, are considered next. In Figure 8 the impact of varying the entrance time of the plume into the SMSA is shown. As expected, the effect can cause a variation of up to an order of magnitude. If part of the entrained air remains in the cell, there will be additional reduction in the below-cloud base radioactivity. For example, when 10% is retained in each cell, there is an additional 30 percent reduction in the dilution.

Figure 7. The Time History of the Movement of Radioactive Material For A More Realistic SMSA. The Flow Rate Pattern of Figure 5 Was Used. All Other Parameters Are the Same As In Figure 6.

Figure 8. The Change of the Dilution Factor Introduced By the Change of the Entrance Time of the Plume Into the SMSA. All Other Parameters Are As In Figure 7.

The radioactive material that is rained out or washed out will increase the concentration on the ground. For the above conditions, about 35 percent is rained out within the cellular substructures. Because of the large area and length of time, the below-cloud base washout removes over 60 percent of the radionuclides from the plume trapped within the SMSA.

The importance of convective entrainment in air and ground concentration calculations can be established using the consequence model of the Reactor Safety Study (RSS) (see Reference 20 for a description of the modeling of plume rain-storm interactions in RSS). For a rainstorm (fixed Pasquill stability class D) a calculation was made with the original model and with a modified dispersion in which the area of the plume was expanded by the rainstorm and the plume was mixed up to the cloud base. Actually this results in an underestimate of the dilution effects of entrainment for distances close to the reactor site. Close to the release point the volume expansion is not as great as the above discussion implies. This is because of the lack of compatibility of simple area expansion with the dispersion model in the RSS consequence model. (The RSS consequence model will not allow expansion above an arbitrary limit.) Even with this volume restriction the reduction in air concentration is considerable as seen in Figure 9. For this calculation the rain occurs throughout the plume dispersion time at rate of 1 mm/hr.

Figure 9. The Effect Of Convective Entrainment of the Plume Upon the Air Concentration Is Shown By the Difference Between No Entrainment In the Original Model and the Entrainment Model Curve.

Because this implies a cellular rain rate of 12.5 mm/hr the resulting ground concentration is increased over that predicted by the simple RSS model. Thus for a specific storm the influence of convective entrainment can dominate the dispersion calculation. The impact upon average consequences however is small. This is because of the small percentage of time that rain actually occurs. However, one must remember that convective entrainment will not always be associated with rain.

The changed air and ground concentration will result in altered conditional probabilities per capita of early and latent fatalities. Again, using the consequence model (CRAC) from the Reactor Safety Study (WASH-1400), the conditional probabilities per capita of early and latent fatalities were calculated for the rainstorm used in Figure 9. The results are shown in Figure 10 and 11. Note that no allowance for runoff was made. The reduced air concentrations and increased ground concentrations over the original model resulted in an increased conditional probability of early fatality for distances out to 1 km. The effective radius for early fatalities is reduced from about 20 km to 1 km. The new model indicates an increased conditional probability of latent fatality to beyond 100 km. (Note that it was assumed in this calculation that no immediate evacuation

of population occurs.) Because of the difficulty of estimating the occurrence of entrainment when rain is not present, no attempt is made here to assess the impact upon a complete (stratified) calculation with CRAC.

Figure 10. The Conditional Probability Per Capita For Early Fatalities for the Rainstorm of Figure 9. First, Calculations were Made Using CRAC of the RSS (Reference 23). No Runoff or Evacuation Occurs. The New Model Calculations Were Made With CRAC Modified to Include Increased Dispersion.

Figure 11. Conditional Probability Per Capita for Latent Effects. (Same Conditions as in Figure 10).

Conclusions

The importance of convective entrainment of a developing plume has been ignored in the past. The modeling of below-cloud-base entrainment can be accomplished by straightforward application of physical laws. Of course, the solution of the descriptive equations may not always be easy. Any complete study will require that the effect of plume moisture and radioactive heating upon convective cell formation be included. This has not been done.

The more rapid dispersion of the airborne radioactivity when a plume encounters a convective storm suggests the need for a more careful modeling effort. The air concentrations can easily be reduced by factors of up to 10^4 close to the site for an entrained plume over those of a nonentrained plume. Therefore, the large percentage of convective clouds which do not produce rain at the plume, but that can greatly add to the dispersion, should be included. If a radioactive material plume encountered a convective rainstorm, large ground concentrations could result. However, the impact upon average consequences would be small because of the small percentage of time that rain actually occurs [20]. Also, the ground concentrations produced by heavy rain-out will result in increased runoff, especially in densely populated areas.

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